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The *Other* Renewable Energy

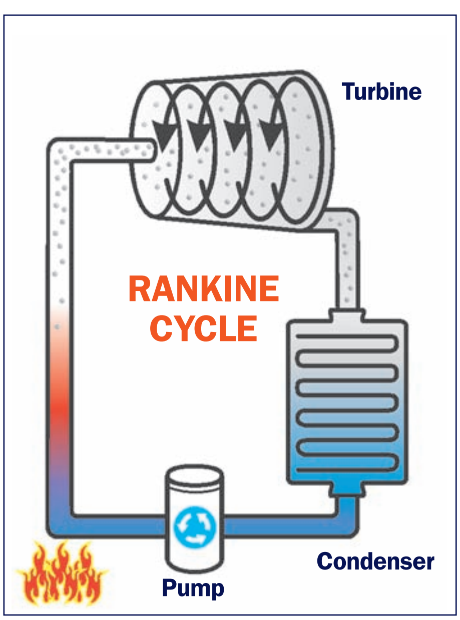
Eighty years ago, a brilliant French inventor staked—and lost—his considerable fortune on developing ocean thermal energy, but his dream of harnessing unlimited energy from the sea still lives today

By James R. Chiles

SIXTY MILES EAST OF HAVANA, along Cuba's north coast, swimmers and skin divers like to gather at a squarish pit filled with lovely aquamarine water, hewn into the rugged basalt just off Matanzas Bay. From a distance it has the look of a Stone Age swimming pool, until one sees electrical wires protruding from aged concrete.

This is the sole remnant of a power plant built by a French inventor so far ahead of his time that his time still has not arrived: the proud and prolific Georges Claude, known as "the Edison of France" for his breakthrough developments of neon lights, industrial gases, and synthetic ammonia. But it was on this gouged reef that his fortune began to founder. Cubans still regard him as the father of ocean thermal power—a process of harnessing energy

French inventor, Georges Claude, opposite, traveled to Cuba's Matanzas Bay, right, in the late 1920s and early 1930s, where he built a power plant on a rocky natural pool, above (note still existing iron stairway and concrete platform), intent on pulling unlimited amounts of energy out of the ocean, a technology known today as OTEC, or ocean thermal energy conversion. Claude based his ocean thermal work on a mid-19th-century thermodynamic system known as the Rankine cycle, below, in which a liquid, converted into a gas then back to a liquid, turns a turbine.



LONNA KOBLICK (ART); LUIS VEGA, PH.D. (TOP); COURTESY OF THE CUBAN HERITAGE COLLECTION, UNIVERSITY OF MIAMI LIBRARIES, CORAL GABLES, FL

from the sea—and mark this spot as its birthplace. If so, the child has been a long time aborning. No ocean thermal plants of commercial scale have been built, and the power output from the scattering of pilot plants to date could be exceeded by firing up the generators at a single big-box home improvement store. Still, today's volatile mix of energy politics and economics is stirring long-dormant hopes among the faithful.

"I think it's an awesome time," says Ron Baird, head of the Natural Energy Laboratory of Hawaii Authority, a facility that has served as a refuge for deepwater applications in the lean decades since the first energy crisis of the 1970s came and went. Among other developments in 2008, the state's governor, Linda Lingle, signed a partnership with a Taiwan research institute and Lockheed Martin to build a small ocean thermal power plant off Honolulu. Also last year, Lockheed received a federal grant to tune up the giant pipes that will stretch to deep waters. The temperatures of such waters, which originate in the wind-whipped North Pacific, stay close to freezing, irrespective of the tropical balminess above.

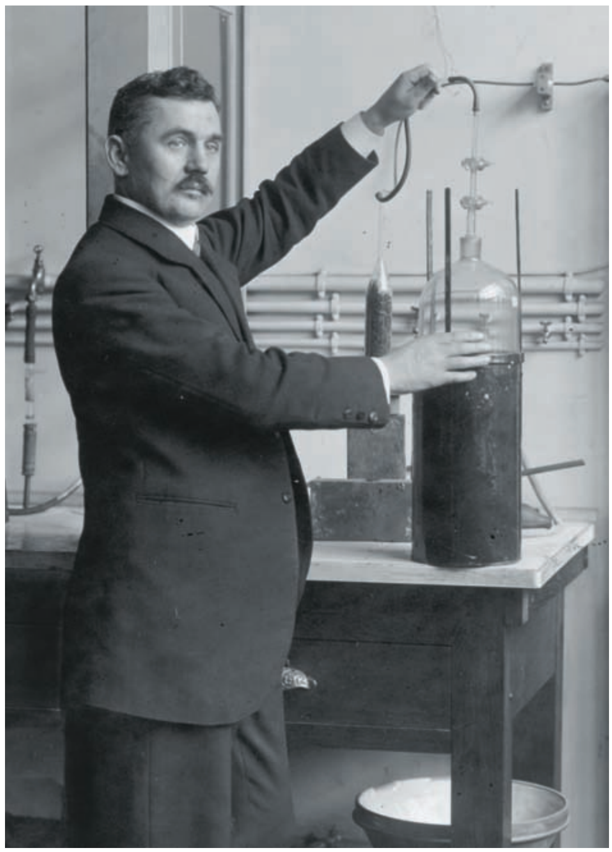
Cold-water flow is critical because oceanic thermal power plants can hope to become economically propitious only at locations with access to a wide differential between warm surface water and cold deep water (called the "delta T"), which can be more than 40 degrees F. If pumps pull enough water through two separate sets of pipes, the warm seawater will evaporate a heat-transfer liquid (such as ammonia or propane) in one part of the plant; elsewhere, cold seawater recondenses the gas to liquid. But as it blows from the first point of phase change to the second, the gas stage will drive a turbine. William Rankine sketched out the principles of such heat engines in 1859.

Engineer Ben J. Campbell of the Keuffel & Esser Company outlined what this might mean for world energy in February 1913: "A natural source of power exists which is abundantly able to supply all power needed by future man." He predicted that the tropical ocean would prove "an indefinitely large storehouse of potential energy, inexhaustible" if tapped by a huge vertical pipe he called the flume. While such large-scale drawing upon seawater would somewhat cool the upper waters, solar input would restore the lost warmth.

Campbell didn't build his flume, though, and it would be Georges Claude who most conspicuously caught the first wave of ocean thermal fever. He would also be the first to produce electricity by running a pipe into deep water; the first to produce a dividend of freshwater along the way; and the first to run out of money doing it.

