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A Brief History of OTEC Research at NELHA

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The Natural Energy Laboratory of Hawaii Authority (NELHA), an agency of the State of Hawaii, operates facilities at Keahole Point on the west coast of Hawaii Island. NELHA was founded in 1974 when the State Legislature established the Natural Energy Laboratory of Hawaii (NELH) and set aside 321 acres of land for research and development of natural energy sources, primarily OTEC. Initial research began in 1976 before any facilities were constructed onshore, using a buoy deployed offshore for biofouling studies of candidate closed cycle OTEC heat exchanger elements. Mini-OTEC, the world's first net power producing OTEC plant, was deployed in NELH's newly established offshore research corridor in 1979. [1]

In 1984, the State Legislature set aside an additional 547 acres of land adjacent to NELH, for commercial expansion of successful NELH research projects. This area, called the Hawaii Ocean Science and Technology (HOST) Park, was administered and developed by another State Agency, the High Technology Development Corporation (HTDC). In 1990, following installation of basic HOST Park infrastructure under HTDC guidance, the Legislature combined NELH and the HOST Park into a new entity, NELHA. Attached administratively to the State’s Department of Business, Economic Development and Tourism, NELHA’s twenty State employees pump seawater to and administer leases for about 25 tenant companies.

OTEC research at NELH began in earnest in 1982, following construction of the laboratory and administration buildings and deployment of the first 30 cm diameter, 600 m intake deep seawater pipeline.

Closed Cycle Research

From 1982 through 1987, Argonne National Laboratory, with funding from the U.S. Department of Energy (U.S.D.O.E.), conducted the Argonne Test Project (ATP), a long term test of biofouling and corrosion of candidate OTEC heat exchanger materials. Deep and surface seawater were pumped continuously, under varying flow conditions, through a series of test loops containing sample coupons and heat transfer monitors installed in tubes of various materials. These tests demonstrated that: 1) significant micro-biofouling developed quickly in the tubes carrying warm surface seawater, but this could be easily controlled with intermittent application of low concentrations of electrolytically generated chlorine; 2) no significant fouling occurred in tubes carrying cold deep seawater; and 3) inexpensive aluminum alloys work well in the flowing seawater environment, especially in the warm surface water where pitting corrosion rates indicated the feasibility of 40 year lifetimes. Slightly more rapid corrosion in the deep cold water could be reduced by inexpensive "claddings" of nearly pure aluminum. [2]

The ATP tests also demonstrated that sponge rubber balls used for mechanical heat exchanger cleaning in other applications did not adequately remove the microscopic fouling films significant to OTEC and also unacceptably accelerated the corrosion of aluminum test elements. An additional series of tests conducted for the U.S.D.O.E. by the Hawaii Natural Energy Institute investigated the efficacy of other non-chemical biofouling control measures for OTEC systems. Both ultra-violet and ultra-sound were shown to have biofouling control potential, but the energy requirements for both were significantly higher than for chlorine generation. [3]

As the ATP tests were terminated in 1987, ALCAN International began additional testing of various types of aluminum heat exchanger modules. Using a logging system modem-linked to their laboratories in Ontario, Canada, ALCAN researchers monitored changes in heat exchange and the chemistry and physical properties of the seawater which they correlated with observed changes in corrosion of samples taken periodically from the apparatus. They confirmed that several relatively inexpensive alloys survive well in flowing seawater under OTEC conditions and initiated a design effort for a 250 kW OTEC plant. [4]

When ALCAN engineers found that the cost of fabricating shell and tube heat exchangers from aluminum in the very large sizes required for OTEC would be prohibitive, they proposed the use of "Roll-Bond" heat exchanger panels that the company had developed and patented for refrigerator condensers. These are constructed relatively inexpensively by passing two large sheets of aluminum through a rolling mill, where the pressure and heat firmly weld the sheets together - everywhere except where one of the sheets was previously painted with a coating of titanium dioxide. The pattern of unwelded areas can then be inflated, leaving passages throughout the interior of the panel through which a working fluid can flow and exchange heat with another fluid outside the panels. Though such panels do not work well in the frost-free refrigerators popular in the U.S., they are commonly used in refrigerators throughout the developing world.

ALCAN's analysis indicated that Roll-Bond heat exchangers can be constructed with the large surface areas required for OTEC applications at approximately 20% of the cost for equivalent shell and tube units. Though the 60 psi differential pressure limitation of earlier roll-bond designs was viewed as a serious impediment to their use in large processes, ALCAN realized that high pressures are not essential to the low temperature OTEC process. Newer units have differential pressure capabilities up to 300 psi, allowing greatly improved overall OTEC process efficiency. ALCAN formed a partnership with GEC/MARCONI via which some roll-bond modules were constructed and tested for heat transfer efficiency using simulated OTEC conditions in the cold intake water and heated condenser discharge at an English power plant.

