Hawaii Energy and Environmental Technologies (HEET) Initiative

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Ocean Thermal Energy Conversion (OTEC) Heat Exchanger Test and Evaluation

Prepared by:

University of Hawaii at Manoa, Hawaii Natural Energy Institute

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HNEI
Hawaiʻi Natural Energy Institute
University of Hawaiʻi at Mānoa

OTEC HX Testing Program
2012 Annual Report

Table of Contents

I. List of Figures

II. List of Tables

III. Executive Summary

Heat exchangers are one of the most expensive components in an Ocean Thermal Energy Conversion (OTEC) power plant. Proper heat exchanger selection is crucial to the economic viability of OTEC. Heat exchanger development must balance size, cost, and performance. To meet this goal, the OTEC Heat Exchanger (HX) Testing Program is divided into three areas: HX Performance Testing, HX Design Development, and Corrosion Testing. This annual report summarizes the activities from October 2011 to February 2013 and summarizes the completion of the Phase 3 Milestones.

Major accomplishments in this period include:

HX Performance Testing Facility

- Facility has been maintained and performance testing procedure streamlined
- Facility used to completed performance testing of the Graphite Foam and Enhanced Tube Heat Exchangers
- Enhanced ammonia pressure control resolution by adding a second (smaller) control valve in parallel with the existing control valve

HX Development

- Lockheed Martin's Graphite Foam Heat Exchanger was designed, fabricated, installed, and performance tested
- Lockheed Martin's Enhanced Tube Heat Exchanger was designed, fabricated, installed, and performance tested

Corrosion Testing

- Removal and analysis of 3-year hollow extrusion corrosion samples
- Pitting performance of the hollow extrusion coupons was quantified using a profilometer system
- Completed initial testing of nitric acid as an in-situ treatment for pit mitigation
- Completed initial testing of Siloxel, a non-toxic replacement for chromate conversion coatings
- Two additional in-situ treatments have been selected for future testing based on results from the nitric acid testing
- Design and installation of representative Lockheed Martin Graphite Foam Heat Exchanger samples, representative Lockheed Martin Enhanced Tube Heat Exchanger samples, and representative roller expanded heat exchanger samples.
- 5 combinations of coatings for use at gasket interfaces are being tested in surface and 674 meter deep seawater. These tests are being carried out with the gaskets in both cross and in-line flow.

Major findings in this period include:

HX Performance Testing Facility

- No major findings to report

HX Development

- Testing of the Lockheed Martin Graphite Foam Heat Exchanger showed that it didn't have the anticipated improvement in performance compared to the plain shell and tube
- Testing confirmed that the Lockheed Martin Enhanced Tube Condenser has a significant improvement in performance verses the plain tube heat exchanger

Corrosion Testing

- Friction stir welded zones exhibit the same or better pitting performance compared to the base metal
- The roller expanded portion of a tube installed into a tube sheet has worse pitting performance then the base metal
- Nitric acid doesn't significantly improve pitting performance when used as a periodic in-situ treatment
- Siloxel coating cannot offer complete protection from pitting
- Initial test results suggest that the general corrosion rates of steel are low enough to make it a viable condenser material

Phase 3 Milestones

Milestone	Deliverable	Status	Due date	Invoice $
1	Develop a corrosion testing apparatus which monitors the accumulation and growth rate of pits in aluminum samples. This work shall include, but not be limited to, development of a detailed design of the rack which includes microscope cameras mounted on a motorized stage for image collection of sample surfaces. The components of this custom rack will be assembled in the corrosion lab, and tests will be conducted on various aluminum samples using warm and cold seawater for the purpose of characterizing pitting resistance for each of the tested alloys. Included in this report shall be a summary of the results of the ongoing corrosion experiment for all existing samples.	Complete	10/1/2011	$160,000
2	Assist Lockheed Martin on the design of a graphite foam OTEC heat exchanger (Heat Exchanger #1). This heat exchanger shall be a full-scale, 2MW thermal capacity condenser, designed for nominal seawater flow rates in the range of 2000-4000gpm. Included in this report shall be a summary of the design features and detail drawings provided by Lockheed Martin. Report a preliminary testing plan for this heat exchanger and schedule for installation and test at the NELHA Test Facility.	Complete	11/1/2011	$25,000
3	Oversee fabrication, accept delivery and install Heat Exchanger #1 at the Heat Exchanger Test Facility. Installation shall include custom 18" diameter fiberglass seawater piping spools as well as 3" and 6" steel piping for ammonia system tie-in. Included in this report shall be a summary of the results of	Complete	2/1/2012	$65,000

	the ongoing corrosion experiment for all existing samples.			
4	Complete design for Heat Exchanger #2. This heat exchanger shall be a full-scale, 2MW thermal capacity evaporator or condenser. Submit final drawings for fabrication, as well as a preliminary schedule for fabrication, delivery and testing.	Complete	3/1/2012	$160,000
5	Run a complete performance test on Heat Exchanger #1. This testing shall include, but not be limited to, steady state operation at seawater flows ranging from 1500 to 4000 gpm, in increments of 500 gpm. This testing shall also include steady state operation at a thermal duty between 1.0 and 2.5MW, at a maximum of 0.5MW increments.	Complete	4/1/2012	$155,000
6	Fabricate and install Heat Exchanger #2. Installation shall include custom 16" diameter fiberglass seawater piping spools as well as 3" and 6" steel piping for ammonia system tie-in. Included in this report shall be a summary of the results of the ongoing corrosion experiment for all existing samples.	Complete	6/1/2012	$230,000
7	Run a complete performance test on Heat Exchanger #2. This testing shall include, but not be limited to, steady state operation at seawater flows ranging from 1500 to 4000 gpm, in increments of 500 gpm. This testing shall also include steady state operation at a thermal duty between 1.0 and 2.5MW, at a maximum of 0.5MW increments.	Complete	8/1/2012	$155,000
8	Submit Annual Report.	Complete	12/1/2012	$50,000

IV. HX Performance Testing Facility

The HX Testing Facility can support testing of up to six heat exchangers (testing is only expected on one pair of heat exchangers at a time). Warm and cold seawater are siphoned to the top of the facility via a vacuum priming system and flow downwards through the heat exchangers and discharge into a common NELHA discharge trench. During testing, liquid ammonia is pumped from the receiver tank into the evaporator using the recirculation pump. The ammonia vapor-liquid mixture exiting the evaporator is separated in the mesh of the separator tank. Ammonia liquid is collected in the separator tank and travels back into the receiver tank via the separator-receiver line. Ammonia vapor exits the separator and travels through the expansion valve and is condensed in the condenser. Liquid ammonia exiting the condenser gravity drains into the buffer tank. A feed pump moves the liquid ammonia from the buffer tank into the receiver tank. Both ammonia pumps are located in a pump pit. During idle periods, most of the ammonia in the system is held in the buffer and receiver tanks and in the piping in the pump pit. Reserve ammonia for the facility is stored in the storage tank.

The system is controlled using data acquisition hardware and a custom designed software program. This HX Control Program is capable of controlling the ammonia pumps, ammonia control valves, and seawater control valves manually or automatically (given predefined setpoints). In automatic mode, ammonia system parameters are monitored and the HX Control Program adjusts valves and pumps to maintain or change parameters. Ammonia system pressure and temperature are monitored at multiple locations, level is monitored in all tanks, and flow is monitored at five points. The seawater system has four pressure sensors, two temperature sensors, and one flow sensor for each water source. Sensor outputs are wired to a data acquisition cabinet located on the structure and data is collected by the HX Control Program. Along with data collection and system control, the software performs preliminary data analysis by calculating heat exchanger performance parameters and determining periods of steady state operation.

TIMELINE OF OPERATION

Nov 2010	Construction completed on the HX Performance Testing Facility
Jan 2011	Shakedown testing completed using temporary heat exchangers
April 2011	Installation of the first pair of heat exchangers – A Chart Brazed Aluminum Evaporator (BAHX3) and Lockheed Martin Shell and Tube Condenser
July 2011	Performance testing completed on BAHX3 and Lockheed Martin Shell and Tube Condenser
July 2012	Installation and performance testing completed on Lockheed Martin Graphite Foam Heat Exchanger ***(task 3 & 5)***
Feb 2013	Installation and performance testing completed on Lockheed Martin Enhanced Tube Heat Exchanger ***(task 6 & 7)***

TIMELINE OF MAINTENANCE PERFORMED FROM 10/1/2011 TO 3/1/2013

Jan 2012	Calibration on all pressure instrumentation

April 2012	Replaced wind sock due to color fade
May 2012	Fixed cracked PVC discharge pipe flange on the CSW side
July 2012	Polished the seats and replaced seals on all NH3 valves 3" and over
July 2012	Replaced O-ring seal on the 2" ammonia check valve below the recirc. tank
July 2012	Calibration on pressure instrumentation
Aug 2012	Resealed all four 2" ammonia control valve stems
	Repainted all ammonia pipes white due to rust
Sept 2012	DT sensor Calibration was done
Jan 2013	Calibration Sea Water Flow meters
Feb 2013	Replaced the air compressor that actuates the pneumatic 24" valves

Minor maintenance items include:

Several times a year galvanized surfaces are touched up with ZRC cold galvanizing

Sea water strainer emptied after each test

Heat exchangers are flushed with Salt Away after testing

Rinse structure with fresh water 4X per year (Deluge test)

V. HX Development

LOCKHEED MARTIN GRAPHITE FOAM CONDENSER

Design

The Lockheed Martin Graphite Foam Heat Exchanger (GFHX) utilizes graphite foam sandwiched between multi-hollow extrusions. The GFHX has cold seawater flowing through rectangular channels in the multi-hollow extrusion to condense ammonia on the shell side of the heat exchanger. There are 113 extrusions fabricated from Al 6063. Figure 1 shows a cross section view of the multi-hollow extrusions. The graphite foam tiles are epoxied between the multi hollow extrusions and provide additional heat transfer area to improve the performance of the heat exchanger. Graphite foam is sandwiched between layers of the multi-hollow extrusions (Figure 2).