CLAUDE'S EARLY SUCCESSES

Claude was born in Paris in 1870, during the Prussian siege of the city. His father, a teacher, taught Georges at home until he began engineering courses at the city's new Ecole Municipale de Physique et de Chimie Industrielles. After working at the Thomson Company, Claude brought out his first successful invention: a means of safely storing acetylene gas, a compound immensely effective in cutting torches when mixed with oxygen (reaching temperatures of 6,000°F), but prone to explode if stored under more than twice atmospheric pressure. Until Claude and his partner Albert Hess came along, the only safe way to transport it for practical application was as its predecessor substance calcium carbide, a soft mineral that generates acetylene on the addition of water. Claude discovered that acetylene dissolved readily in acetone, eliminating the need for high-pressure storage in tanks.



Georges Claude, above, made a fortune and became known as the "Edison of France" for his work inventing neon tubes, the signage now used worldwide.

BOYER-ROGER VIOLLET/GETTY IMAGES

Having subdued one gas by chemistry, Claude took an interest in liquefying another. By 1902 he had learned how to modify a steam engine's pistons to produce liquid oxygen for industry and metalworking much more cheaply than via the distillation process commercialized by Carl von Linde. In these early days, the Air Liquide company, which Claude helped form with Paul Delorme and still exists today, began collecting the "noble" gases neon, argon, and xenon as residues. The formation of these byproducts would lead to Claude's most famous invention, the neon light. While earlier experimenters had discovered how to use high-voltage electricity to make gas-filled tubes glow, Claude's historic contribution was the durable electrical system that first made them practical.

As he had with Air Liquide, Claude stayed close to the new business. His first commercial display went up in 1910 for an auto show at the Grand Palais in Paris, followed by a stylish sign over the Paris Opéra in 1919. The United States saw its first neon signs in 1923, brought to Los Angeles by an auto dealer after a trip to Paris. Raymond Chandler evokes that early image of nighttime Los Angeles in *The Little Sister*, one of his Philip Marlowe novels: "The lights were wonderful. There ought to be a monument to the man who invented neon lights."

By 1924 Claude was a wealthy man, impeccably groomed and with a confident and imperious manner. He had consistently succeeded by picking young technologies with a good engineering foundation that were held back by specific technical gaps. A technological optimist, he predicted in a 1929 article for MIT's *Tech Engineering News* that inventors would never run out of things to create, because "every new resource, every new invention, is able to combine with some of the other existing possibilities to permit many other combinations." There was one danger for them to be wary of, he added, rather presciently: "An inventor's mind is a fiery steed which often leads its master where he would prefer not to go." That steed would drag him deep into the ocean in search of renewable energy.

Harnessing the Sea's Thermal Energy

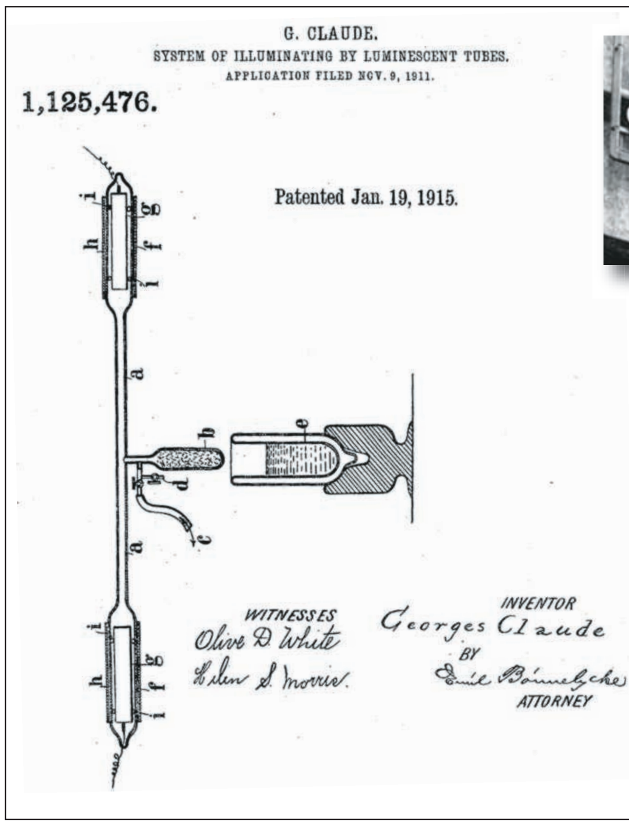
How did renewable energy—still a minor player in 2009—ever get such a grip on a hardheaded inventor back when fossil fuel was dirt cheap? After a well-publicized international geology conference in Toronto in 1913, forward-thinking people, including Claude and his former schoolmate and fellow engineer Paul Boucherot, began to worry about the world's supply of coal. They trekked to the Sahara to inspect rudimentary engines for harnessing solar energy. To Claude and other enthusiasts, ocean thermal power (while still derived from solar energy) would serve better than sun-aimed collectors, because it could produce power night and day.

As in the familiar car battery with its positive and negative terminals, oceanic heat energy has two parts. Uppermost is a turquoise-colored, pleasantly warm layer, which the sun warms each good weather day, reaching less than 200 feet deep. About a half mile down lies a dark, cold level that hardly changes at all, except to arc slowly across the ocean basins. Occasionally weather conditions drag the cold deep water to the surface, as in the upwelling, fish-feeding Humboldt Current off Peru, but most of the time this cold, nutrient-rich water—which can plunge to 36°F even in the tropics—stays deep because it's denser than warm water.

Before Claude took a hand, the early ocean thermal thinkers Jacques-Arsène d'Arsonval (1881) and Campbell (1913) had sketched out a "closed-cycle" plant based on the Rankine cycle. As the working fluid to change from liquid to gas and back in its closed loop, d'Arsonval proposed sulfur dioxide; Campbell favored carbonic acid. In no case do the streams of warm or cold seawater mix with the working fluid in a closed-cycle plant; all heat is transferred through metal walls in a process akin to running a refrigerator in reverse.

After two years of experimentation alongside Boucherot, Claude publicly demonstrated an "open-cycle" means of harnessing thermal differences by performing a laboratory experiment during a speech to the Académie des Sciences in November 1926. Some members responded that the idea would never be practical; as the *New York Times* phrased it, they were "not astonished." Claude immediately stopped his business plans and prepared a proof-of-concept test at the Ougrée-Marihaye steel mill in Belgium.

