Founded by particle physicist Frank Oppenheimer in 1969, San Francisco’s Exploratorium seeks to change the way the world learns with a focus on self-teaching and exploration. The hands-on science museum features exhibits such as a wind table where visitors can create flying objects; a fog bridge, which creates the mist that frequently envelops the Bay area; and an “Algae Chandelier” where visitors can pump oxygen to nourish tanks of colored algae, also known as phytoplankton.
Bay water in its heating and cooling system to reduce energy use. The LEED Platinum museum, which consumes significantly less energy than a baseline comparison, is striving to eventually operate on a net zero energy basis.

**Energy-Efficient Design**

The net zero energy goal is an especially challenging pursuit for a number of reasons. Museums typically have very specialized and intensive requirements for exhibits and lighting that consume large quantities of electricity.

In addition, the Exploratorium’s specialized exhibits consume even more power than typical museums to encourage interaction by children and adults alike. Lastly, this new home is actually a renovated warehouse that is suspended over chilly San Francisco Bay.

These challenges, however, also offer ample opportunities for innovation. The 700 ft long pier building is oriented east-west and is ideally designed with a rooftop monitor and vertical glazing to take advantage of good daylighting. Its low sloped roof tilted south serves as the perfect platform to mount 1.4 MW of photovoltaic panels.

The bay water is put to use for geothermal exchange and free waterside cooling for up to eight months out of the year. The structural slab and wood roof, both in need of seismic upgrades and waterproofing repairs, were retrofitted with continuous rigid insulation and in-slab PEX tubing for radiant heating and cooling.

Taken together, these improvements transformed the nearly 100 year old Exploratorium into a high performing building that leverages passive strategies and energy-saving technologies.

Over time, the Exploratorium outgrew its home and was forced to limit its continuing education and teacher training due to a lack of space. The museum found a new home in San Francisco’s Pier 15, which was originally constructed in 1914 and rebuilt in 1930.

The overhaul of the 330,000 ft² of indoor and outdoor space takes advantage of daylighting and uses...
historic warehouse into an efficient and modern Exploratorium ready to educate and entertain visitors for another 100 years, and hopefully enlighten children to the possibilities of greener buildings in the future.

The building design incorporates a number of strategies to achieve a 40% energy savings (93% including PVs) as compared to an ASHRAE/IESNA Standard 90.1-2007 baseline building, as described:

• Radiant in-slab heating and cooling with 9 in. on center 0.625 in. diameter PEX (approximately 28 miles of tubing), which provides premium comfort throughout the building;
• A 100% dedicated outside air system (DOAS) with 30% greater ventilation than ASHRAE Standard 62.1-2007, Ventilation for Acceptable Indoor Air Quality, (67,000 cfm, ~0.3 cfm/ft²) and MERV 13 filtration. A total of 81,000 cfm, ~0.43 cfm/ft² of OA is provided at peak
occupancy to deliver supplemental cooling in perimeter spaces with historic but uninsulated walls;
• Displacement ventilation supplied via overhead diffusers in main exhibit halls and low wall diffusers in offices and classrooms provides excellent indoor air quality and more airside economizer hours;

SCIENCE FOR ALL AGES

The Exploratorium museum is a leader in education for people of all ages. The interactive exhibits expose visitors to all types of science by using their hands and minds to see and experience the world around them. Visitors learn about the living world, human phenomena, seeing and listening, and enjoy some tinkering. The Exploratorium also includes classroom, workshop and lab spaces for visitors to observe and learn about the science behind the exhibits.
• Supplemental cooling provided with ceiling radiant panels in high density classrooms and conference rooms;
• Bay water source heat rejection and absorption, with titanium flat plate heat exchangers, gravity microscreen filtration and water source heat pumps;
• Bay water free waterside cooling for eight months out of year;
• Medium temperature chilled water (55°F to 60°F) and low temperature hot water design (100°F);
• Low pressure drop duct and air-handling unit design for additional fan energy savings;
• Daylighting from existing rooftop monitor and north and south clerestory glazing, existing skylights, and new double-pane low-e glazing;
• Low energy ambient and exhibit lighting design with digitally addressable fixtures; and
• A 40 kW server room with hot aisle-cold aisle arrangement and medium temperature chilled water low pressure drop coils.

