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Chapter 29

Design and development of the Steinhart aquarium's Philippine coral reef exhibit

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ABSTRACT

The Steinhart Aquarium and the California Academy of Sciences will reopen its Golden Gate Park facility in late 2008 following a total renovation. A major component of the new museum is an exhibit gallery focusing on Philippine coral reefs. The centerpiece of this gallery is an 800 m^3 living coral aquarium that is 7.6 m deep. Visitors will observe this exhibit from the water surface, as well as through five distinct underwater views. An aquarium of this size and scope created multiple challenges for the design team. In order to stock this exhibit in an ecologically responsible manner, we constructed an indoor coral farm in downtown San Francisco. Here we are growing more than 1,000 colonies obtained as cuttings from fellow zoos and aquariums as well as from private hobbyists. We have researched and designed an artificial lighting system that provides sufficient Photosynthetically Active Radiation (PAR) at depths varying from 0.3 to 7.6 m, while remaining unobtrusive from the visitor space. This paper will describe how the challenges of creating such an exhibit have been overcome through the collaborative efforts of architects, exhibit designers, engineers, electricians, research scientists, outside consultants and Steinhart Aquarium biologists.

EXHIBIT DESIGN INTENT

The Steinhart Aquarium maintains the living collection of the California Academy of Sciences (CAS): a combination aquarium, planetarium, natural history museum, and research and education center. We have been a pioneering science institution for more than 150 years. The California Academy of Sciences will move into a brand-new, state-of-the-art facility in 2008. This new building, designed by Pritzker Prize winning architect Renzo Piano, will be an international tourist destination. It is a San Francisco green building pilot project, and sustainable building features are integrated throughout. A living roof composed of native California plants tops the structure. Floor to ceiling glass walls surround the public spaces. The Academy is proud to be part of a campus of museums, botanical gardens and other attractions in San Francisco's historic Golden Gate Park. Our new building embodies our mission: to explore, explain and protect the natural world. It focuses our efforts to educate our guests about biodiversity, conservation and the importance of preserving vital habitats. One of the habitats we highlight is a Philippine coral reef.

There are three main reasons that led us to select the Philippines for a major iconic exhibit in the new California Academy of Sciences facility. First, CAS researchers have conducted surveys, documented and described species from Philippine reefs since the early 1990's. The California Academy of Sciences has developed a memorandum of understanding with the Philippine Bureau of Fisheries and Aquatic Resources (BFAR) to partner on issues of marine conservation, scientific training and education, the collection of living specimens for husbandry research and to develop new opportunities for ornamental aquaculture in the Philippines. Second, the Philippine islands are an epicenter of marine biodiversity and evolution (Carpenter and Springer, 2005). Although these reefs have been greatly affected by anthropogenic stresses, there are numerous conservation stories that can be told about the reversal of destructive fishing practices and the success of grass-roots environmentalism in areas like Mabini, Batangas (Oracion *et al.*, 2005). Finally, the San Francisco Bay area has a large population of Filipino immigrants and Filipino-Americans that we can engage and develop relationships with through programming, partnerships and opportunities for continuing education.

The Philippine Coral Reef exhibit will be a centerpiece of the new Steinhart Aquarium, showcasing the interrelationships of mangrove, lagoon and reef habitats. The exhibit is integrated into the architecture: “iconic” in scope and scale. We are determined to have one of the largest and the deepest reef tanks in the world, and we understand the challenges regarding husbandry, life support systems and stocking the tank with a diversity of aquatic organisms. This paper will summarize our efforts at planning such an ambitious exhibit: including developing the reef structure, a sustainable stocking plan and in particular, the design of effective lighting systems for large, deep tanks.

WINDOWS, ROCKWORK AND WATER CIRCULATION

There are five independent underwater views into the Philippine Coral Reef exhibit in the new Steinhart Aquarium. The main window is 9.4 m across and 5 m tall. It is a complex, toroid curve, bowing in two directions, and creates a panoramic, theater-like view in a space complete with seating. In addition, there is a smaller window, nicknamed the “Buddha” window by our construction crew due to its belly-like curve projecting into the exhibit space. This window is 4.8 m across and 3.3 m tall. The cave window will provide a very dramatic, 27 m view-path through a cavern penetrated by shafts of light streaming down through openings in the overhead rockwork. Finally, a pair of windows, including an acrylic dome “pop-up” will offer an up close and personal experience with garden eels.

The independent nature of these views necessitated a complex arrangement of rockwork. Dixon Studios (Tuscon, Arizona, USA) fabricated all of the rockwork in our major exhibits. They worked closely with our exhibit designers (Thinc Designs, New York City, USA), art director (Richard Graef, ACE Design, Sausalito CA), CAS scientists and various contractors, to insure that the rockwork accentuates our guest experience by maintaining the discrete views, hiding the in-tank plumbing, and appearing naturalistic and scientifically accurate. The rockwork infrastructure also incorporates various attachment sites for the living coral and live rock.

The rockwork is a solid mass, constructed of concrete block and poured concrete, with a sprayed on texture coat. It is a permanent structure, carved and sculpted to resemble coral rock of the kind found in the Philippines. We have identified approximately 93 m^2 where the artistically treated texture coat will be minimized, and concrete ledges will be constructed to receive the live rock and living corals. Dixon Studios has been working with samples, scientific specimens and photographic reference material to insure that there will be a relatively seamless transition between the artificial rockwork and the natural materials added by the aquarium staff.