He later claimed that he had begun work without knowing about the writings of pioneers d'Arsonval, Campbell, Carlo Boggia, or Mario Dornig. (A skeptic could point out that Claude had been in touch with d'Arsonval as recently as 1913, when the latter wrote a foreword to Claude's book on liquid air.) In any case, Claude convinced himself that the open cycle was preferable. One downside of the closed cycle is the problem of biofouling—warm seawater's tendency to foster the growth of scum on the water side of the heat exchangers surrounding the evaporation chamber. Even a thin layer of microorganisms can ruinously insulate such a plant, which needs exceptionally efficient heat exchangers to offset the cost of pumping huge volumes of seawater. (Any biofouling solution imposes


G. CLAUDE.
SYSTEM OF ILLUMINATING BY LUMINESCENT TUBES.
APPLICATION FILED NOV. 9, 1911.
1,125,476.
Patented Jan. 19, 1915.
WITNESSES
Olive D White
INVENTOR
Georges Claude
BY
ATTORNEY

Claude obtained his neon sign patent in 1915, left, and America's first such sign, above, appeared atop a Los Angeles car dealership in the early 1920s, shipped over from France.

U.S. PATENT OFFICE

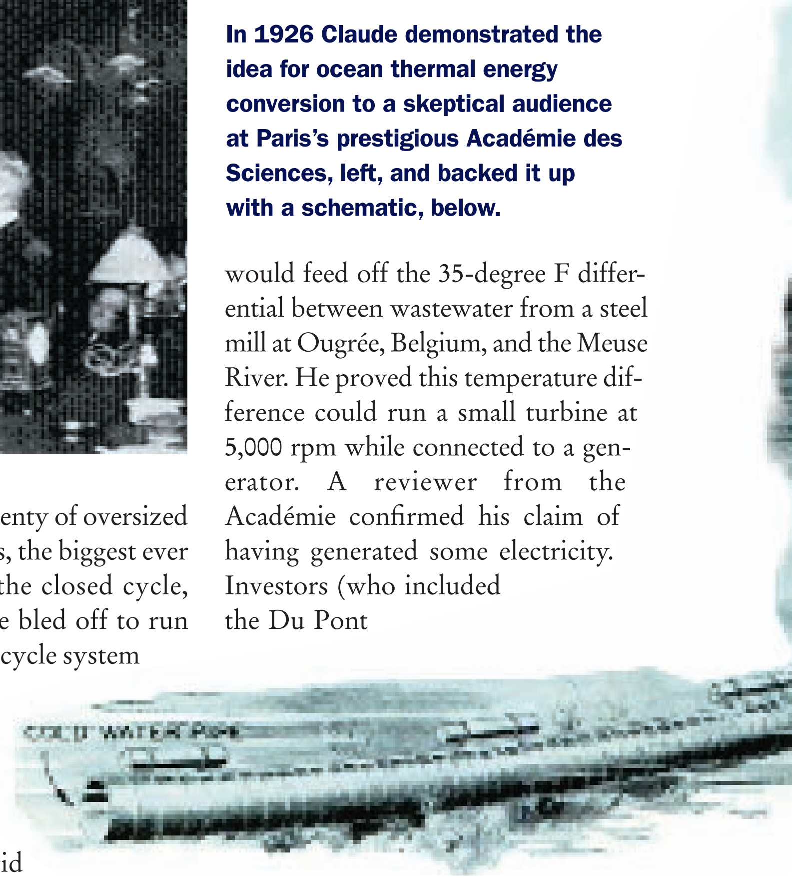
In 1926 Claude demonstrated the idea for ocean thermal energy conversion to a skeptical audience at Paris's prestigious Académie des Sciences, left, and backed it up with a schematic, below.

costs and drawbacks of its own).

Open-cycle systems mostly avoid scum formation because they do not send warm seawater through the heat exchangers. A siphon draws warm water into an evaporation chamber, which employs a high vacuum to bring some of the water to a minimal-pressure boiling point as it flows through. (Note to lowlanders: the lower the air pressure, the lower a fluid's vaporization temperature.) The steam's path of least resistance drives a large turbine. It finishes inside a condenser, where cold seawater flowing on the other side of the heat exchanger wall chills the water vapor back into droplets. The steady condensation into a much smaller volume sustains the partial vacuum that keeps pulling steam into the condenser.

Certain logistical hurdles keep the open-cycle system from outshining the closed cycle: a full-sized open-cycle power plant would require giant vacuum chambers and plenty of oversized low-pressure turbines, the biggest ever made. And as with the closed cycle, much power must be bled off to run the pumps. An open-cycle system does offer a rich dividend of fresh, cool condensed water. Open and closed cycles can be combined into a hybrid design that produces both power and freshwater.

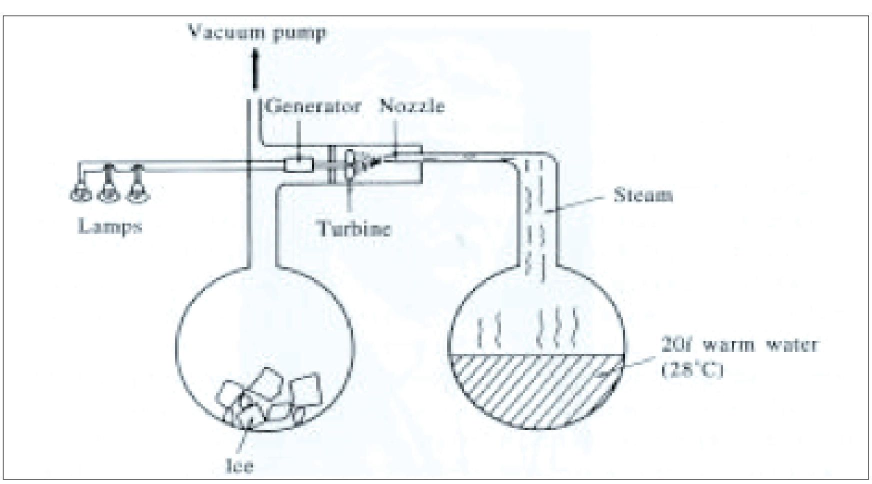
Claude's sequential assault on ocean power entailed four steps prior to mass production: a laboratory bench test to prove the principle; a field test on a river; construction of a pilot plant on the ocean shore; and revenue production with a shipboard plant on the open sea. In 1928 Claude embarked on the second stage by amassing such parts as were already commercially available to assemble a small power plant that would feed off the 35-degree F differential between wastewater from a steel mill at Ougrée, Belgium, and the Meuse River. He proved this temperature difference could run a small turbine at 5,000 rpm while connected to a generator. A reviewer from the Académie confirmed his claim of having generated some electricity. Investors (who included the Du Pont