Positive results from the English tests and from the initial seawater corrosion testing of roll-bond heat exchanger elements at NELHA gave ALCAN the confidence to pursue their use in the OTEC plant designs they were developing for Keahole Point. The high cost of an independent seawater system for the planned pilot plant led to plans to reduce the size to 50 kW by using the turbine left from Mini-OTEC and incorporating the new plant into existing seawater systems that delivered seawater to NELHA tenants, most of which were pursuing commercial aquaculture businesses. [5] ALCAN expected that NELHA would provide the seawater to the plant, but the existing aquaculture tenants were not stable enough to ensure that the nearly $1M annual pumping cost would be covered by tenant usage. An agreement was eventually reached in which ALCAN agreed to purchase the seawater at NELHA's standard rates covering electricity and system maintenance and the State of Hawaii would provide Capital Improvement Project funding to cover the cost of plant fabrication. NELHA secured the needed $725K CIP appropriation through the 1992 State Legislature, but financial reverses resulting from the fall of the Soviet Union and Russia's subsequent dumping of aluminum on the international market forced ALCAN to withdraw from the project shortly thereafter.

In early 1994, NELHA reached agreement with the Pacific International Center for High Technology Research (PICHTR) to construct the 50 kW plant designed by ALCAN and their subcontractors. The project was funded from the $725K using the State CIP appropriation combined with $460K PICHTR internal funds and a $50K contribution from Hawaiian Electric Company. The heat exchangers were purchased from former ALCAN subsidiary, ALGOODS, which fabricated them following the designs developed by the ALCAN/GEC collaboration. The limited funding forced a reduction in heat exchanger size to approximately 30 kW and curtailed plans for detailed instrumentation of the system. Shortly after project initiation, however, the Defense Advanced Research Projects Agency of the Department of Defense (DARPA) funded through CEROS (the National Defense Center of Excellence for Research in Ocean Sciences) a proposal from Makai Ocean Engineering of Waimanalo, Hawaii to restore the full heat exchanger complement and increase the instrumentation to allow collection of operational data in support of the design for a 1 MW plant that DARPA felt would demonstrate the suitability of OTEC for remote military applications.

PICHTR engineers found that the project developed by ALCAN needed significant re-design to accommodate manifolding and other requirements. The ALGOODS heat exchanger sizes were increased and instrumentation was ordered to accommodate the improvements required for the CEROS contract. The plant construction was completed in May of 1996, but the heat exchangers developed serious ammonia leaks in nearly all panels during shakedown operations, necessitating return of the units under warranty to the manufacturer. The leaks were initially thought to have resulted from small ammonia leaks that led to accelerated corrosion resulting in further leaks. The corrosion that led to the leaks was eventually traced to electrolysis caused by the nitrile rubber spacers that ALGOODS had used to maintain the pitch between the roll-bond panels. ALGOODS initially proposed to re-furbish the units by sealing the leaks with epoxy, but CEROS-sponsored testing by Makai Ocean Engineering demonstrated that such repairs would quickly fail, so, in August 1997 ALGOODS agreed to completely re-manufacture the units.

The new modules were made with a welded aluminum frame to hold the panels in the correct positions. ALGOODS experienced difficulty with the brazing of the 200 thin-walled inlet and outlet tubes (100 each) that connect the 100 panels in each module to the inlet and exhaust headers, but the units were eventually assembled and received at NELHA in October 1998. Though the contract funds were nearly depleted, a no cost extension was negotiated, whereby PICHTR re-assembled the plant and performed initial shakedown operations before turning it over to Makai Ocean Engineering which will complete their CEROS contract by collecting operational data for approximately six months. Data from this project, completed by the end of 1999, have established the heat exchange and flow efficiencies of the roll-bond heat exchangers and thus clarified the economic tradeoffs between competing heat exchanger types. If much larger surface areas are required, for example, lower cost aluminum may still not presently be competitive with titanium. The relative scarcity of titanium will, however, significantly change these economics for future large-scale expansion of the technology.

Open-Cycle Research

Prof. Jorn Larsen-Basse of the University of Hawaii at Manoa began initial research on the open-cycle (or Claude-cycle) process in 1983. With minimal funding from the Hawaii Natural Energy Institute and some later U.S.D.O.E. money from the Solar Energy Research Institute (SERI, now the National Renewable Energy Laboratory), he erected on top of the 22-ft high NELH header tank tower two 4-ft high chambers made from sections of the 2-ft diameter Mini-OTEC cold water pipe. These served as evaporator and condenser in a simple test apparatus where he was able, for the first time, to observe and measure various parameters of the vaporization and condensation of seawater at low pressure and OTEC temperatures. These tests confirmed measurements made earlier with fresh water at SERI, indicating that high efficiency could be obtained using the spout evaporator configuration for which SERI had won national design innovation awards. [6]