Figure 1: Multi-hollow extrusion cross section

Figure 2: Graphite foam sandwiched between the multi-hollow extrusions

Figure 3 shows the condenser as it arrived at Makai's OTEC Test Facility on 6/26/2012. It was installed during the period of 3 days. Figure 4 shows a view from the end of the heat exchanger, looking at the tubesheet. The extrusions are friction stir welded into the tubesheet. Friction stir welding allows for a full strength joint while avoiding a corrosion-prone heat affected zone. The tubesheets are attached to the shell with a bolted and gasketed flange joints.

Figure 3: Lockheed GFHX arriving at NELHA

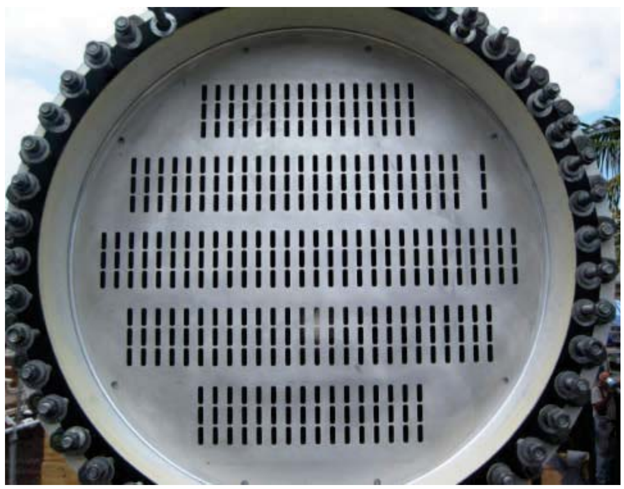


Figure 4: GFHX tubesheet

The majority of heat exchanger fabrication was completed prior to shipment. The only assembly undertaken by Makai was installation of the cold water nozzles on each end of the unit.

Test Description

All testing was carried out on July 31, 2012. A total of 17 operating points were tested. These points are defined by the test matrix shown in Table 1.

Data was recorded continuously once every 5 seconds throughout the length of the testing, but only data taken during steady-state operation was used to determine the test results. Each operating point was held at steady-state for 12 minutes. For this set of testing, steady-state was defined by having the standard deviation of the seawater flow less than 300 gpm and the standard deviation of the condenser pressure less than 4 kPa for at least 3 minutes.

Table 1: GFHX Test Matrix

		Duty (KW)			
		1000	1500	2000	2500
Cold Water Flow (gpm)	1500	X		X	
	2000	X	X	X	X
	2500	X	X	X	X
	3000	X	X	X	X
	3500	X	X		X

Test Results

A wide variety of data were collected during the tests. Of primary interest are the heat transfer coefficient, waterside pressure drop and ammonia-side pressure drop as these parameters directly affect OTEC system design. Additional parameters such as approach temperature, ammonia operating pressure and convective heat transfer coefficients are also examined to provide deeper insight to the performance of the heat exchanger.

Overall heat transfer coefficient

The overall heat transfer coefficient, U, is a measure of the condenser's efficiency. Heat exchangers with higher U values require less surface area to transfer a given duty. This is important for OTEC because more efficient heat exchangers require less space, which equates to big savings on the cost of the remoras. The overall heat transfer coefficient is typically plotted two different ways, with lines of constant seawater flow and with lines of constant duty.

U is very dependent on the water velocity in the extrusions, which suggests that the water-side convective heat transfer coefficient is the limiting factor in the overall efficiency. The U value has logarithmic relationship to water velocity; i.e., gains in U diminish for the same incremental increase in water velocity.

Water-side pressure drop

Waterside pressure drop affects the amount of OTEC-generated power as any power produced must first be used to supply seawater pumps on an OTEC plant. High pressure drops require large amounts of power, which reduces the net-power output from the OTEC plant.

The water-side pressure drop is independent of duty and has a power-law relationship to water velocity. Pressure drop increases exponentially with increasing water velocity, opposite to U value, which shows diminishing increases with increasing flow. These two trends indicate that there will be an optimum water velocity that balances increased U value with increased pressure drop across the condenser.

Ammonia-side pressure drop

Ammonia-side pressure loss is not expected to be a significant factor in a well-designed condenser. Condensers typically operate at a nearly constant pressure on the working fluid side. As expected, the test data indicates a general trend of increased pressure drop with increased flow. However, there is quite a bit of scatter in the data. The scatter is most likely due to the graphite foam, which adds significant complexity to the ammonia flow path. The magnitude of the pressure drop on the ammonia side is much smaller than the pressure drop on the waterside.

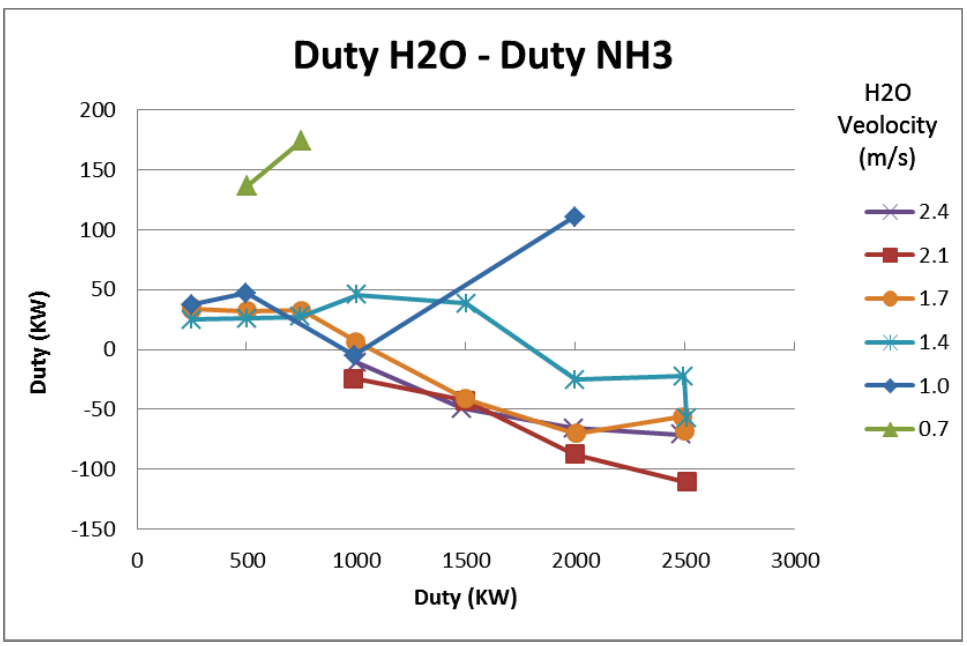
Ammonia-side operating pressure

The operating pressure of the ammonia is important to the overall OTEC cycle because it is related to the power generated in the OTEC cycle. The power generated in an OTEC plant is a function of the pressure drop across the turbine and the ammonia flow rate. Thus, a lower pressure on the condenser side is generally better for OTEC as this should increase the pressure drop and create higher power output.

For a given duty, the condenser pressure decreases with increased flow rate. This means that gross power output should be greater for higher water flow rates.

Difference between ammonia and seawater duty

Theoretically, if the condenser was perfectly insulated, the ammonia duty should be identical to the seawater duty. However, during testing heat from the outside environment and errors in sensor calibration can cause the two duties to be unequal. In general, the agreement between the two duties was very good; the two values were within 6% for all tested points (Figure 5).