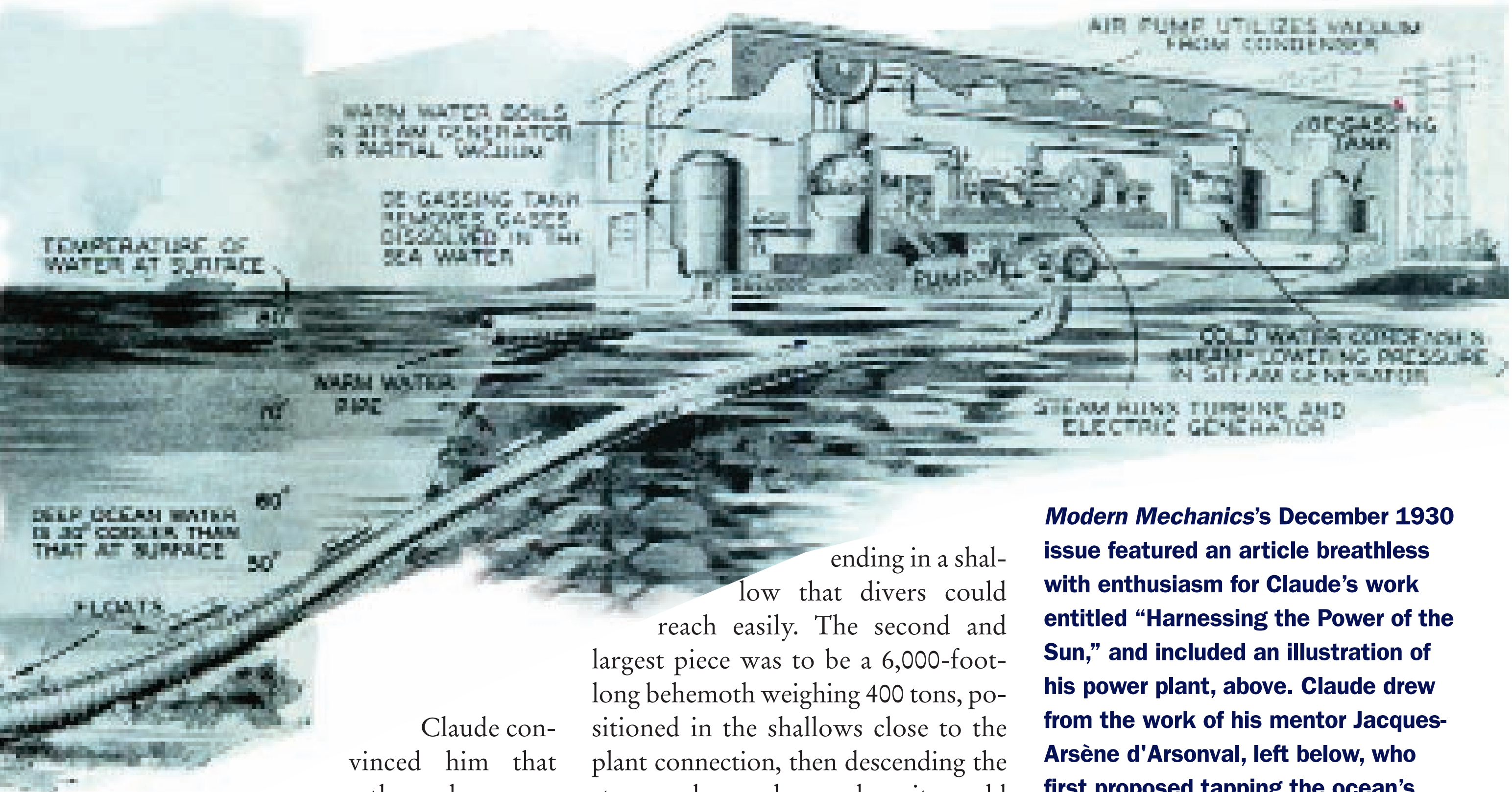
family) agreed to fund a major demonstration that would tap the ocean itself. Claude cited the Ougrée results to slam his 1926 detractors as having made "laughable" scientific errors.

THE CUBAN VENTURE

Claude then planted his flag at Matanzas Bay, Cuba, where, just a mile offshore, he and his nephew André found splendidly warm currents running above and breathtakingly cold water below. Equally lucky, Cuba's headstrong dictator, Gerardo Machado, saw this as the magic instrument with which he could wean the island from its dependence on a sugarcane economy, throng it with factories, and create a "Switzerland of the Americas." (One of Machado's grand projects, the Central Highway, had boosted the career of contractor Henry J. Kaiser, who would later gain fame as a dam and ship builder and pioneer in health insurance.) But Cuba had no coal or oil to drive an industrial revolution.

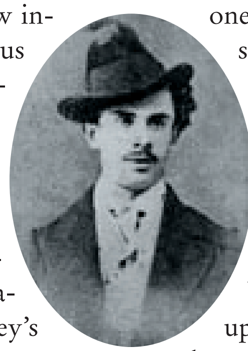


WWW.EUROCEAN.ORG (LEFT AND TOP LEFT); *MODERN MECHANICS* 1930 (TOP)



Modern Mechanics's December 1930 issue featured an article breathless with enthusiasm for Claude's work entitled "Harnessing the Power of the Sun," and included an illustration of his power plant, above. Claude drew from the work of his mentor Jacques-Arsène d'Arsonval, left below, who first proposed tapping the ocean's energy in 1881.

Claude convinced him that ocean thermal power plants could light up not only the entire island and its new industry but also deliver surplus power to Florida by undersea cable. (Claude also proposed a pipe to connect the Red Sea and the Mediterranean. The sweep of such plans earned him a prominent place in popular magazines and later in Willy Ley's visionary book of 1954, *Engineers' Dreams*.) Machado signed a contract placing labor, equipment, and a fleet of boats at Claude's disposal.



Claude packed up the small Ougrée power plant and a stack of six-foot-diameter by 70-foot-long corrugated steel pipe lengths to pull cold water from the abyss. Welded together, these pipes would stretch 2,200 yards from the plant to the deepwater intake. Claude optimistically predicted that the job would be no more difficult than laying a transoceanic telephone cable.