The solid mass of rockwork also facilitates hiding the complex arrangement of in-tank plumbing. There are five circulation zones consisting of either an array of nozzles (Hayward Hydrostream Model SP-1420, 3.8 cm fitting with 2.5 cm diameter adjustable nozzle) or eductors (BEX Tank mixing eductor model T4MP, 3.8 cm). Eductors were placed along the sides of the viewing windows, where the rebate between the acrylic and tank walls allows them to be hidden. There are 15 eductors on each side of the main viewing window and the Buddha window. Nozzles are located at the tops and bottoms of windows, as well as in various locations throughout the tank. There are 10 nozzles above and below both of the large windows, and an additional 20 embedded in the rockwork. Individual 40 HP jet pumps controlled by variable frequency drivers supply each of the five circulation zones. The zones are switched via actuated valves, so that the direction of the water current changes at programmable time intervals. There is a total of more than 1,000 $m^3.h^{-1}$ of flow through the circulation loops alone.

ETHICALLY STOCKING A LARGE-SCALE REEF AQUARIUM

While it is technically possible to travel to tropical islands, collect hundreds of corals, and transport them successfully back to the United States for exhibit, this does not reflect the mission of the California Academy of Sciences: "to explore, explain and protect the natural world". In order to stock our exhibit in an ecologically responsible manner, we constructed an indoor coral farm in downtown San Francisco. Working with various partners, including our sister institutions, Waikiki Aquarium, Henry Doorly Zoo, Monterey Bay Aquarium, Atlantis Marine World Aquarium, and New England Aquarium, as well as with private hobbyists and local aquarium societies, we obtained more than 1,000 cuttings of reef corals. We are currently growing these in 41 modular bins we call "coral rearing pods" (CRPs). We have also formed a relationship with United States Fish and Wildlife Service inspectors, providing identification and temporary housing of confiscated or abandoned specimens, and retaining many of these when the investigation has been completed. This relationship has led to the placement of more than 300 living specimens in our aquarium. Many of these are species that are currently not suited to propagation, for instance *Trachyphyllia geoffroyi* (Audouin, 1826), and thus would have to be purchased as wild-collected specimens.

Aquarium staff and volunteers mounted stony coral fragments onto live rock substrate using underwater epoxy putty. The majority of this substrate is Walt Smith's cultured Fiji live rock. A smaller percentage of natural (collected) live rock was used in order to boost diversity, and to vary shapes and sizes. We have also received confiscations of live rock, which were added into the mix.

The CRPs are simple systems, consisting of five or six plastic agricultural bins (Xytec Magnum containers) linked together in series to simulate a raceway. A Hubbell 1kW metal halide fixture with a NEMA-4 reflector (Hubbell Lighting, Greenville, South Carolina, USA) and a Sunmaster Cool Deluxe (Venture Lighting International Solon, OH, USA) lamp illuminates each bin. Circulation is provided by a single 2 HP pump (Sweetwater, Aquatic Eco-systems Inc, Apopka, FL, USA), which draws from the first bin and returns to each bin independently through a spray bar mounted just below the surface of the water. An ETSS 1800 (AE Tech Inc., Beacon, NY, USA) protein skimmer is the primary method of filtration; it is fed by a dedicated 0.75 HP Sweetwater pump. An Aqualogic Delta Star in-line chiller (1.75 HP) (Aqualogic Inc., San Diego, CA, USA) controls the water temperature on each system. This is critical, since the temperature in the CRP room exceeds 37.7 °C every day due to the 36 kW of light and all of the heat from the pumps- even with a large fan exhausting the hot air out of an open window. It truly is a tropical oasis in the middle of foggy San Francisco.

Calcium is supplemented by the daily addition of 20 to 40 L of saturated kalkwasser, depending on salinity and evaporation rates. We also have built and installed calcium reactors, which are based upon the design used on our large coral display at our temporary Howard Street museum (see additional paper in these proceedings for design details). The CRP calcium reactors are 1.7 m tall, and have a reactor chamber that is approximately 10 cm in diameter, for a total media capacity of 11.3 L.

Our goal is to grow approximately 93 m^2 of coral between our coral farm and our display. We are well on our way, with more than 65 m^2 as of April 2008. We are optimistic that by acquiring and growing hundreds of corals over a period of two years, we will be able to stock our new exhibit to approximately 50 % reef coverage on opening day. In this way, we can limit the number of wild-collected colonies necessary and still provide an inspirational and educational experience for our visiting guests.

METHODS FOR EVALUATING LIGHTING SYSTEMS

By far, the most critical design aspect for such a large and ambitious reef aquarium is the lighting system. This is especially important in temperate areas where natural sunlight is neither intense nor reliable. Sunlight studies by Space, Light and Time Advanced Lighting Design (Amsterdam, Netherlands) commissioned during the early stages of our design process determined that there are only 75 cloudless days per year in Golden Gate Park, San Francisco, California. In order to utilize available natural light to the greatest degree possible, the exhibit plan for the building was revised to place the exhibits with the highest light requirements in the areas with the most natural sunlight. Even with these adjustments, we recognized that artificial lighting is essential, and the effectiveness of our lighting system will in large part determine the success of the exhibit.