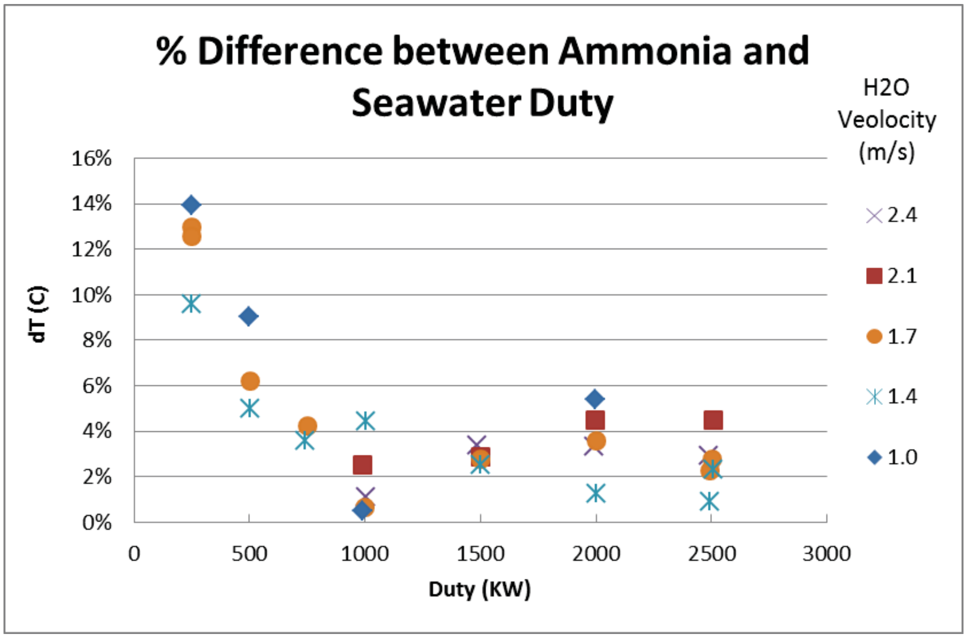


Figure 5: GFHX difference between ammonia duty and seawater duty

Approach Temperature

The approach temperature is the difference in temperature of the two fluids at the condenser outlet. Ammonia-side duty is used in this calculation because the ammonia pressure sensors are used to calculate the ammonia temperature at saturation and provide a more accurate temperature measurement than the temperature sensors on the seawater side. The approach temperature is important because small approach temperatures indicate that the amount of heat transferred toward the end of the heat exchanger is greatly diminished due to small temperature differences between the two fluids.

There is a linear relationship between duty and approach temperature, with the slope of the line dependent on the water velocity. The approach temperature increases with duty because higher duty corresponds to higher ammonia operating pressure, and thus a higher saturation temperature.

Convective heat transfer coefficients

The ammonia-side and seawater-side convective heat transfer coefficients were calculated for the condenser. The coefficients were calculated using the definition of the overall heat transfer coefficient as a function of the convective and conductive heat transfer coefficients (shown below). For the evaporator, h_1 and h_2 are the ammonia-side and water-side convective heat transfer coefficients, k is the conductivity of aluminum and dx is the wall thickness of the aluminum extrusion.

$$U = 1/(1/h_1 + dx_w/k + 1/h_2)$$

In order to determine h_1 and h_2, the water-side heat transfer coefficient was assumed to be constant for each water flow rate set point and the ammonia-side heat transfer coefficient was assumed to be constant for each duty set point. The method of least squares was then used to determine a single heat transfer coefficient for each set point. The calculated heat transfer coefficients had a residual error of only 0.6%, i.e. re-computing U values obtained from these coefficients gives values within 0.6% of the original U measured.

Please contact Makai Ocean Engineering for in-depth data analysis and discussion on the GFHX.

LOCKHEED MARTIN ENHANCED TUBE CONDENSER

Design

The Lockheed Enhanced Tube Heat Exchanger (ETHX) consists of 283 enhanced tubes fabricated from Al 6063. The majority of heat exchanger fabrication was completed prior to shipment. The only assembly undertaken by Makai was installation of the cold water nozzles on each end of the unit.

Figure 6 shows the ETHX as it arrived at Makai's OTEC Test Facility on 1/16/2013. It was installed during the period of 3 days. Figure 7 shows a view from the end of the heat exchanger, looking at the tubesheet. The tubes are friction stir welded into the tubesheet. Friction stir welding allows for a full strength joint while avoiding a corrosion-prone heat affected zone. The tubesheets are attached to the shell with a bolted and gasketed flange joints.

Figure 6: ETHX arriving at NELHA

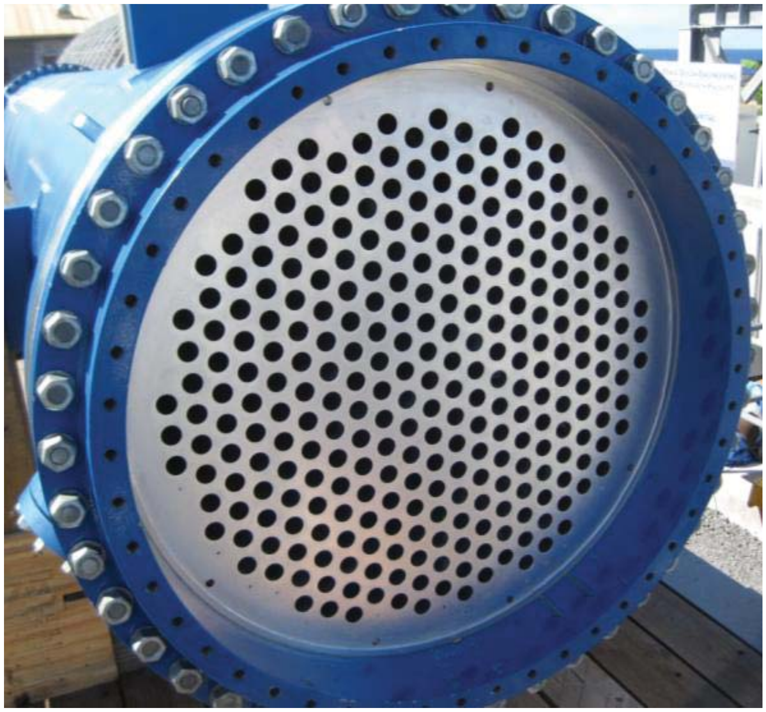


Figure 7: ETHX tubesheet

Test Description

All testing was carried out on February 6, 2013. A total of 25 operating points were tested. These points are defined by the test matrix shown in Table 2.

Table 2: ETHX Test Matrix

		Duty (KW)				
		1500	2000	2500	3000	3500
Cold Water Flow (gpm)	2500		X			
	3000		X	X		
	3500	X	X	X	X	
	4000	X	X	X	X	
	4500	X	X	X	X	
	5000		X	X	X	
	5500		X	X	X	
	6000		X	X	X	X

Data was recorded continuously every 5 seconds throughout the length of the testing. Each operating point was held for at least 10 minutes while data was recorded.

Test Results

A wide variety of data were collected during the tests. Of primary interest are the heat transfer coefficient, waterside pressure drop and ammonia-side pressure drop as these parameters directly affect OTEC system design. Additional parameters such as approach temperature, ammonia operating pressure and convective heat transfer coefficients are also examined to provide deeper insight to the performance of the heat exchanger.

Overall heat transfer coefficient

The overall heat transfer coefficient, U, is a measure of the condenser's efficiency. Heat exchangers with higher U values require less surface area to transfer a given duty. This is important for OTEC because more efficient heat exchangers require less space, which equates to big savings on the cost of the remoras. The overall heat transfer coefficient is plotted below in two different ways: with lines of constant seawater flow and with lines of constant duty.

U is very dependent on the water velocity in the tubes. This suggests that the water-side convective heat transfer coefficient is the limiting factor in the overall efficiency. Note that the U value has a logarithmic relationship to water velocity. This means that as water velocity increases, the gains in U begin to diminish.

Water-side pressure drop

Waterside pressure drop affects the amount of OTEC-generated power that must be used to supply seawater pumps on an OTEC plant. High pressure drops require large amounts of power, which reduces the net-power output from the OTEC plant.

The above graph shows that, as expected, the water-side pressure drop is independent of duty and has a power-law relationship to water velocity. Note that the power-law relationship has an exponent of ~2.3. This means that pressure drop continues to increase exponentially with increased water velocity, opposite to the trend of U value which shows diminishing increases with increased flow. These two trends indicate that there will be an optimum water velocity that balances increased U value with increased pressure drop across the condenser.

Ammonia-side pressure drop

Ammonia-side pressure loss is not expected to be a significant factor in a well-designed condenser. Condensers typically operate at a nearly constant pressure on the working fluid side. The data indicate a general trend of increased pressure drop with increased flow. The magnitude of pressure drop on the ammonia side is much smaller than the pressure drop on the waterside.