The cold-water pipe would land on the seafloor in three sections: first a 350-foot-long stretch that began at the plant and passed through the surf zone, ending in a shallow that divers could reach easily. The second and largest piece was to be a 6,000-foot-long behemoth weighing 400 tons, positioned in the shallows close to the plant connection, then descending the steep undersea slope, where it would plunge off a cliff and end in cold water one-third of a mile down. A short splicing section would connect the two big pipes once their exact positions were known. In late August 1929 Claude's Cuban crew floated sections of the long pipe on pontoons out on the bay and began to link them up. A storm sank most of these—mishap no. 1.

Claude called for more pipe from France and decided he would weatherproof the construction by assembling it on a river that opened onto Matanzas Bay. The Rio Canímar was twisty, infested with crocodiles, and blocked from the sea by a sandbar hundreds of yards across. Claude hired a dredge to cut a path for his creation, by now being compared to a gigantic sea snake.

A storm sank most of the pipe—mishap No. 1

On the appointed day in June 1930, he ordered the cables slipped that anchored the pipe in the river current. The pipe advanced toward the open ocean, its middle part grounded on the sandbar—and then the rear portion folded up under thrust from the Canímar current. High tide and tugboats freed it later, but it was cracked in manifold places and sank in half-mile-deep waters, snapping its restraining cables on its way down. Mishap no. 2. Claude raged about saboteurs hired by "opposing interests."

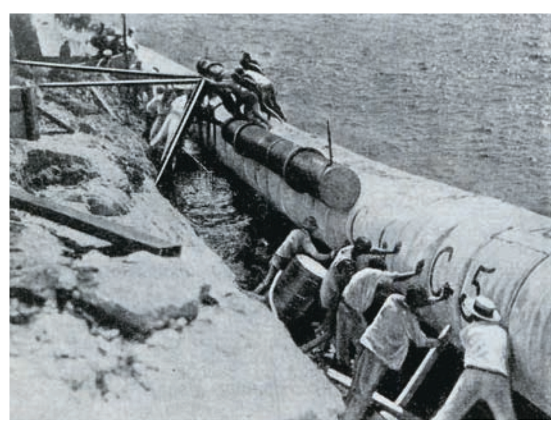
Undaunted, Claude ordered yet more pipe from France, defended his ramparts with Cuban gunboats, and pondered a better way to hatch his sea snake. García Vásquez, one of the Cuban engineers on loan from the Department of Public Works, offered an elegant solution: assemble the entire pipe on a temporary rail line perpendicular to the shore, attach floats, and drag it into the water with tugboats. (To recap: the dapper Claude had begun with a compellingly clear vision of a few pipes and a turbine that, linked up, would provide a source of power *inépuisable*, without end. Along the way he had somehow gotten mixed up with a dictator, dredges, crocodiles, and railroad tracks, a story line worthy of a *Tintin* comic book.) Tugs began towing the pipe, which started rolling out to sea as promised, only to set the stage for mishap no. 3: despite "40 expert native swimmers," pontoons bearing the head of the pipe were somehow flooded ahead of the plan, so the pipe broke into pieces and sank for yet another complete loss.

Claude, above (at left), found a willing ally in the Cuban dictator Gerardo Machado, above (at right), whose island, right, offered large sea temperature differentials ideal for ocean thermal energy work.

Claude blamed worker stupidity, but more likely the cause was his inability to communicate changes of plan quickly and clearly over a long distance. He waved flags and bellowed through a megaphone from his motorboat but was not able to get his increasingly frantic messages through.

He ordered more pipe. (Investors having made themselves scarce, he had to write checks on his own account.) Machado sent in troops to guard the fourth attempt, on September 7, 1930, which succeeded. The power plant ran for a total of 11 days, reaching peak capacity during a demonstration for visitors the following month, when it lit 40 500-watt bulbs. Because the deep water had warmed on the way up and the pipe reached to a lesser depth than planned, the final differential was just 22 degrees F, much reducing the power available. "Backers thought the brilliant light was not a big enough show for their $2,000,000," reported *Newsweek*. According to the retired French ocean engineer Michel Gauthier, who has assembled a thorough account of Claude's work, the entrepreneur reimbursed the investors out of his dwindling fortune.

Claude told the press that commercial use was "just around the corner" and that his next project would be a 25-megawatt power plant at Santiago de Cuba, which would scale up the short-lived Matanzas experiment by a factor of 1,000. But backers did not come forward, and meanwhile the long-suffering Cuban people finally drove Machado out of office and into hiding.

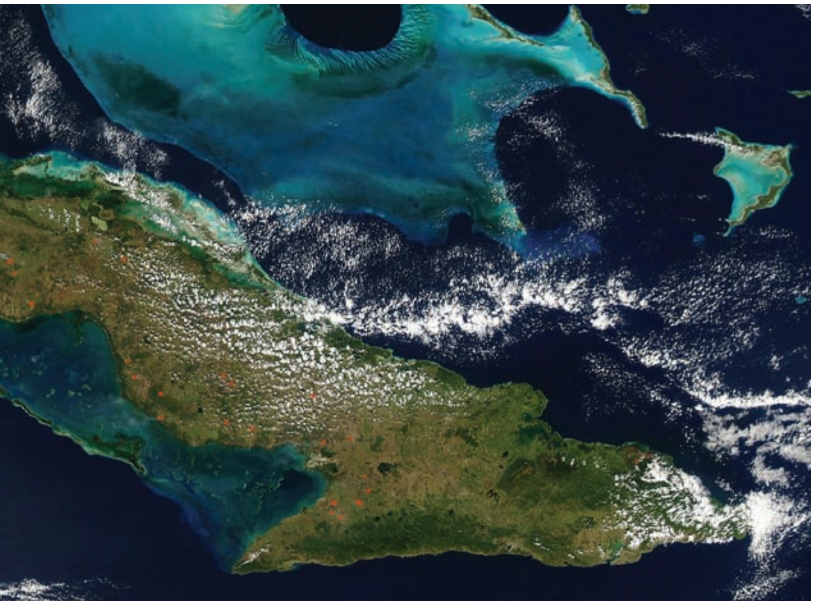


THE BRAZILIAN BUST

Claude's final foray into ocean energy was self-funded and self-inflicted. He would make money by tapping ocean thermal energy from the open ocean. His mother ship would be the *Tunisie*, a dumpy 10,000-ton freighter idled by the Depression. Claude bought it and paid 800 workers for a year to modify it into an ocean thermal ice factory. It steamed out of the Chantiers de France shipyard in Dunkirk in 1934, appearing strikingly top-heavy, with four vacuum chambers and five condensers packed onboard. Claude justifiably told reporters that "The *Tunisie* is the type of ship which would have delighted Jules Verne." Claude explained that he was going to make 1,000 tons of ice per day and sell it in Brazil to residents of Rio de Janeiro, because "ice is needed in the tropics to make life more comfortable." He hired a second freighter, the *Myson*, to haul 2,100 feet of cold-water pipe, which

COURTESY OF THE CUBAN HERITAGE COLLECTION, UNIVERSITY OF MIAMI LIBRARIES, CORAL GABLES, FL (TOP LEFT); NASA (CENTER) would hang vertically a short distance from the *Tunisie*.