The lighting system that was installed in our temporary museum was a prototype of the system that we intended to use in our new building. This setup consisted of ten 2 kW Sill fixtures with narrow-beam reflectors. One of our main goals for our temporary facility was to evaluate the techniques and the technology that we would be installing in our new building in Golden Gate Park. Lighting systems were at the top of this list. So, in order to influence the design through scientific investigation, we tested both 1 kW and 2 kW lighting systems from several manufacturers (Table 1). Lamps were chosen based upon their spectrum and wattage. Fixtures and reflectors were specified according to optics; corals growing in shallow water require more even light, while narrow spot reflectors are necessary to penetrate depths greater than 3 m. Several ballasts were evaluated for the Sill 2 kW system due to problems encountered with the initial design, and the subsequent re-engineering of this system by our staff.

Light penetration was evaluated by measuring PAR as photosynthetic photon flux in µE.m^{-2}.s^{-1} using a Li-Cor LI-193SA spherical quantum sensor and Li-1400 datalogger (Li-Cor, Inc. Lincoln Nebraska, USA). The sensor was mounted vertically to a weighted rig suspended from a long pole by a string marked in 30 cm increments. For each fixture, the brightest spot (the hypothetical center point of the beam) was found and recorded for depths from 0.15 to 4.5 m. The rolling average function of the Li-1400 datalogger was used at a setting of 1 second in order to control the variations seen at each depth. Three trials were performed for each fixture/ballast/lamp combination and the results of these trials were averaged. All 2 kW fixtures were measured from a mounting height of approximately 2.4 m off of the water surface. Color temperatures were measured with a Konica Minolta CL-200 chroma meter (Konica Minolta Sensing Americas, Inc., Ramsey, NJ, USA).

In order to test the hypothesis that combinations of lower wattage lamps could match the performance of single 2 kW fixtures, we mounted three Hubbell 1 kW fixtures (with narrow-beam, NEMA-2 reflectors) on a triangular frame approximately 1.2 m above the water surface. These fixtures were mounted 60 cm on center, and all angled slightly inward, so that at depths of 3 to 4 m, the beams would overlap. The methodology described above was used to record PAR from 0.15 to 4.5 m for single, double and triple lamp combinations.

We defined light requirements for corals according to the following criteria. Spectral quality needs to be consistent with or above the color temperature of natural sunlight (5,500 K or

Table 1: A summary of the various fixtures, ballasts and lamps evaluated in this study. These are the systems currently available in the United States that operate lamps with the appropriate spectrum for maintaining corals and are suited for wet, aquarium environments.

Wattage (kW)	Fixture	Reflector	Ballast	Lamp	Lamp code	Reported color temp. (K)	Measured color temp. (K)	Reported lamp life (h)
2	Sill/Se'lux	Type-1	Sylvania	Osram	HQI-2000 W D/S	5,900	5,800	3,000
2	Sill/Se'lux	Type-1	Advance	Osram	HQI-2000 W D/S	5,900	8,700	3,000
2	Sill/Se'lux	Type-1	Vossloh/ Schwabe	Osram	HQI-2000 W D/S	5,900	5,800-6,200	3,000
2	Sill/Se'lux	Type-1	Vossloh/ Schwabe	Ushio	HIT-DE-2000 dw	6,600	6,400-6,600	2,000
2	GE	S01	GE	APL	APL2KWMUSCO 13"DL	5,600	6,000-6,500	3,000
1	Sill/Se'lux	Type-1	Vossloh/ Schwabe	Osram	HQI-1000 W D/S	5,800	5,800-6,200	3,000
1	Hubbell	NEMA-2	M47	Sunmaster	M1000WU37/CDX	6,500	8,000-10,000	10,000
1	Hubbell	NEMA-2	M47	Venture-Blue	BT561000W	20,000	>10,000	10,000

greater). Light intensity should be between 200 and 1,000 µE.m^{-2}.s^{-1} for optimum coral health and growth, based upon our experience with other captive coral systems, and conversations with consultants and colleagues (Delbeek, pers. com.). Any lighting system developed for the new exhibit needed to meet these basic criteria.

RESULTS OF LIGHTING TESTS

The Sill 2 kW type-1 fixture with the Sylvania ballast has the highest PAR output of all the fixtures tested (Figure 1). The Sill fixture, with a narrow beam reflector, provides more than 3,000 µE.m^{-2}.s^{-1} at the water surface, and penetrates through more than 5 m of water. At first we were quite pleased with the performance of this fixture, and we were confident that it would be suitable for our new exhibit. However, the Sill/Sylvania combination quickly revealed serious design problems. Within the first six months of operation, many of these fixtures failed: some of them in a very dramatic fashion involving smoke, sparks and hot, dripping electrical compound. We made several inquiries to try and uncover the root of this malfunction. As time passed, and lights continued to fail, the lighting system no longer met the needs of the living collection housed within this display. The manufacturer was unresponsive to the urgency of our situation, and it became necessary to re-engineer the system in-house. It was only due to the talent and ingenuity of the CAS electrical and electronics departments that we came to a working solution. We managed to re-design this system and expand it beyond the manufacturer's stated capacity. We remote-mounted the ballasts, installed protective mechanisms (such as fuses, and fans to disperse the heat from sensitive electronic components) and made the system work for us in the short-term. We determined that the most likely reason for this failure was that the American Sylvania ballasts do not meet the specific requirements of the European Osram HQI 2 kW lamp. Operating the lamp with this ballast quickly diminished its usable life, and after a few months, the lamps became progressively more difficult to ignite. These repeated "hard starts" eventually caused the capacitors to explode, destroying the entire ballast system.