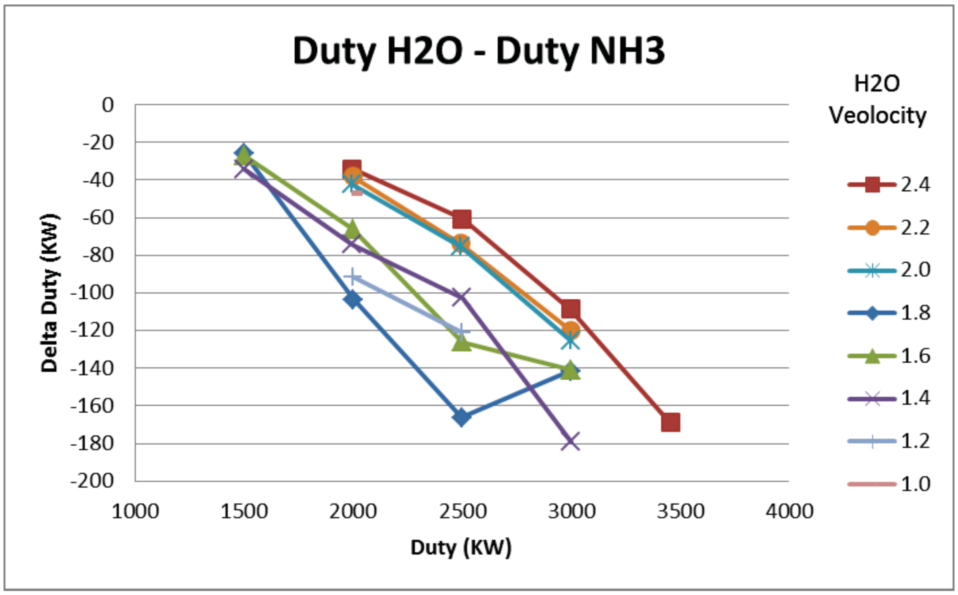
Ammonia-side operating pressure

The operating pressure of the ammonia is important to the overall OTEC cycle because it is related to the power generated in the OTEC cycle. The power generated in an OTEC plant is a function of the pressure drop across the turbine and the ammonia flow rate. Thus, a lower pressure on the condenser side is generally better for OTEC as this should increase the pressure drop and create higher power output.

For a given duty, the condenser pressure decreases with increased flow rate. This means that gross power should be greater for higher water flow rates.

Difference between ammonia and seawater duty

Theoretically, if the condenser was perfectly insulated, the ammonia duty should be identical to the seawater duty. However, during testing, heat from the outside environment and errors in sensor calibration can cause the two duties to be unequal. In general, the agreement between the two duties was very good; the two values were less than 7% different for all set points, as seen in Figure 8.



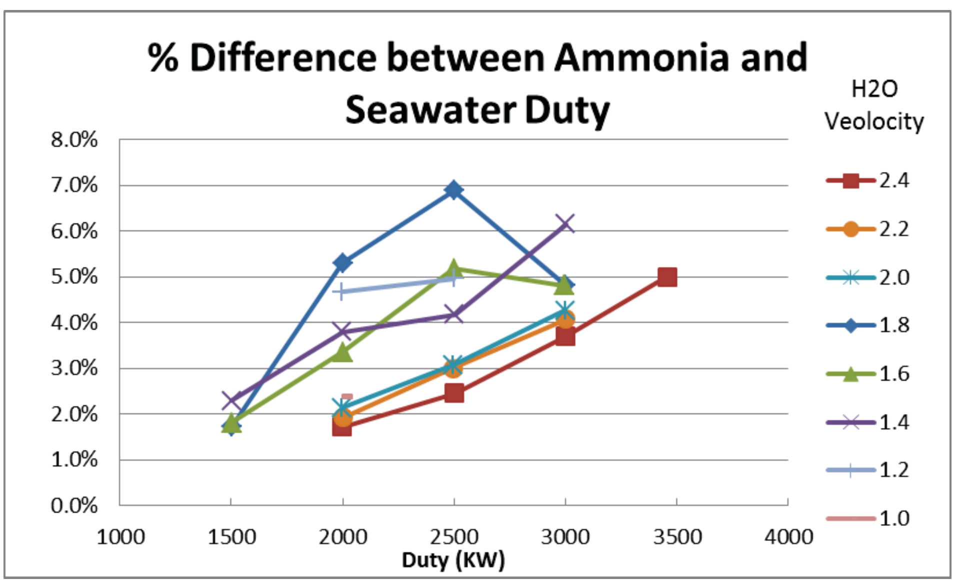


Figure 8: ETHX difference between ammonia duty and seawater duty

Approach Temperature

The approach temperature is the difference in temperature of the two fluids at the condenser outlet. Note that the duty of the ammonia is used in this calculation because the ammonia pressure sensors used to calculate the ammonia temperature at saturation provide a more accurate temperature measurement than the temperature sensors on the seawater side. The approach temperature is important because small approach temperatures indicate that the amount of heat transferred toward the end of the heat exchanger is greatly diminished due to small temperature differences between the two fluids.

There is a linear relationship between duty and approach temperature, with the slope of the line dependent on the water velocity. The approach temperature increases with duty because higher duty corresponds to higher ammonia operating pressure, and thus a higher saturation temperature.

Convective heat transfer coefficients

The ammonia-side and seawater-side convective heat transfer coefficients were calculated for the condenser. The coefficients were calculated using the definition of the overall heat transfer coefficient as a function of the convective and conductive heat transfer coefficients (shown below). For the evaporator, h_1 and h_2 are the ammonia-side and water-side convective heat transfer coefficients, k is the conductivity of aluminum and dx is the wall thickness of the aluminum tubes.

$$U = 1/(1/h_1 + dx_w/k + 1/h_2)$$

In order to determine h_1 and h_2, the water-side heat transfer coefficient was assumed to be constant for each water flow rate set point and the ammonia-side heat transfer coefficient was assumed to be constant for each duty set point. The method of least squares was then used to determine a single heat transfer coefficient for each set point. The calculated heat transfer coefficients had a residual error of only 0.4%, i.e. re-computing U values obtained from these coefficients gives values within 0.4% of the original U measured.

Please contact Makai Ocean Engineering for in-depth data analysis and discussion on the ETHX.

Design Discussion

The externally enhanced tubes provided a nearly direct comparison to the plain-tube heat exchanger, previously tested. The tube enhancement provided an increase in performance, but also an increase in cost. In this case the increase in performance outweighed the increase in cost, so the enhancement is justified and necessary.

VI. Corrosion Testing

The goal of the corrosion testing program is to evaluate the corrosion resistance of potential heat exchanger materials for use in future OTEC plants.

Makai's testing effort has been underway for just over 3 years. In this time the general corrosion rates of 6 aluminum alloys in surface seawater, 674 meter deep seawater, and 915 meter deep seawater have been documented with a high level of certainty. Testing has shown that the major corrosion mechanism of concern for an aluminum heat exchanger is pitting. The pitting susceptibility of all alloys has shown to be drastically increased in deep seawater (both 674m and 915m). It has also been observed that the pitting characteristics of aluminum are heavily influenced by many factors in addition to alloy type and water depth. These factors include; material form (ie. Extrusion, rolled, drawn, etc), extrusion quality, flow characteristics, and others. In response to this finding, Makai developed a unique testing apparatus to allow for corrosion testing of various pitting mitigation techniques such as coatings or chemical treatments. These racks allow continuous monitoring of the samples which makes it possible to determine the onset of pitting and monitor pits as they grow. The developed testing system is referred to as the imaging rack. In parallel with this effort, corrosion coupons that physically resemble the anticipated heat exchangers are being installed into test loops for prolonged testing.

In addition to testing aluminum, Makai is investigating steel for use as a condenser material. Although steel has a higher general corrosion rate than aluminum, it is believed to have more desirable pitting characteristics than those associated with aluminum. This ultimately translates into a more reliable life prediction which reduces risk when designing a high cost condenser for an OTEC plant. Steel is also a more common material used in the heat exchanger industry which increases the number of potential suppliers. This helps ensure competition which ultimately implies more stable and predictable costs. Initial test results have shown steel to be a viable candidate which has led to an increase in the steel testing effort.

IMAGING RACK

Four imaging racks were constructed. Two of the racks were mounted such that they can test samples in 674 meter deep seawater and two such that they can test samples in surface seawater. Each imaging rack can be used to conduct four isolated tests.

These racks were used to test nitric acid as an in-situ treatment for pit mitigation and Siloxel a corrosion inhibiting coating. This testing provided feedback on the effectiveness of the imaging rack design which led to the development of a second version of this rack. Version 2 incorporated several improvements to increase the reliability and accuracy of the collected image sets.

TESTING UPDATE

Hollow Extrusion (box) Coupons

3 year box coupon samples were removed and processed on 1/8/13. There were no new significant observations when removing the 3 yr coupons. General corrosion rates are still low, making pitting the corrosion mechanism of interest. The surface seawater coupons showed little to no pitting across all alloys, while the alloys showed similar pitting characteristics as past coupons in the 674m

and 915m deep seawater. The coupons pretreated with warm seawater for 40days prior to being placed in 674 meter deep seawater all showed improved pitting resistance. Alloy 6063 exhibited the worst corrosion performance with severe pitting and crevice corrosion in three out of the four water sources. Alloys 1100, LA83I and LA83P exhibited poor performance with severe pitting and crevice corrosion in one or more water sources. Alloy 5052 performed moderately with shallow pitting in several water sources. Alloy 3003 performed the best overall with very shallow or no pitting in all water sources.

This corrosion test will continue for at least another 2 years, with 12 samples being removed from each water source at year 4 and 5 for analysis. Refer to Figures 9-19 for box coupon test results.