Though some newspaper writers liked to call him "the indefatigable Georges Claude," the inventor was suffering from fiscal fatigue by August



1934, when the *Tunisie* dropped anchor 70 miles south of the entrance to Guanabara Bay. Business was down worldwide, and his key patents on neon lights had expired two years before. Now he was paying the salaries of 80 seagoing workers and sundry other expenses for the six boats in his

Deploying the 2,200-yard, cold water intake tube in Cuba, far left, proved the undoing of Claude, standing, left, inside the pipe. Storms, waves, and logistical problems encountered while laying the unwieldy and vulnerable pipe, above, sank Claude's dream to harvest energy from the ocean.

COURTESY LUIS VEGA, PH.D. (RIGHT)

flotilla, even as logistical troubles and bad weather gnawed into the prime-market hot-weather months. Then a barge load of pipe fell into the ocean, dredging up memories of Cuba. In February 1935, a quietly desperate Claude decided to launch the cold-water pipe. As in Cuba, he had no reliable weather forecast to rely upon.

Each section of the eight-foot-diameter pipe would be placed atop the stack on the surface, then lowered into the depths, passing through a custom-designed, spherical iron float 30 feet in diameter and with a hole in the middle. This float was submerged to a depth of 50 feet and held there by a long cable anchored to the seafloor, which Claude thought would keep it safe from wave action. The float would support the upper end of the long vertical string of cold-water pipe, upon whose completion crews would add a giant rubber hose to link it to the *Tunisie*, thus closing the last 50 feet of the cold water's passage to the condensers. Claude was trying to solve one of the biggest hurdles facing a large ocean thermal plant at sea: how to build a strong and fluid-tight connection between a massive, wave-tossed surface object (the ship) and a massive, mostly unmoving submerged object (the pipe). Today's deepwater oil and gas industry has hammered out solutions to a smaller problem, connecting drillships to vertical "riser" pipes that drop as much as two miles to the seafloor. Claude had no such gear.

The float-pipe combo might have worked had the weather remained calm long enough for a full string of pipe to be put into place and stabilize the system. But on February 8, with just four pipe sections in place, storm waves caused a violent harmonic between the float and the short length hanging from it. Claude tried to maintain control by adding weight to a ballast bin bolted to the end of the pipe, but instead the assembly broke free and sank to the bottom. Now $800,000 in the hole for the Brazilian venture, he could think of no solution with such cash as remained to him.

So he decided to end his ocean thermal career on the spot, and further to remove all temptation to take up the cause ever again. He simply attached a charge of dynamite to the costly spherical float and blew it up. Claude steamed home, never to pursue another ocean thermal project, though he did dabble with the extraction of precious minerals from seawater aboard the steamer *San Jose* in 1936.

"It's been said that he failed because of ocean engineering problems, but he would have failed anyway due to the state of technology for vacuum pumps available at the time," says consultant Luis Vega, who directed a project that built and ran an open-cycle ocean thermal plant from 1993 to 1998 on the Big Island of Hawaii. "The pumps he had used so much energy," said Vega. The pumps for Vega's open-cycle plant used just a third as much power.

After publicly calling for the United States to enter the European war in 1939, Claude resigned himself to the German victory he believed inevitable. Perhaps still bitter over the prewar French government's refusal to back some of his ideas, he aligned with the puppet government in Vichy in 1940 and joined a pro-German, anti-Soviet group of upper-class citizens called Le Groupe Collaboration. The speeches he gave and the articles he wrote brought him, in 1945, a life sentence and the forfeiture of his many assets. Freed from prison in 1950 at age 79, Claude wrote his memoirs before dying in 1960. The man once known as "the Edison of France" never regained his prewar public stature, but streets still bear his name in Tours, Vaux-sur-Mer, and Meaux.

Claude's final experiment with ocean thermal energy focused on retrofitting the *Tunisie*, above, into an ocean thermal ice factory with vacuum chambers and condensers. Off the coast of Rio de Janeiro, the *Tunisie* ran into problems with its long intake tube, a failure that finally bankrupted Claude.

COURTESY LUIS VEGA

NEW INTEREST IN THE 1970'S

So, two lessons from the Claude era. First: never underestimate the difficulties of a cold-water pipe. Second: don't let enthusiasm override judgment. The 1970s saw much of the latter. Leading the charge was President Richard Nixon's Project Independence, the original "all of the above" energy plan. During a period of unshakable resolve that lasted nearly a year, Americans vowed to wean themselves of imported energy by 1980. Nixon promised support for fission and fusion, breeder reactors, solar power and other renewables, oil from Alaska, North American natural gas, synthetic crude oil and coal from the West, gummy tar sands—anything that wasn't oil from an Arab-dominated cartel. In pursuit of conservation, Texas flicked off the lights in its capitol dome.

Many of these ideas aspired to be heroic. According to one faction of academics, ocean thermal energy would be the biggest of them all. William Heronemus of the University of Massachusetts Amherst proposed to power all of New England by stationing 90 supersized ocean thermal energy manufacturing "plantships" off South Carolina, capturing heat from the Gulf Stream and generating hydrogen for delivery to utility boilers by pipeline undersea.

The Reagan Administration pulled the plug on OTEC research in 1981

To vet such claims, the new Energy Research and Development Administration hired TRW and Lockheed Missiles & Space to examine the plans. Lockheed published a report in 1977 laying out its vision of a giant floating plant with a cold-water pipe cast out of lightweight concrete that would measure 120 feet across and reach 1,000 feet deep. Among other ideas floated at this heady time, recalls Lawrence Donovan, then a naval officer who helped review ocean thermal power proposals, was the transmission of electrical power by microwave beam as well as by undersea cable.

The last hurrah came in 1980, when federal laws laid down goals and incentives for a full-scale ocean thermal industry. "The mandate was a hundred 100-megawatt plants, to start a new industry," remembers Luis Vega. "It was not a bad idea. A lot of corporations took an interest. But in hindsight we should have done first what Georges Claude tried to do, to build a commercial-scale plant with off-the-shelf technology." Congressional staffer Willis D. Smith later reflected that a small number of ocean thermal zealots had "poisoned the well" of political support with excess optimism. At the Department of Energy, Robert Cohen had been ready to sponsor a federally backed 40-megawatt closed-cycle plant, but the 1980 election pulled the plug. "We were on the fast track, then in 1981 we got the message that the Reagan Administration did not like renewables," recalls Cohen. "So we've lost 27 years. We could have had them running by now."