Recognizing that unless we found a suitable alternative, we were likely to inherit a new facility full of these fixtures, we immediately began to identify all applicable fixture/ballast/lamp combinations. We thoroughly investigated both 1 kW and 2 kW fixtures operating lamps that meet our requirements for growing corals.

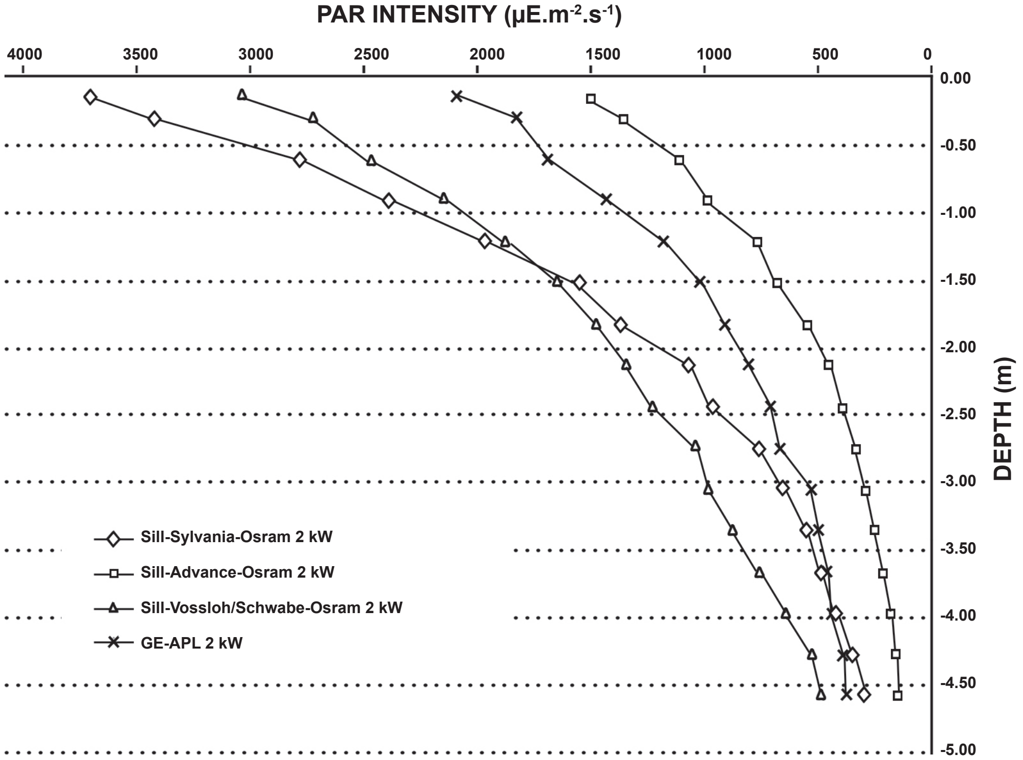

Figure 1: Light output, measured as PAR intensity (µE.m^{-2}.s^{-1}), for all 2 kW fixtures included in this study across a range of depths from 0.2 to 4.7 m. We evaluated 3 different ballast systems for the European Sill fixture, along with the GE 2 kW system.

The first option that we pursued was to find a readily available and reliable alternate ballast for the Sill fixture. The 2 kW metal halide ballast manufactured by Advance Corporation produced less PAR output than the Sylvania system (Figure 1). Also, the color temperature was measurably higher (8,700 K), which suggests that this ballast does not fire the European Osram HQI 2 kW lamp properly.

After more than a year of inquiries, Sill supplied us with some of their European ballast systems to evaluate. The 2 kW European system, with the Vossloh/Schwabe ballast, requires a transformer to operate in the United States. We ran tests with the European setup, and found that it does approach the PAR output of the Sylvania ballast. It does not appear to be plagued with the design problems of the Sylvania ballast, and has performed efficiently and reliably for over 1,000 h of lamp life. It is our belief that the European Vossloh/Schwabe ballast system is the only ballast we tested that properly energizes the Osram HQI 2 kW lamp. Unfortunately, at the time, this system was not UL listed (Underwriters Laboratories: an independent, public-safety-oriented organization that insures that the equipment has been evaluated and meets testing standards), and requires a transformer to work with American electrical systems, precluding its installation by our contractors. Note: Sill has since obtained UL listing for their 2 kW fixture, Vossloh/Schwabe ballast and transformer, and we have installed many of these units over terrestrial exhibits in our new facility.