Surface seawater

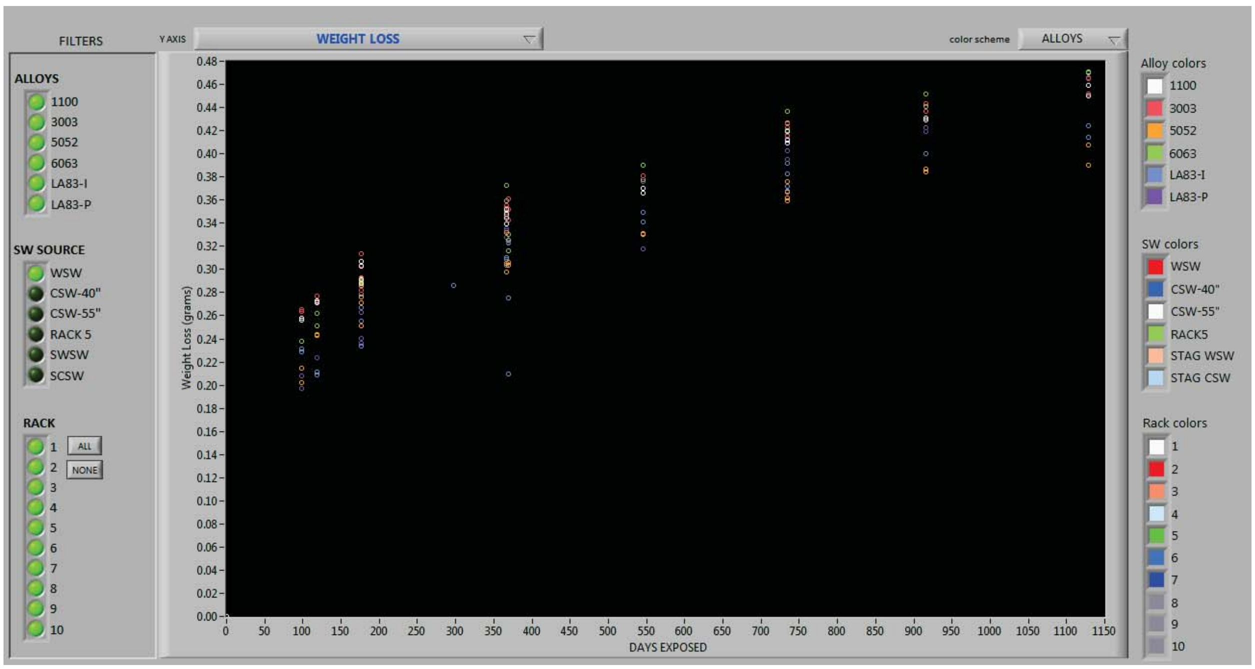
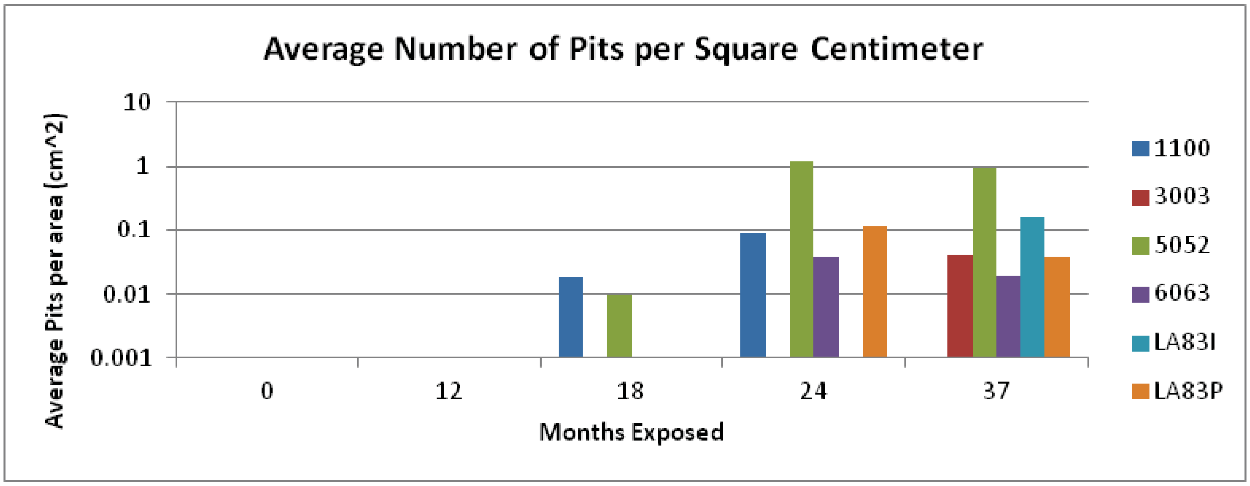


Figure 9: Weight loss results for box coupons exposed to surface seawater. Data point colors correspond to the "Alloy color" legend in the upper right portion of the image.

Figure 10: Representative images of the surface seawater samples exposed for 3 years.



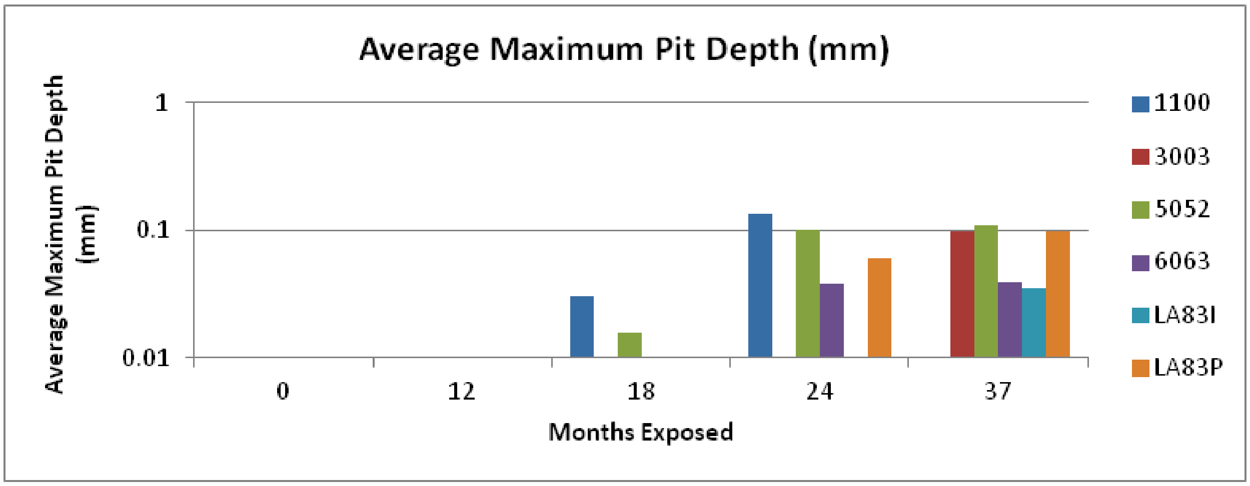


Figure 11: Average number of pits per square centimeter (Top) and average maximum pit depth (Bottom) on coupons exposed to surface seawater for 12, 18, 24 and 37 months.

674 meter deep seawater

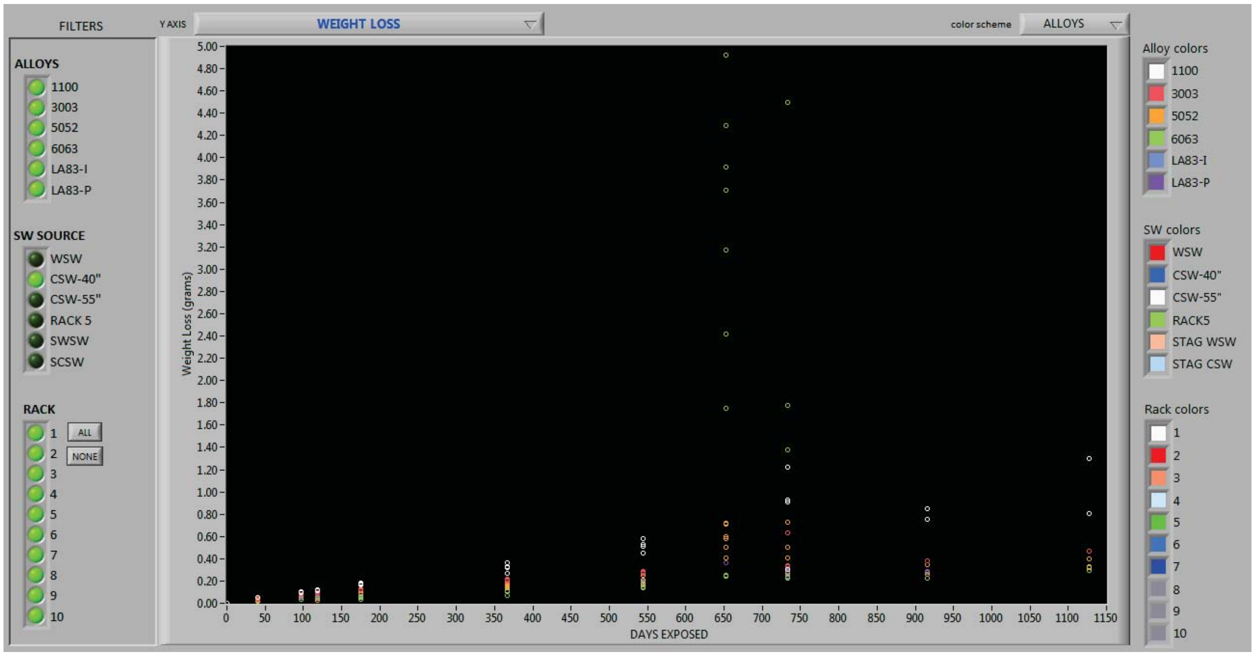


Figure 12: Weight loss results for box coupons exposed to 674m deep seawater. Data point colors correspond to the "Alloy color" legend in the upper right portion of the image. Note that additional samples were removed at 650 days of exposure as they were causing leak issues.