TOWARD AN ENERGY INDEPENDENT HAWAII

The Hawaiian congressional delegation succeeded in wresting a small sum of federal research money from the budget, but only for open-cycle work. The Clinton administration put an end even to that during the budget cuts of 1995. Yet despite all such hurdles and competition from abroad, Hawaii has managed to remain a hub of ocean

In 1979 the state of Hawaii, Lockheed, and two other corporations partnered to create the first successful closed-cycle, self-sustaining ocean thermal energy operation at sea, rendered above, on a barge using a two-foot-in-diameter, 2,150-foot-long polyethylene pipe for its cold-water intake.

COURTESY MAKAI OCEAN ENGINEERING

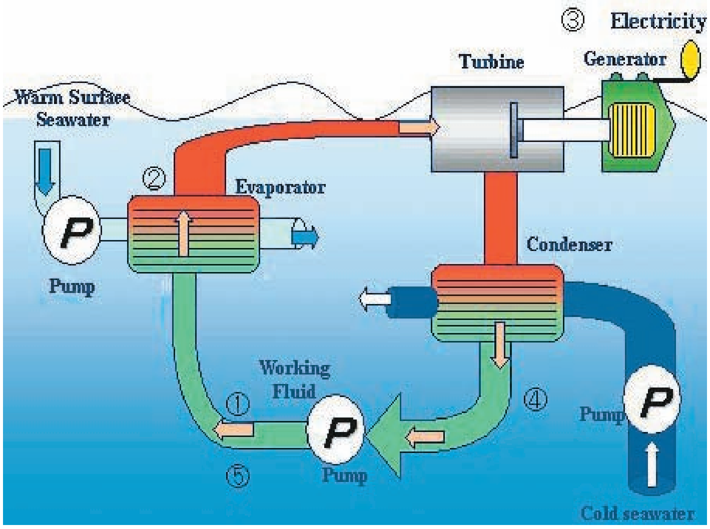
thermal energy activity, having hosted three such projects from 1979 through 1998. The third still holds the record for longevity (five years) and net power production (over 100 kilowatts). While no ocean thermal energy plant is currently running on Hawaii, dozens of businesses and research shops have taken up residence on 870 rocky acres at the Natural Energy Laboratory of Hawaii Authority (NELHA) and are paying for millions of gallons of cold seawater piped from the deep, prized for its chilliness, high percentage of nutrients, and lack of modern-day pollution, which gives it particular value for fish farmers, who need fresh, cold seawater to grow clams, abalone, seahorses, and lobsters. Strawberry farmers also run it past their plants in closed pipes, which chill the roots for tastier berry production. Other companies remove the salt with osmosis and sell the bottled water to boutique markets in Japan. Other users put the cold water to work in heat exchangers, which substitute for conventional building air conditioners.

Meanwhile, NELHA's original objective—ocean thermal plants—have no such toehold. Experts and observers say money and patience will be required to stick with a series of scaled-up projects in tropical and subtropical waters.

Environmental Defense Fund ocean scientist Rod Fujita warns that the potential risks to the ocean ecology from big facilities are not known. He suggests beginning with small power plants serving island communities now suffering the high cost of oil-powered electricity; the U.S. Navy is considering such a plant to supply its base at Diego Garcia in the Indian Ocean's Chagos Archipelago. James Anderson, a veteran engineer with Sea Solar Power, predicts that the new generation of small plants will come by sea, not land: "I've concluded that the land-based plant is for the birds." Such small sea-based plants will send power to shore by cable and use thrusters to hold their position in the deep water.

If these "precommercial" plants of about ten megawatts perform as promised, the next step will be ship-sized plants, tethered in deep water near coastal cities in the tropics and subtropics, producing up to 100 megawatts of power. At this commercial scale, says Vega, ocean thermal power may compete with a broader range of electric generators. Still debated is which plant layout will squeeze the most energy out of the water. One contender is a new approach called the "Uehara cycle," originating at Japan's Saga University.

Although engineers have tried to devise a scheme to avoid hauling up cold water (perhaps by piping the heat-transfer gas down below to be condensed into liquid), future plants will probably still depend on cold-water pipes, and these will be much bigger than ever. That's the object of federally funded research getting under way at Lockheed Martin Maritime Systems in partnership with West Virginia University. Robert Varley, manager at Lockheed, reports that two years ago the company took a fresh look at its studies from the 1970s: "Lockheed de-



cided that yes, there was a market, and it could be feasible, but a lot of work was needed. And it was big enough to be interesting." To feed a 100-megawatt plant, a cold-water pipe would need to be about 35 feet in diameter and reach as much as a third of a mile down, depending on its location, and might face a threat in time from "vortex-induced vibration" caused by underwater currents. Fatigue caused by vortex shedding already has given major headaches to the deepwater oil and gas industry. Another challenge will be building the flexible, large-diameter connection to move cold water from an unmoving pipe to a wave-tossed vessel. "The connection is in my mind the biggest technological hurdle now," says Varley. "It has to be robust and have a fairly long life, meaning 20 to 40 years."

Just getting the pipe into place remains a problem. An Indian Ocean thermal offshore vessel accidentally dropped its full length of cold-water pipe into the deeps of the Bay of Bengal, twice, in 2003 and 2004. Perhaps after such problems are licked, ocean-grazing "plantships," the size of supertankers, will rumble onstage, sucking up and discharging 1,000 tons of equatorial waters each second and extracting or synthesizing something for sale onshore, perhaps liquid hydrogen or ammonia. Plantships making the latter would use their ocean thermal power to electrolyze water into hydrogen and oxygen. Elsewhere aboard, nitrogen taken from the air could be fused with hydrogen by heat, pressure, and an iron catalyst to form ammonia, using the Haber process. On paper, a 400-megawatt plantship could manufacture 1,200 tons of liquid anhydrous ammonia per day.

What to do with hundreds of supertankers topped off with a pungent liquid? Ammonia is a fundamental chemical feedstock for vital nitrogen-containing compounds like nitric acid, and farmers widely use it for fertilizer. It's combustible and can be used in appropriately modified engines. Claude himself once concocted a vehicle fuel that was 60 percent ammonia and 40 percent acetylene. He also had harbored hopes for fleets of floating islands, each with six energy factories and so numerous that they would lower the tropical oceans' temperature by five to ten degrees. Today British architect Alex Michaelis is hoping to win the Virgin Earth Challenge with a similarly grand concept of 50,000 energy islands to supply the world's population with ocean power.