GE is one of the few American manufacturers of a 2 kW fixture and ballast combination. Their fixture does not have a wide range of reflector types like the Sill, but it does fire a lamp (APL 2 kW) that meets the spectral requirements of corals. While this combination does not match the PAR output of the Sill-Vossloh/Schwabe system, it does perform well across a wide range of depths (Figure 1). In addition, it does not require a transformer, and it has integrated electronic protection systems. It is not currently UL listed, although the manufacturer assured us that attaining this certification would be relatively simple. The APL lamp has a higher color temperature than the Osram lamp, and the blue-white color is more pleasing to the eye. Our primary concern regarding committing to the GE system is the availability of the APL 2 kW lamp, which is a special-order product, and may not be obtainable for the foreseeable future.

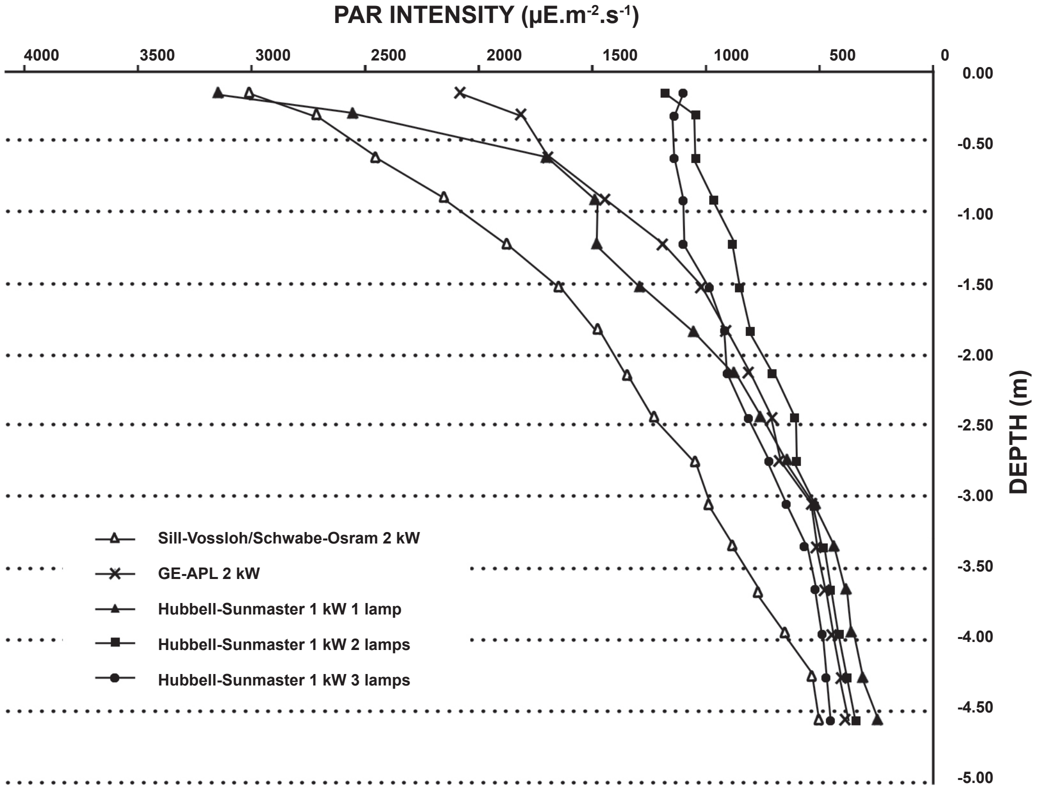

Figure 2: Light output, measured as PAR intensity (µE.m^{-2}.s^{-1}), for Hubbell 1 kW fixtures with NEMA-2 reflectors compared to the two leading 2 kW systems, across a range of depths from 0.2 to 4.7 m. We evaluated the performance of a single fixture, as well as the results of overlapping beams from two and three fixtures.

We also investigated the more readily available, and more proven technology of 1 kW metal halides. Hubbell Sportsliter fixtures are commonly used in public aquariums, incorporate a range of reflector angles, and have a good reputation for value and reliability. We have used these fixtures with great success in our coral farm and on other exhibits. As expected, at depths greater than 1 m, the Hubbell 1 kW fixture had less light output than the Sill 2 kW fixtures (Figure 2). However, a single Hubbell 1 kW did perform comparably to the GE 2 kW system, when it was placed closer to the water surface. By extrapolating the curves generated by our measurements from the surface to 4.5 m, we were also able to predict how the various fixtures would perform at depths up to the 7.6 m in our new exhibit (Figure 3). Combinations of two Hubbell NEMA-2 reflectors with the Sunmaster Cool-Deluxe lamp outperformed both the Sill and the GE fixtures at depths greater than 6 m. The highest performing fixture combination that we tested was three Hubbell fixtures overlaid, which met or exceeded our requirements at all depths. Certainly, one aspect influencing the higher performance of the Hubbell fixtures was a lower mounting height. The 1 kW fixtures were mounted 1.2 m above the water surface: roughly half the distance of the 2 kW fixtures we tested. This discrepancy in our setup was unavoidable due to the limited space available for mounting the additional fixtures above our exhibit for the research trials. However, this lower height more accurately mimics the mounting system employed over our new aquarium.