Figure 13: Representative images of the 674m deep seawater samples exposed for 3 years.

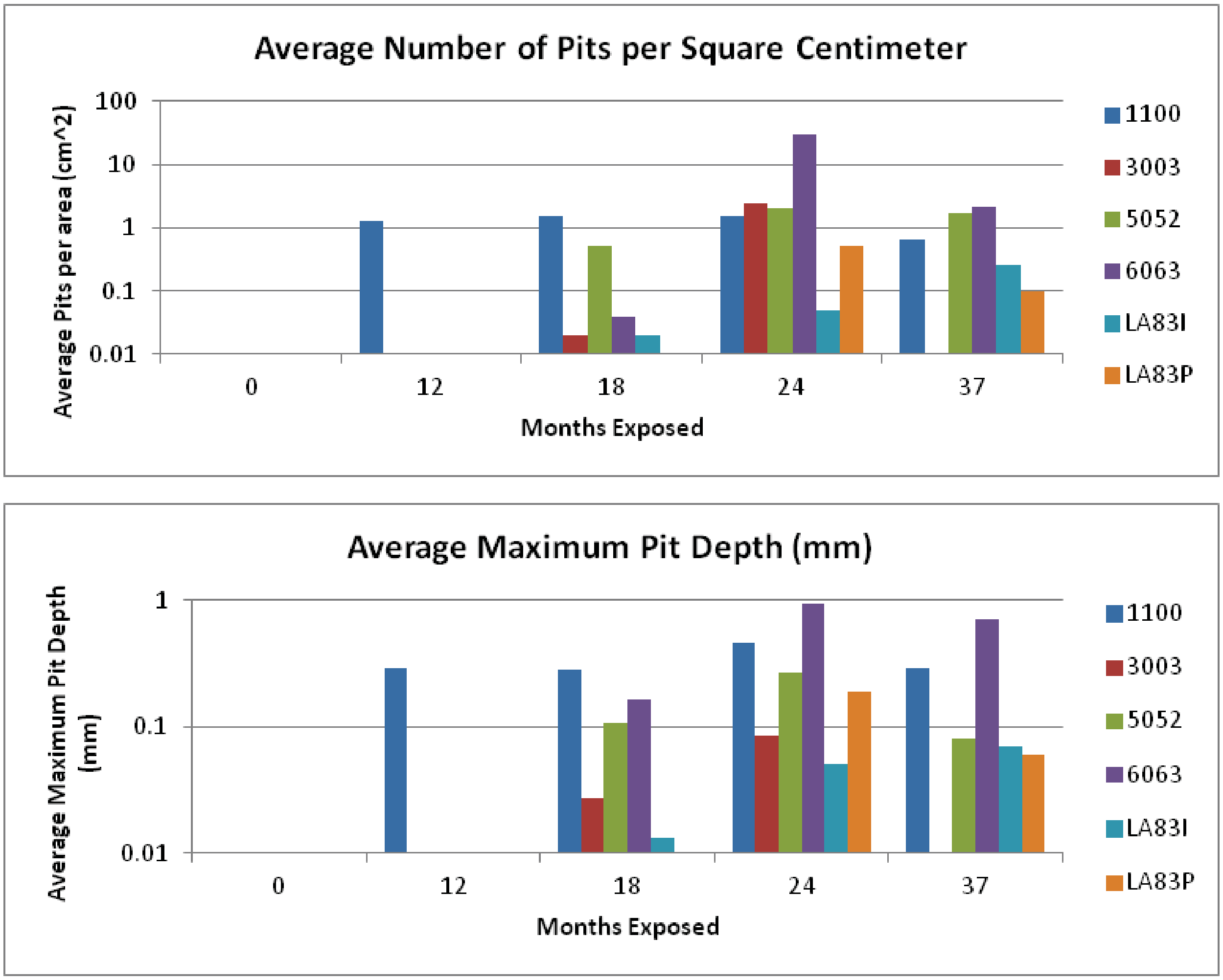


Figure 14: Average number of pits per square centimeter (Top) and average maximum pit depth (Bottom) on coupons exposed to 674 meter deep seawater for 12, 18, 24 and 37 months.

915 meter deep seawater

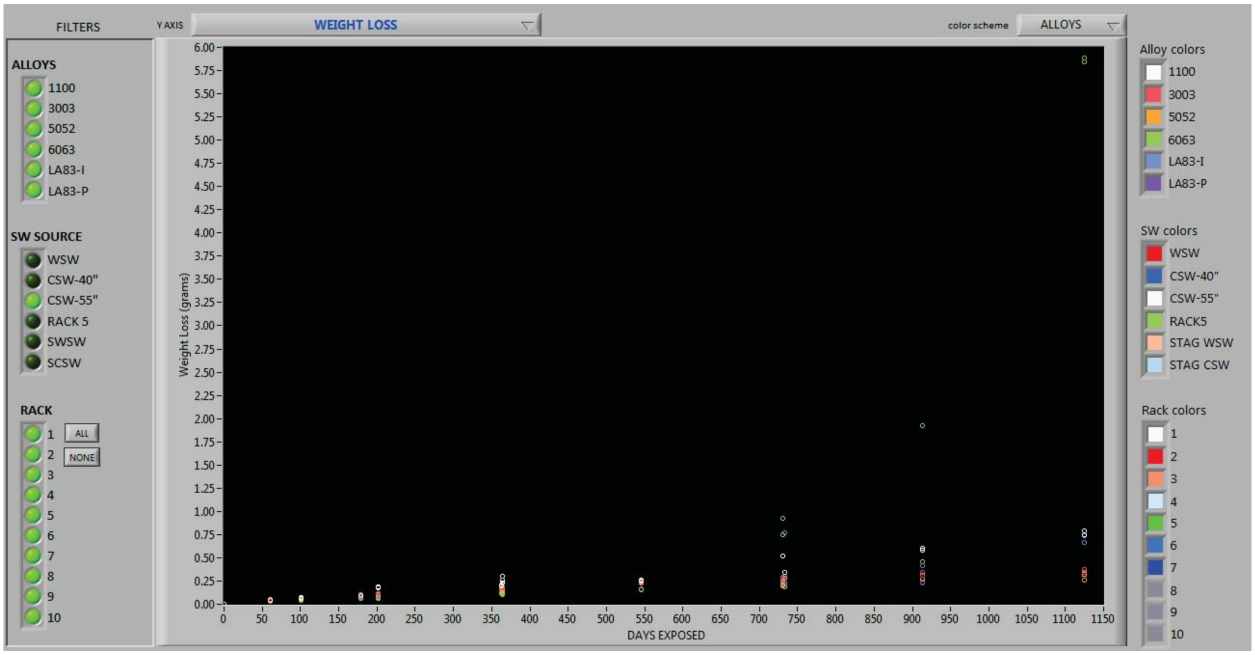


Figure 15: Weight loss results for box coupons exposed to 915m deep seawater. Data point colors correspond to the "Alloy color" legend in the upper right portion of the image.