Also beginning in early 1983, Dr. Stuart Ridgway of R&D Associates in Los Angeles erected an apparatus at NELHA to verify operational parameters of his "Mist-Lift OTEC" design. In a mist lift plant, the water vapor from the open-cycle evaporator is constrained to rise vertically in a column where it couples with a mist of liquid water droplets and "lifts" the liquid water vertically (up to 100 m). The liquid water is separated from the vapor at the top of the column and then falls through a hydraulic turbine which extracts the stored energy. The hydraulic turbine, similar to that in a hydroelectric power system, is much more compact than the low pressure vapor turbine required for the Claude-cycle. The Mist Lift concept thus overcomes the primary difficulty of Claude-cycle systems - the inability to construct large enough turbines for commercial-sized plants. Dr. Ridgway, with Department of Energy support through SERI, conducted about one year of experiments that demonstrated the feasibility of generating appropriate mist droplets and verified the theoretically-predicted coupling between the mist and the vapor. [7] Though this system has received little further attention, it appears to some that it may be the most efficient scheme for large-scale OTEC power production.

The successful results of Dr. Larsen-Basse's initial experiments led SERI, in cooperation with ANL, to build the Heat and Mass Transfer Scoping Test Apparatus (HMTSTA), which incorporated a 5-ft diameter evaporator chamber and a similar-size direct-contact condenser as well as a separate surface condenser. The HMTSTA evaporator and condenser were mounted on a 30-ft high steel tower erected over two 24-ft deep by 8-ft diameter below-grade sumps. This allowed creation of a true barometric head so that the surface and deep seawater were pulled into the chambers from the sumps, simulating the operation of an open-cycle system on a floating platform. SERI researchers conducted experiments on the HMTSTA for about two years, beginning in 1987. [8] They initially re-verified the efficiency of the spout evaporators and also demonstrated that the amount of energy needed to remove the non-condensable gases from seawater was significantly less than that required for the same process in fresh water. Later experiments investigated optimization of the spout configuration, validated the predicted extremely high efficiency from the direct contact condenser, and demonstrated production of fresh water from the surface condenser.

The success of the HMTSTA experiments led SERI researchers, working with PICHTR, to develop plans for a much larger Net Power Producing Experiment (NPPE). This project, initially designed to utilize the DOE component of the 40-in diameter pipeline installed jointly in 1987 by the State of Hawaii and the U.S.D.O.E., evolved into a 210 kW (gross electrical) open cycle plant that was designed and built by PICHTR. Completed in 1992, the 210 kW OC-OTEC system (the NPPE name was dropped when there were insufficient funds to install the higher efficiency seawater pumps that would have been needed to assure net power under all conditions) operated experimentally through 1998, producing a maximum of 255 kW gross electrical output (40 kW net) when the surface seawater was its warmest. [9]

The 7.5 ton vertical axis radial inflow turbine rotated at 1800 rpm inside the top of this 210 kW Open-Cycle OTEC Experimental Facility that operated at NELHA from 1992 through 1998. The fresh water production vapor to liquid surface heat exchanger is at the right of the picture.

Major accomplishments of the 210 kW open cycle OTEC project include:

- Largest OTEC plant yet operated, with largest net power output
- First net power production from open-cycle process

- 10 ft diameter, 7.5 ton turbine rotated at 1800 rpm
- Synchronized with electric power grid through fluid clutch
- Developed use of magnetic bearings for high efficiency very high speed (to 48,000 rpm) vacuum pumps
- Developed and utilized flexible PC-based monitoring and control system
- Verified spout evaporator effectiveness data
- Demonstrated very high condenser efficiency from structured-packing design
- Operated continuously for eight days, though not designed for continuous use
- Successfully demonstrated about 7000 gal/day fresh water production with minimal power loss from an auxiliary vapor to liquid surface condenser (designed and added following completion of the initial facility)
- Demonstrated increased fresh water production from an auxiliary direct contact condenser fed with fresh water chilled by cold seawater in a standard titanium plate heat exchanger

Following successful completion of these experiments, the 210 kW O-C OTEC plant was shut down and demolished in January 1999.

References

NOTE: We highly recommend the following book as the most complete presentation available of the technology and economics of OTEC:

Avery, William H. and Chih Wu. *Renewable Energy from the Ocean*. Oxford University Press, 1994, 446 p. For more information, Click here.

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[2] Panchal, C., H. Stevens, L. Genens, A. Thomas, C. Clark, D. Sasscer, F. Yaggee, J. Darby, J. Larsen-Basse, B. Liebert, L. Berger, A. Bhargava and B. Lee, October 1990, "OTEC Biofouling and Corrosion Study at the Natural Energy Laboratory of Hawaii 1983-1987", Argonne National Laboratory Energy Systems Div., ANL/ESD-10, Argonne, IL, 161 p.

[3] Takahashi, Patrick K., Study of the Non-Chemical Methods of Biofouling Control in OTEC Heat Exchangers, Final Report to Solar Energy Research Institute, Contract No. XX-4-04095- 1, April 1986, 180 p.

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[7] Lee, C.K.B. and S.L. Ridgway, "Vapor/Droplet Coupling and the Mist Flow (OTEC) Cycle", *J. Solar Energy Engrng.*, v. 105, May 1983, p.181-6.

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