APPLYING THESE RESULTS TO THE LIGHTING DESIGN

There are several competing priorities to consider when designing a lighting system for a large-scale reef aquarium. First of all, the system must meet the PAR requirements for corals at all depths in the exhibit. In our case, this meant providing between 200 – 1,000 $\mu E.m^{-2}.s^{-1}$, with a color temperature of 5,500 K or greater, from depths of approximately 0.3 to 7.6 m. Second, the system must be sustainable from a maintenance and operational standpoint. The fixtures must be easily accessed, serviced and cleaned. The ballast systems must be reliable and components should be off-the-shelf items readily available for replacement. Most American institutions also have the requirement of UL listing. In addition, the lamps must be readily available, have a long lifespan (≥ 3,000 h), and be economical to replace.

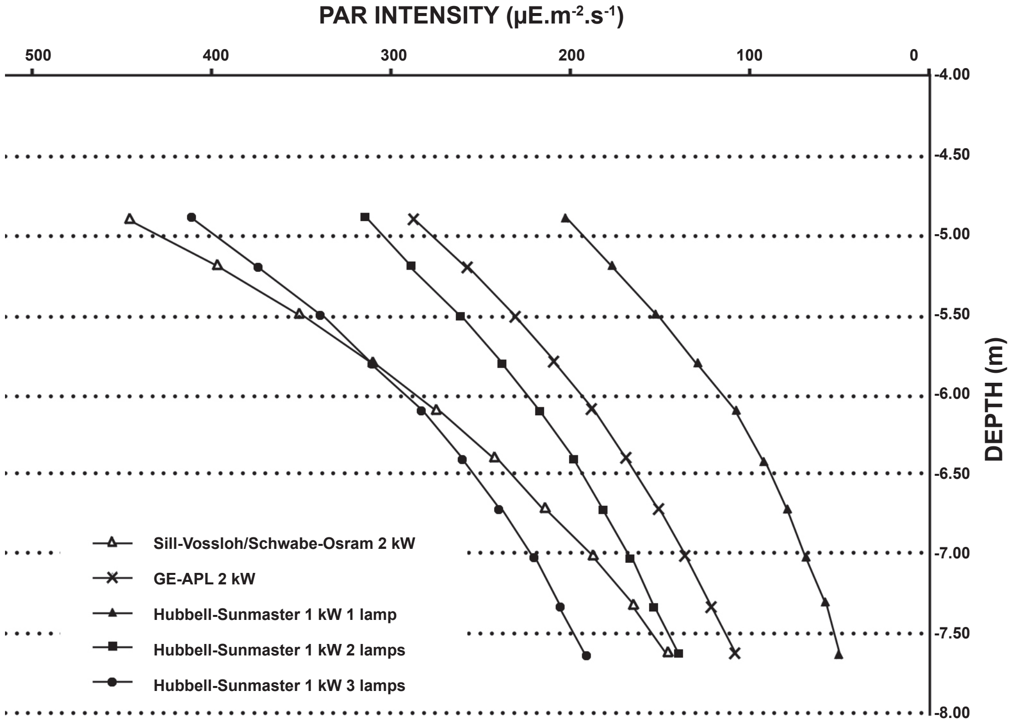

Figure 3: Predicted light output, as PAR intensity ($\mu E.m^{-2}.s^{-1}$), for three fixture-ballast-lamp systems being considered for our new display. We used the data generated from 0.2 to 4.7 m to calculate the expected performance of these systems up to depths of 7.6 m. According to these predictions, combinations of two and three 1kW lamps perform as well as, or better than single 2 kW fixtures, especially at depths greater than 5.8 m.

The number of fixtures required to illuminate a large-scale exhibit compounds all of these considerations. In our case, we are looking at more than 100 fixtures. With multiple lamp changes per year, the operational costs quickly add up. Finally, the lighting rig must not affect the guest experience or the architectural space in a negative manner. This is especially difficult in our new building, where the visiting public can walk around and view the water surface. In other words, there is no behind-the-scenes support area to hide fixtures, ballasts and mounting systems.

The initial design for the new Steinhart Aquarium Philippine Coral Reef exhibit specified a combination of 86 x 1 kW and 2 kW Sill fixtures mounted from a catwalk at a height of approximately 6 m above the water surface. An additional 36 Sill fixtures were to be mounted in an architectural space, known as the planetarium “eyebrow”, where the planetarium’s dome cantilevers out over the water surface. Lower wattage, wider reflector fixtures were to be used at the lower mounting heights in the eyebrow and over shallow areas in the tank. An array of 2 kW fixtures mounted on the catwalk with the narrow beam spread necessary to penetrate through 6 m of air before reaching the water would provide suitable PAR levels at depths of up to 6 m. A lighting mock-up using a scale model of the exhibit, a fiber optic lighting system and computer modeling confirmed that we would be able to accomplish this even with a 6 m mounting height.

Unfortunately, there is no clear 2 kW solution. All of the fixture/ballast/lamp combinations currently available in the United States entail taking considerable risks. At the time of installation, none of them were UL listed, which is required by our contractor. The 2 kW lamps are expensive, short lived, and in the case of the APL lamp, may not be consistently available. High Kelvin (≥ 10,000 K) 2 kW lamps are not available in the United States. The Osram HQI 2 kW lamp loses between 50 and 70 % of its output, depending on depth, by 1,000 h of use (Figure 4). This necessitates replacing lamps at least three times per year in order to maintain adequate PAR levels in the exhibit, which is extraordinarily expensive. With these considerations in mind, and taking into account the experiences of some of our sister institutions, we made the decision to fall back on the proven technology of 1 kW fixtures. This necessitated bringing the lights down close to the water surface in order to maximize their ability to penetrate the 7.6 m deep tank. With the agreement of architects, project managers, contractors and electricians, this is the direction that we have pursued.