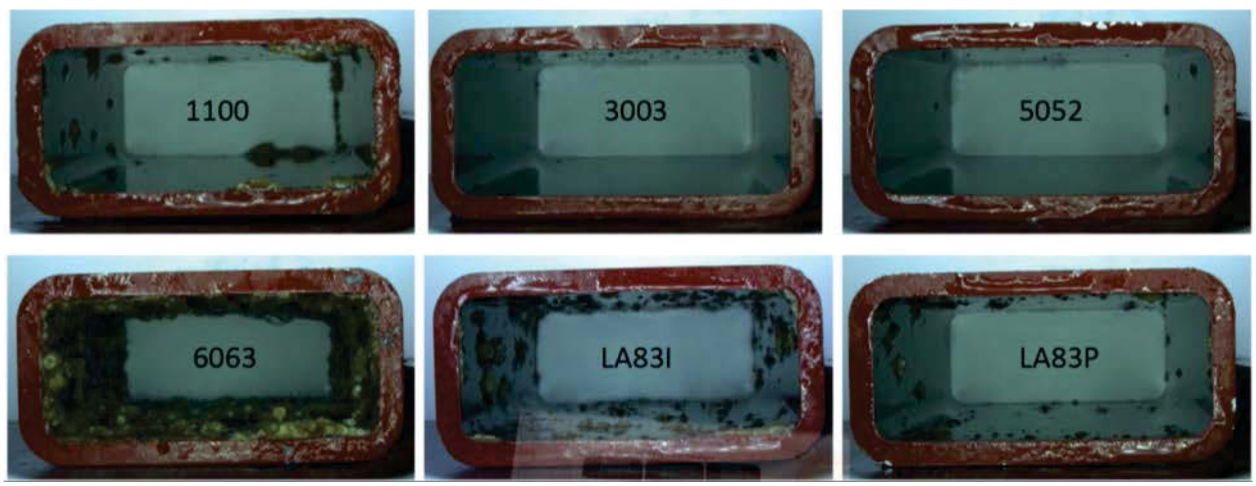
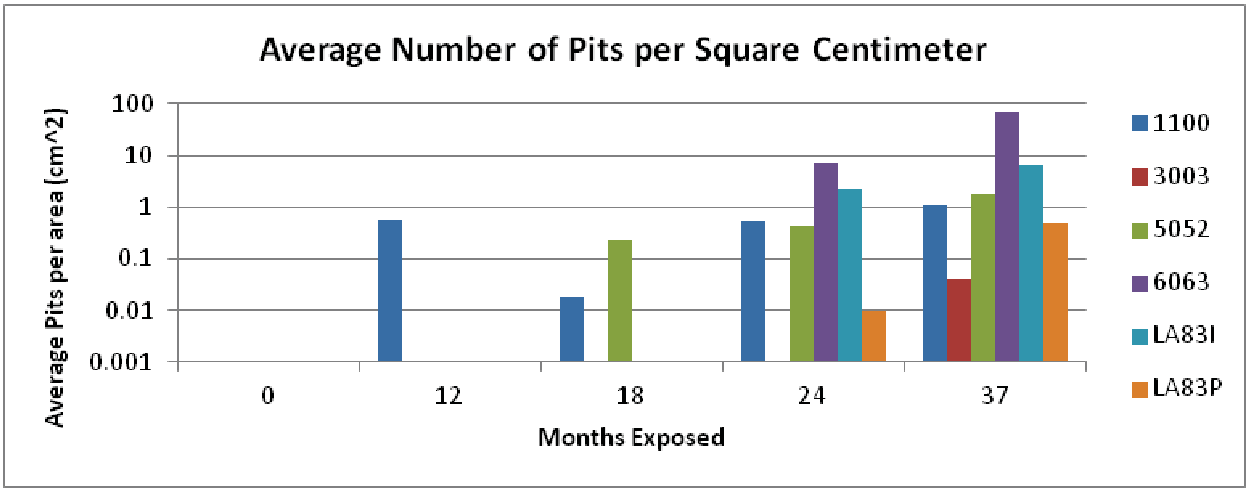


Figure 16: Representative images of the 915m deep seawater samples exposed for 3 years.



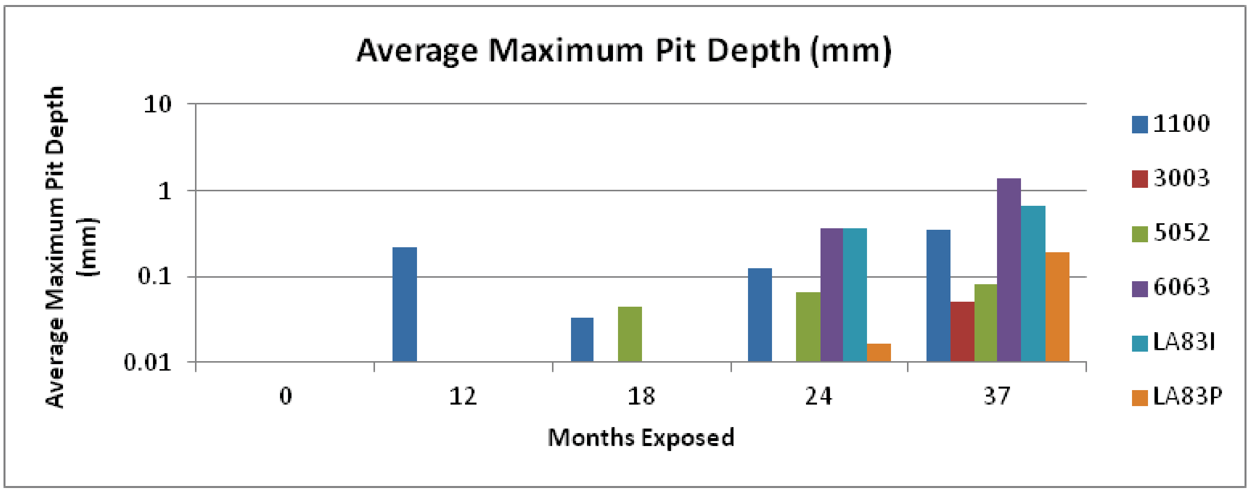


Figure 17: Average number of pits per square centimeter (Top) and average maximum pit depth (Bottom) on coupons exposed to 915 meter deep seawater for 12, 18, 24 and 37 months.

674 meter deep seawater – pretreated with surface seawater for 40 days

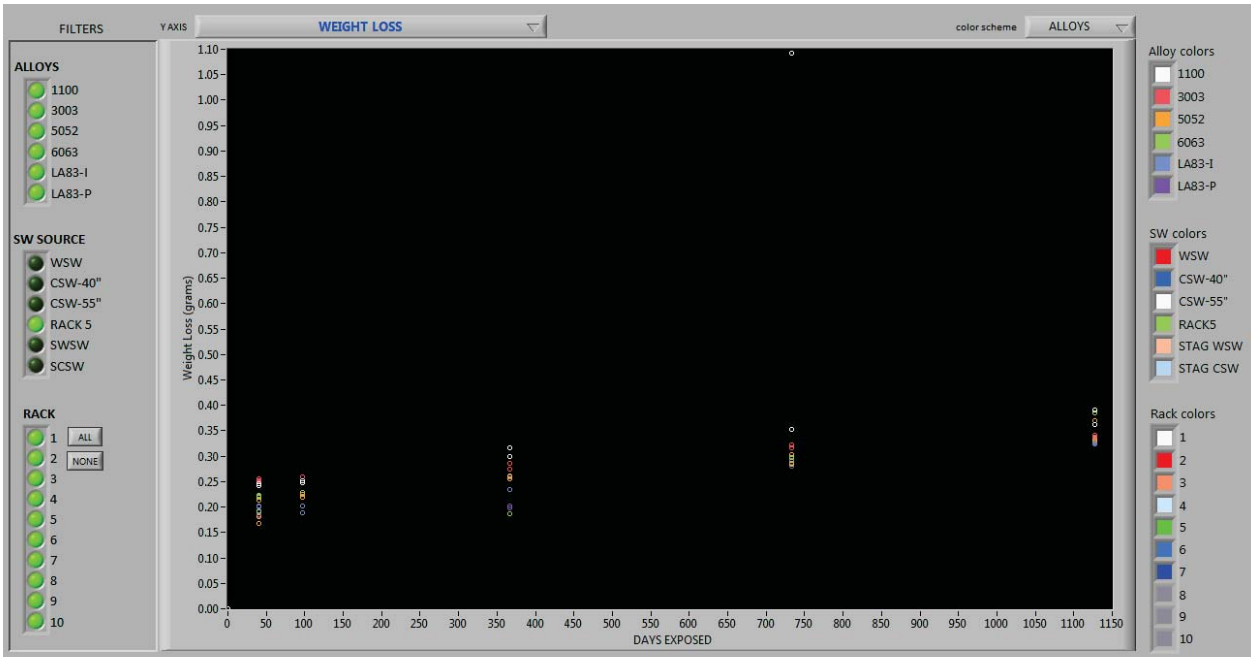
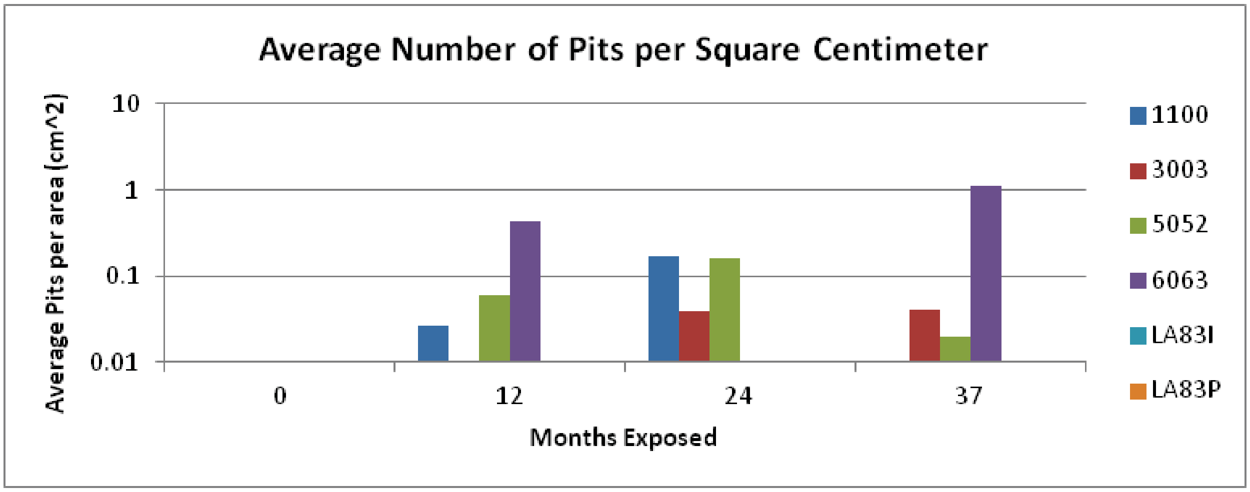


Figure 18: Weight loss results for box coupons exposed to 674m deep seawater after being treated with surface seawater for 40 days.