Performance
Figure 1 shows a comparison of the building’s baseline and proposed energy use, actual energy consumption, and PV production as measured from November 2013 through November 2014. While the building has achieved its efficiency goals with regards to HVAC and lighting systems, it has only achieved a

WATER AT A GLANCE
Annual Water Use 2.29 million gallons (3.19 million gallons w/ small café)

ENERGY AT A GLANCE
Annual Energy Use Intensity (EUI) (Site) 44.8 kBtu/ft² (50.1 kBtu/ft² w/ restaurants)*
Natural Gas Only used by restaurants for cooking and water heating. Actual data not available.
Electricity (From Grid) 23.33 kBtu/ft² (28.64 kBtu/ft² w/ restaurants)
Renewable Energy (PV) 21.42 kBtu/ft²
Annual Energy Use (kWh/yr) 5,000,000 3,750,000 2,500,000 1,250,000 0
ASHRAE 90.1-2007 Baseline Proposed Design Actual Building Consumption Actual Solar Production
Mechanical Lighting Plug Loads Restaurants Solar Production
Net Zero Goal

Above At the Exploratorium’s wind table, visitors can make flying objects out of everyday items—strawberry baskets, craft sticks, ping-pong balls, pieces of foam—and test the creation’s aerial abilities.

Above left Pier 15 was once occupied by shipping lines and now is a high performing museum pursuing net zero energy operation.

*The restaurant and small café are subtenants, and the Exploratorium has no control over their energy use. The restaurants were not included in establishing the net zero goal.

**Baseline model was not calibrated to actual operation.
was 13.35 kBtu/ft² (including the restaurants). The net zero target was originally established by assessing the maximum amount of PV energy that could be generated with high efficiency panels installed only on the roof of Pier 15.

The original goal was to offset all of the building’s operations with the exception of the tenant-designed and operated restaurants, which pay their own energy bills. The original net zero goal also requires the Exploratorium to cut plug loads by a more substantial 50% as described in Plug Load Performance. Many of the measures to accomplish this plug load reduction have not yet been adopted, but there are specific phased plans to make this a reality.

Predicted solar production in Figure 3 is based on typical year insolation data for San Francisco. Actual production is reported from the PV utility meter. Actual annual production was 3% less than expected for a typical year. However, prior data from the first year showed that based on the number of sunny days the panels should have produced even more.

In the first year (February 2013 through January 2014), total production was only 86% of that expected based on rooftop measured insolation values. According to the installer and service provider, the PV panels have produced less than their potential due to infrequent cleaning and because the Exploratorium was pressured by neighbors to turn off a rooftop loudspeaker system that imitated the screeching of hawks to prevent marine birds from nesting on the panels.

The Exploratorium is in the process of installing fishing line across the panels to prevent nesting and have also agreed to increase the frequency of panel washing from twice annually to quarterly. Both of these measures should bring the PV energy output

10% reduction in overall plug loads compared to the baseline building. Its restaurants are consuming nearly twice as much energy as anticipated in the baseline model.

The systems’ performance (Figure 2) resulted in an annual energy use intensity (EUI) of 50.05 kBtu/ft² (including the restaurants). This energy use represents an overall energy savings of 40% compared to the Standard 90.1-2007 baseline.

However, the Exploratorium has not yet met its original net zero energy target; its annual net EUI (after PV) was 13.35 kBtu/ft² (including the restaurants). The net zero target was originally established by assessing the maximum amount of PV energy that could be generated with high efficiency panels installed only on the roof of Pier 15.

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closer to its potential and help close the gap on the net zero goal.

**Mechanical Systems**
The heart of the Exploratorium’s heating and cooling system is an innovative sea water heat exchange loop that takes advantage of the pier’s location directly over the bay water. The bay water temperature only fluctuates between 50°F and 66°F seasonally and is used as a heat source and heat sink for water-cooled heat pumps to produce hot and chilled water for the building’s radiant slab.

With a medium temperature chilled water loop designed for 55°F to 60°F supply to radiant in-slab tubing, radiant panels and chilled water coils, the building can run on full waterside economizer for up to eight months per year. Also with in-slab radiant heating, the building can be heated with only 100°F water that can be produced very efficiently with the heat pumps.

The radiant heating and cooling system covers 90% of the floor space. Eight 50-ton water-to-water heat pumps handle the job of raising or lowering the temperature of the chilled water and hot water loops to meet comfort demand. No other type of space-heating equipment is used in the building.

Hot or chilled water is pumped through a variable primary pumping system through a 200,000 ft network of PEX tubing embedded in concrete slabs on two levels spanning 82 different heating-cooling zones. Each zone has a set of switch-over control valves and a conventional thermostat to switch...
between heating and cooling based on demand.

The radiant system is ideal for heating at the floor level where the people are instead of conditioning a large volume of air in spaces like the exhibit hall where exposed roof heights are 30 ft to 40 ft above the finished floor.