Our current lighting scheme consists of a

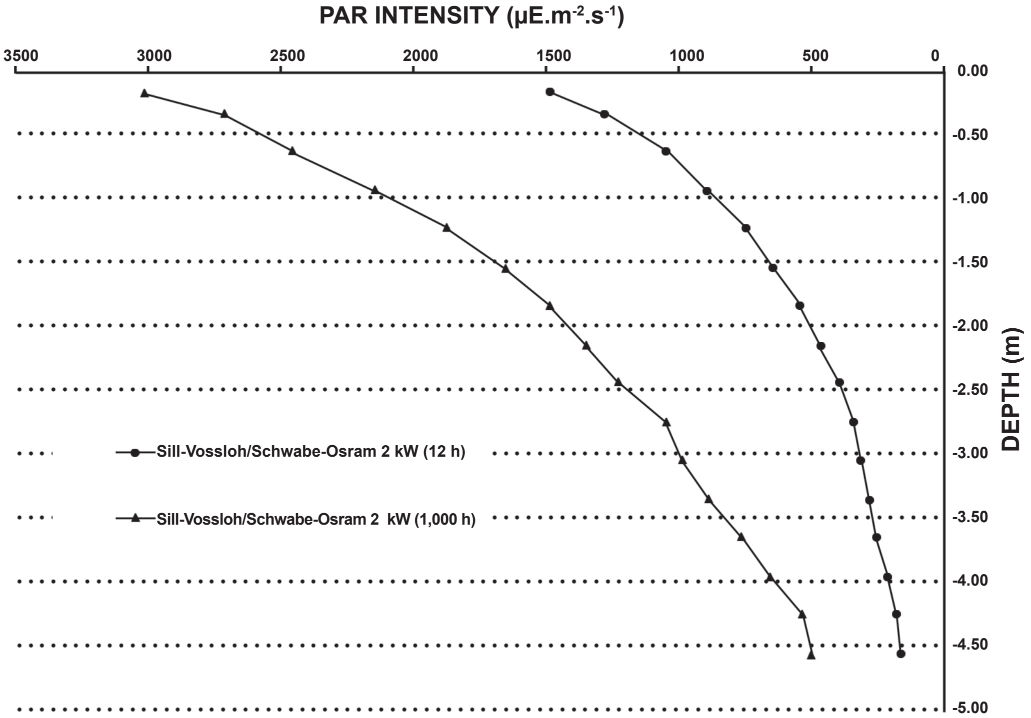

Figure 4: A comparison of a brand-new lamp (12 h use) and an old lamp (1,000 h use) across the same range of depths reveals that the Osram HQI 2 kW lamp loses most of its intensity after a relatively short period of time (approximately 3-4 months).

curved catwalk located at finished floor level, which places the light fixtures approximately 1 m from the water surface. There are more than 100 x 1 kW Hubbell fixtures with four different reflector types (NEMA 2 through 5) arranged along the catwalk and under the planetarium eyebrow. Theatrical light bars mounted 6 m above the water surface at both ends of the tank will be used for a shallow, beach-like area and three mangrove planters. We are confident that this approach will illuminate the exhibit in a more sustainable manner, in terms of ease of operations, electrical consumption and cost-effectiveness.

CLOSING REMARKS

The Steinhart Aquarium, totally reconstructed within the new state-of-the-art California Academy of Sciences facility, will open its doors to the public in late 2008. One of the iconic exhibits of this new museum facility is a large-scale, 800 m^3 Philippine Coral Reef. The main tank, with depths up to 7.6 m, five distinct underwater windows and surface viewing will be like no other coral reef exhibit in North America. Design and development of this tank has proceeded over a period of seven years, and it is quickly becoming reality. Efforts at creating a sustainable exhibit have led us to construct a coral farm in downtown San Francisco. We have tested and evaluated numerous lighting systems from around the world in order to develop an efficient, maintainable method of illuminating such a large exhibit. Interactive programs, environmental education, and CAS research will be highlighted in this space, and we aim to bring the majesty, diversity and complexity of Philippine coral reefs to the million or more guests visiting our facility each year.

ACKNOWLEDGEMENTS

Many people helped to make this exhibit possible: Dave Powell and Charles Delbeek provided extraordinary insights during our initial brainstorming. Charles continues to have a positive effect on most aspects of the exhibit development process: including facilitating the stocking of our coral farm. Thinc design, in particular Tom Hennes, Mike Shakespear, David Lazenby and Chris Tebutt, along with Richard Graef (Ace design) focused the vision with intense creativity. Dan Langlands, Gus Marino, Dean Do and Steve Hefferen were essential in addressing the complex issues surrounding lighting design. Paul Cooley, Dave Cover and Milica Kaludjerski designed robust life support systems based upon very strict requirements. Dixon studios produced extraordinary rockwork and were politely responsive to comments from far too many art critics. Meg Burke and Terry Gosliner integrated CAS education and research goals and priorities in the aquarium exhibit development process and were exceptional dive buddies in the Philippines. Collaborators from Pusod and the members of the CAS Filipino Focus Group, in particular, Ipat Luna, provided references for the successes of Philippine grass roots environmentalism and introduced CAS, first hand, to many of the people behind these efforts. The Kingfisher Foundation provided significant support for our efforts at sustainable collection building. Seth Wolters, Dave Chan, Tom Tucker, Ken Howell, Chris Andrews, April Devitt, Matt Wandell, and the rest of the Steinhart Aquarium staff, past and present, have helped, and will continue to help to make all of this a reality as the California Academy of Sciences moves into an extraordinary new building full of opportunities.