Meanwhile, skeptics of the vision persist. According to Andrew Revkin, who writes the *New York Times* Dot Earth blog, "There is a batch of engineer/scientists who've already written off OTEC [ocean thermal energy conversion] and, similarly, ocean fertilization as raising too many questions

Engineers at Lockheed Martin Maritime Systems, the recent beneficiary of federal money, unveiled preliminary drawings of an OTEC system, top, and an artist's rendition of a closed-system, 100-megawatt offshore plant, below.

COURTESY LOCKHEED MARTIN

when considered at a scale the atmosphere would find perceptible." One of those issues, says Ken Caldeira of the Carnegie Institution for Science's Department of Global Ecology, is the failure to prove economic viability.

"All I'm looking for is getting a fair shake for ocean thermal based on its merits," maintains Robert Cohen, who donates his time as an unpaid lobbyist for the field. "And if anyone can show me a demonstrable 'showstopper' [an insurmountable technical, environmental, or economic barrier], I would fold my advocacy tents and save myself the expenditure of a lot of time and resources."

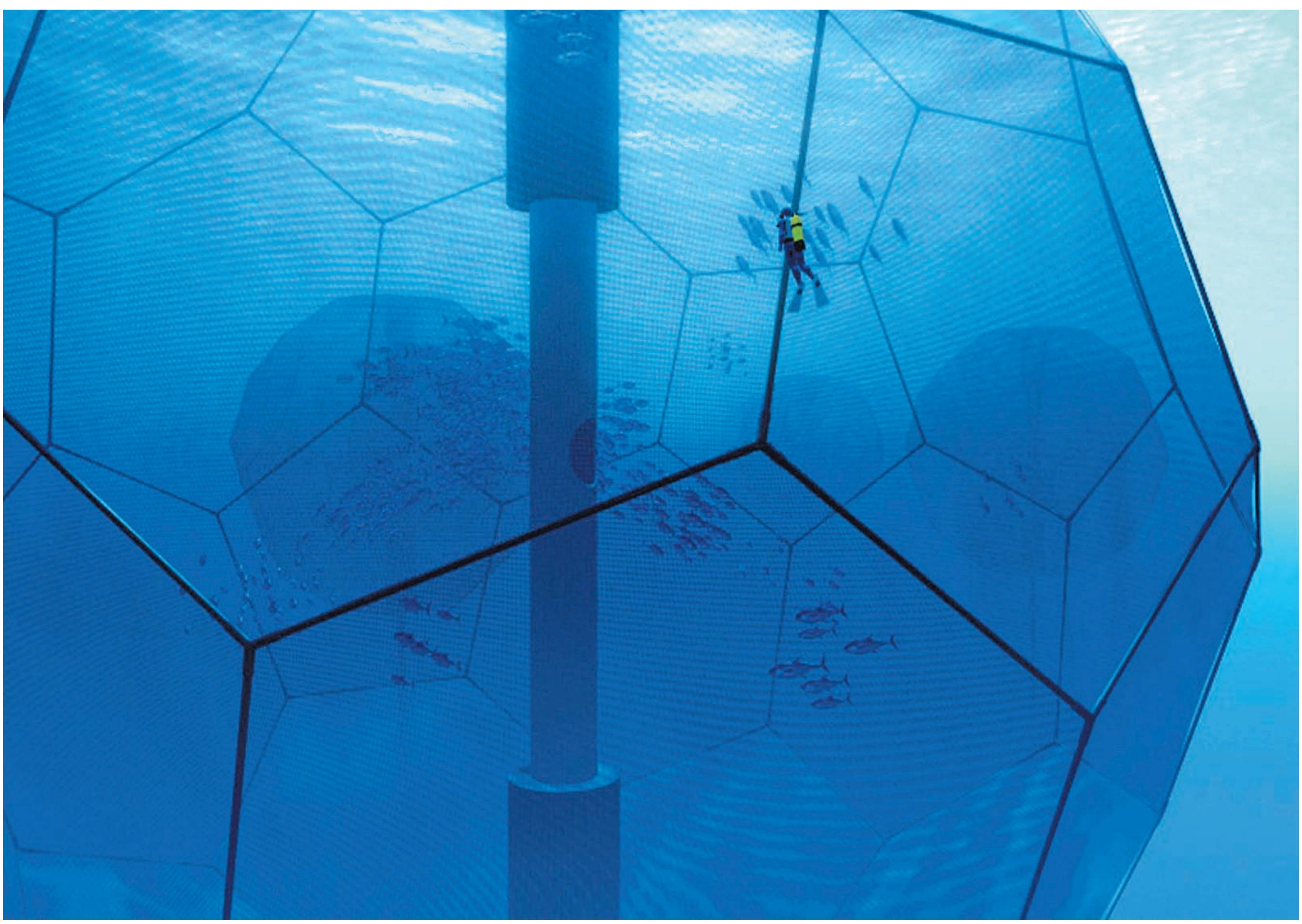
"The time may come when nations will struggle for supremacy over tropical waters as they do now over coal and petroleum fields," wrote Claude just after the Cuban experiment. So far nations like Japan, India, France, Taiwan, and the United States have been struggling just to get ocean thermal onto the grid. But whatever the future holds—showstoppers or major breakthroughs—Hawaiians will be among the first to find out. Given the new renewable energy laws and utility commitments recently signed in Hawaii, the first precommercial plants could appear off Oahu in a few years. Hawaiian residents pay three times the national average for electricity because of the island's heavy reliance on oil-fired energy as opposed to the hydroelectric, nuclear, or coal resources of the mainland. That means experimental processes like ocean thermal energy should find it easier to compete with conventional sources in the Aloha State.

The first precommercial plants could appear off Oahu in a few years

If ocean thermal power plants ever do take to the waves in large numbers and sizes, the vindication prize should go to Georges Claude, who once observed that "stubbornness is the greatest virtue of the inventor."

***James R. Chiles**, a frequent contributor to these pages, is author most recently of* The God Machine: From Boomerangs to Black Hawks, The Story of the Helicopter *(Bantam Dell, 2007).*

Hawaii Oceanic Technology's proposed Oceansphere, in an artist's rendering below, counts on a hybrid OTEC system to power open-ocean fish farms.



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