Taking lessons from a similar system at the Monterey Bay Aquarium, the sea water heat exchange loop is designed to withstand the corrosive saltwater environment and damaging wave and tidal forces. It is also designed to be maintained for the most part from above the pier deck and without the use of chemicals.

A specially designed set of 316 stainless steel intake screens meets all regulations to prevent the impingement or entrainment of baby salmon. The design also uses low pressure drop (only 1 ft w.g.) micro-screen filtration adapted from the fish farming industry (as compared to typical sand filters), enabling small 15 horsepower pumps to be used and lowering pumping energy dramatically.

The sea water loop is coupled thermally to the building condenser water loop through the use of two titanium heat exchangers. Overall, this system results in only a seven-year payback compared to conventional chiller, cooling tower and boiler systems. The portion of this system above the pier is on display for visitors (P. 11).

**Lighting and Daylighting**

The lighting designers discovered when talking with the Exploratorium’s exhibit designers that a lower level of ambient lighting was preferred, resulting in installed lighting densities only half of that typically provided (at about 0.5 W/ft² compared to 1 W/ft²). Exhibits have their own efficient and programmable lighting to supplement the ambient lighting as needed.

Galleries and interior clusters are designed to take advantage of natural daylight and maximize views, and daylighting and occupancy controls are implemented to automatically reduce lighting levels and turn lights off when not needed. A centrally located lighting server enables remote programming of lighting circuits.

The lighting designers, working together with Exploratorium staff and the installing contractors, spent nearly two weeks programming the different lighting devices. The lighting devices were later spot-checked by the commissioning agents. All together, the strategies implemented resulted in over 50% lighting energy savings as compared to Standard 90.1-2007 and a lighting EUI of 6.8 kBTU/ft²·yr based on a gross building area of 190,000 ft².
Plug Load Performance

One of the most challenging parts of doing a net zero building today is dealing with plug loads. Building designers typically have little influence over what gets plugged in and how often those appliances get used.

As buildings and building systems have become more efficient, the number of appliances using electricity inside buildings has grown. Knowing this would be a challenge, several steps were taken throughout the design and construction phases to better understand this problem and provide practical solutions.

One of the tests conducted was measuring electrical loads for a two week period in the existing Exploratorium. The most shocking result of this study was that 33% of the electrical consumption was at night when the museum was unoccupied.

It was simply too time consuming for staff to run around and turn every exhibit and light off each night. Because the facility paid very low city subsidized rates for electricity at its old facility, little incentive existed to change ways. However, with the decision to move into the new facility, the non-profit organization was faced with paying dramatically higher utility bills on the order of $300,000 to $500,000 annually.

The design team also worked with Exploratorium staff to complete an extensive plug load study, breaking the plug load challenge down into smaller buckets. Measurements of existing equipment were taken and estimates of new equipment to be purchased were made to determine expected plug load energy in the new building.

Then a suite of recommendations were made, broken into three tiers based on the difficulty of implementation. Some of the recommendations were implemented in the base building design. One of the most effective of these recommendations

Below The SEAGLASS restaurant is located within the Exploratorium. Offerings include seafood items such as sushi and fresh oysters, and it features locally sourced menus that showcase small producers. The restaurant, which is a tenant, was not included in designers’ calculations for a net zero museum.

Right Kids use everyday objects and components to make simple circuit boards. A typical exploration begins with the simplest of circuits being completed: a battery makes a light bulb turn on.

<table>
<thead>
<tr>
<th>TABLE 1 EXAMPLES OF PLUG LOAD REDUCTION RECOMMENDATIONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retrofit microscopes with LEDs</td>
</tr>
<tr>
<td>Encourage use of stairs over elevators</td>
</tr>
<tr>
<td>Turn off exhibits during events</td>
</tr>
<tr>
<td>Only run outdoor exhibits while open</td>
</tr>
<tr>
<td>Server virtualization</td>
</tr>
</tbody>
</table>

BUILDING TEAM

Building Owner/Representative
The Exploratorium

Architect
EHDD

General Contractor
Nibbi Brothers

Mechanical Engineer, Energy Modeler
Integral Group

Electrical Engineer
Cammisa + Wipf

Structural Engineer
Rutherford & Chekene

Civil Engineer
Kennedy/Jenks

Environmental Consultant
EIP Associates

Landscape Architect
GLS Architecture – Gary Strang

Lighting Design
David Nelson & Associates

Fundamental/Enhanced Commissioning
Integral Group/Enovity
mechanical and plug loads are installed throughout the building. In addition three submeters are installed for the tenant spaces including the small and large cafés and the retail space.