REFERENCES

Carpenter, K.E. and V.G. Springer, 2005. The center of the center of marine shore fish biodiversity: the Philippine Islands. Environmental Biology of Fishes, 72:467-480.

Oracion, E.G., M.L. Miller and P. Christie, 2005. Marine protected areas for whom? Fisheries, tourism and solidarity in a Philippine community. Ocean and Coastal Management, 48:393-410.

PERSONAL COMMUNICATIONS

Delbeek, J.C., 2007. Waikiki Aquarium, Honolulu, HI, 96815, USA.

APPENDIX I: Aquarium Passport

Tank name	Philippine Coral Reef
Location	Steinhart Aquarium, California Academy of Sciences, 55 Concourse Drive, Golden Gate Park, San Francisco CA 94118
Opening date	Fall 2008. Tank stocking began February 1, 2008

INFRASTRUCTURE / PHYSICAL DESCRIPTION

Volume	800 m^3
Surface area	Concrete reef structure with approximately 93 m^2 for coral placement
Depth	7.6 m. Corals from 0.2 to 7 m.

LIGHT CONDITIONS

General	110 x Hubbell 1kW fixtures (M47 ballast, Sunmaster 6,500 K lamp) Hubbell Lighting, Greenville, South Carolina, USA Sunmaster lamp- Venture Lighting, Salon, Ohio, USA Fixtures are mounted on a suspended catwalk (1 m above water surface), beneath a cantilevered section of the building (2-5 m above water surface), and on suspended light bars (5 m above water surface) Some natural sunlight through skylights and windows
Hours of illumination	12 h (8 am to 8 pm) with lamps gradually sequenced on and off
Maximum PAR	Varies extensively throughout the exhibit from 100-1,600 µE.m^{-2}.s^{-1} (not including natural sunlight). Corals planted in zones between 200 and 1,000 µE.m^{-2}.s^{-1}

FILTRATION (external)

Protein skimmers	2 x RK600PE 1.5 m diameter Foam Fractionators (RK2, Escondido CA, USA)
Ozone injection	Ozone supplied through centralized ozone generators (Ozone Water Systems, Sunnyvale CA, USA), controlled by ORP probes at several locations in the filter system.
Sand filters	4 x Neptune-Benson (Neptune-Benson Inc., Coventry RI, USA) 1.5 m diameter horizontal high-pressure sand filters

FILTRATION (internal)

Live-rocks	4.5 metric tons of live rock: 60 % collected, 40 % cultured (Walt Smith International, Fiji)
Substrate	Coral sand substrate present on approximately 10 % of tank bottom

WATER MOVEMENT / CIRCULATION

External pumps	3 x 30 kW jet-pumps
Total flow	5-zone water circulation system. 3 x 30 kW jet-pumps provide approximately 360 $m^3.h^{-1}$ through manifolds consisting of eductors or adjustable nozzles (see text). Flow rate and sequencing of zones is flexible and controlled by LSS management computer. Filtration system provides 408 $m^3.h^{-1}$ through Fractionators and high pressure sand filters
Turn around rate	Approximately 30 minutes, verified by flow meters

WATER CHANGES

Source of "new" salt-water	Natural seawater collected offshore at Ocean Beach, San Francisco, and pumped to facility. This water is mixed with Instant Ocean (Mentor, Ohio, USA) synthetic sea salts to maintain 32-35 ppt

APPENDIX I (continued): Aquarium Passport

Rate of water replacement	Unknown at time of writing. Tank is currently being stocked and husbandry protocols are being developed.
FEEDING REGIME	
Dead food	Various commercial dried and frozen foods, along with a homemade gelatin diet for herbivores. Tank is fed 2-3 $x.d^{-1}$
Live food	Enriched *Artemia* adults and nauplii
WATER QUALITY	
Salinity	32 to 35 ppt
Temperature	25-26 °C
pH	8.1 to 8.3
Redox (mV)	300 to 380 mV
Calcium	380-420 mg $Ca^{2+}.L^{-1}$
Alkalinity	2.5 to 4.6 $mEq.L^{-1}$
Nutrients	Nitrate: none measured at time of writing (tank lightly stocked) Phosphate: 0.06 to 0.15 mg PO_4^{3-}-$P.L^{-1}$
CHEMICAL ADDITIONS	
Calcium and Alkalinity	6 x Schuran CR500 calcium carbonate reactors (Schuran Seawater Equipment, Jülich, Germany) Automatic makeup system using deionized freshwater and Nilsen-style kalkwasser reactor compensates for all water lost to evaporation
Trace elements	No additions made