Water
The Exploratorium is committed to saving water and energy with a goal of cutting annual water consumption by up to 60% compared to the LEED baseline. No-flush urinals and dual-flush toilets are projected to save an estimated 1 million gallons annually. Meanwhile, the use of bay water for the heating and cooling system saves an additional 2 million gallons per year by eliminating the need for conventional cooling towers to absorb heat during the cooling process. A third major contributor to water savings is a rainwater recapture system collecting rainwater from one-third of the total roof area. Rainwater is routed from the roof to underneath the pier into a waterproof-sealed cavity inside one of the building’s new structural pile caps.

The Exploratorium’s monthly water consumption averages about 250,000 gallons per month including the small café, but not the large restaurant. Because the restaurants are subtenants and because this is
Lesons Leaned

Allow Sufficient Time for Commissioning. Make sure that complex systems like rainwater reuse, energy and water monitoring, and lighting programming are included as part of the commissioning scope and sufficient time is allowed in the construction schedule for complete testing. Even though these systems were commissioned, the time allowed was insufficient to properly test them and problems showed up later that should have been addressed.

For example, the rainwater system commissioning was pushed out and shortened because construction was completed late. When the rainwater system was enabled, the load side pressure in the pipes varied widely. The system was returned to bypass mode to protect the pipes. The system sat idle after commissioning for more than six months before it was discovered that there was a problem when the system ran for more than a few days continuously.

Multiple problems were discovered—improper calibration of pressure relief valve setpoints, pump scheduling, improper setup of the booster pump controllers, and a malfunctioning pump. These problems have all been resolved, but if more time had been allowed for commissioning, the system could have been saving water from day one.

Monitor PV Panel Electricity Production Against Solar Insolation. This should be done continuously after occupancy, and periodic cleaning should be increased if needed.

In this case, the solar PV installer also has a long term service contract to clean and monitor the panels. The installer produced a report at the end of the first year of operation comparing actual production to expected production based on measured insolation. This information led to the recommendation to increase panel cleanings, but this recommendation could have been made earlier based on continuous monitoring.

Plug Loads Are a Stubborn Problem That Deserve Special Attention. Given that plug loads can account for 50% or more of a building’s energy use, and that the energy use comes from many varied sources, the facility owner and design team need to collaborate early in the design process to realize significant plug load savings.

In this particular case, while several improvements were made in design like adding programmable circuit breakers, the bulk of the plug load discussion was pushed into the construction phase. The owner did work hand-in-hand with the design team to develop a plug load action plan showing a path to a 50% plug load energy reduction.

However, many of the measures have yet to be implemented because getting the museum up and running in its new home took priority over the additional tasks needed to reduce plug loads. Had this entire process taken place earlier in design, more savings could have been realized in the first year of operation. Still, having this roadmap will help the Exploratorium going forward to reach its goal of net zero operation.

Innovative Solutions. Look for systems that produce multiple benefits to achieve maximum performance at minimal added cost, i.e., using the structural pile cap for rainwater storage. This innovative solution actually came about because the design team couldn’t find another place to add an approximately 5,000 gallon tank in the main exhibit space.

It was only because the design team collaborated across disciplines that a structural engineer recognized there was a cavity about that size already being designed into the structural pile caps below pier that could be waterproofed and also used for rainwater storage. So a structural engineer in this case played a key role in designing the rainwater reuse system.

Lessons Learned

Considered process water, it is not included in the LEED calculations for water savings.

The proposed design includes savings from the low flow fixtures, bay water heat exchange and the rainwater system, resulting in an overall expected savings of 83%.

Unfortunately, due to a combination of lack of rain in California and some glitches with the start-up of the rainwater system, the building realized none of the expected 364,000 gallons of reused rainwater.

The actual water use data from October 2013 to September 2014 results in 34% savings, or over 1.3 million gallons of potable water saved annually. The actual data includes the small café, (the large restaurant is excluded), lab process fixtures, and hose bibs for exhibit and outdoor washdown, which are not separately submetered or included in the LEED baseline and proposed numbers.

This difference likely explains some if not most of the discrepancy between actual and proposed water savings and argues for a more complete study of water than currently required by LEED, especially in a region like California where water is such a precious resource.

With more typical rainfall and a fully functioning rainwater system, annual water savings could rise to more than 1.6 million gallons.

Conclusion

The new Exploratorium continues to inspire families and educators, and now its operation is offering insights for building professionals into the possibilities of adaptive reuse and other sustainable design strategies. The bay water heat exchanger, the radiant system, the plentiful amount of daylighting supplied and many other innovative features contribute to this building’s transformation from a run-down warehouse on a pier to a high performance building.

About the Authors

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