Data point colors correspond to the "Alloy color" legend in the upper right portion of the image.

Figure 19: Representative images of the 674m deep seawater samples pretreated with surface seawater exposed for 3 years.



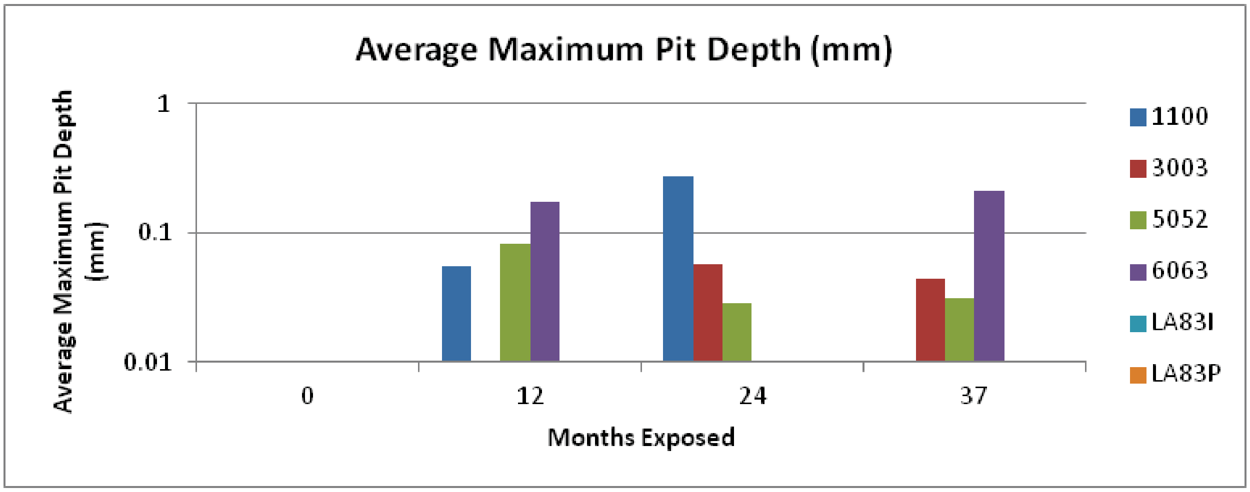


Figure 20: Average number of pits per square centimeter (Top) and average maximum pit depth (Bottom) on coupons pretreated with surface seawater for 40 days than exposed to 674m deep seawater for 12, 18, 24 and 37 months.

Flat Coupons

One flat rack which was testing samples in 674 meter deep seawater was decommissioned on 1/9/2013 due to heavy corrosion causing samples to break free from their support structure. It has been concluded that the large gasket-area to sample-area ratio of these samples, as well as the flow regime of these racks, skewed results. Thus no conclusions relative to pitting performance will be drawn from coupons taken from the flat racks.

The flat racks are being decommissioned as needed with the results being viewed as suggestive rather than definitive. This is due to test induced biases that were found to have a heavy influence on pitting characteristics of the aluminum.

Tubular Friction Stir Weld Coupons

A series of 2-tube tubular friction stir welded (TFSW) coupons were placed in the 674m deep seawater on 8/2/11. These coupons began to pit in the roller expanded portion of the tube in approximately 3 months. After pitting was found, Lockheed informed Makai that the coupons were welded tube rather than seamless which is the tube type that will be used in a shell-tube style heat exchanger. Thus, they are more interested in the friction stir welded portion of the coupon. Makai performed an initial test of nitric acid on these samples, but was unable to mitigate pitting for a significant amount of time.

Eight coupons are still being tested in series; however there isn't a detailed removal or analysis plan. Pits are well established and continuing to grow in the expanded portion of the tube. Refer to Figure 21 and Figure 22 for images related to tubular friction stir welded testing.

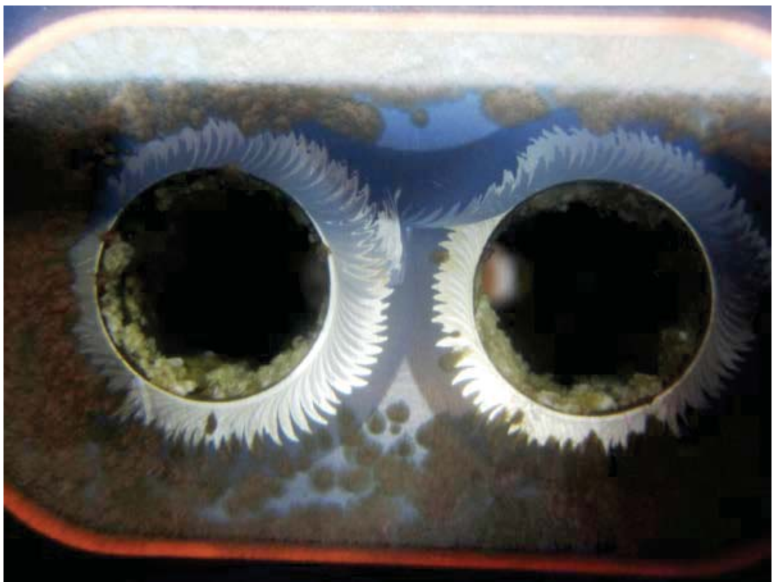


Figure 21: TFSW coupon exposed to 674m deep seawater for 1.5 years.

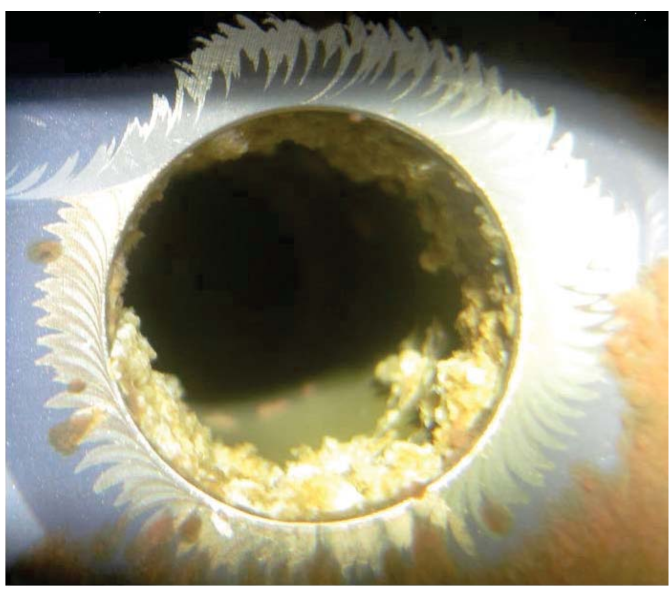


Figure 22: Close up of a single tube of a TFSW coupon exposed to 674m deep seawater for 1.5 years.

Pit Mitigation Testing

Nitric Acid

Nitric Acid flushing was investigated as a pitting mitigation technique. It was theorized that removing the corrosion product from the surface of the sample would allow the local environment which develops inside pits to mix with the macro environment allowing the pit to repassivate. However, no improvements were noticed in 674 meter test when compared to a baseline samples that were untreated. The coupon that was treated in the warm water actually showed increased pitting over the baseline sample, so this treatment has been deemed ineffective and no more testing is planned with Nitric Acid. It is believed that the nitric acid is overly corrosive to the inter-metallic particles in aluminum which causes holes to be left in the surface of the sample. These features then become future pit initiation sites.

The baseline samples for the nitric acid tests were extruded 3003 bars that were put through a heat cycle by Chart Industries to match the process they use to braze their heat exchangers. The sample began pitted in ~3 weeks in the 674 meter cold seawater and the pits have continued to grow in size and number. This is very different than the box beam coupon results. The heat cycle and the geometry difference (extruded bar rather than port-hole extrusion) are the only known difference between the samples. The warm seawater sample doesn't have any noticeable pits. Sample exposure times range from 8 to 11 months. The baseline samples are continuing to be tested in the 674m deep and surface seawater. Refer to Figure 24 through Figure 26 for images related to nitric acid testing.

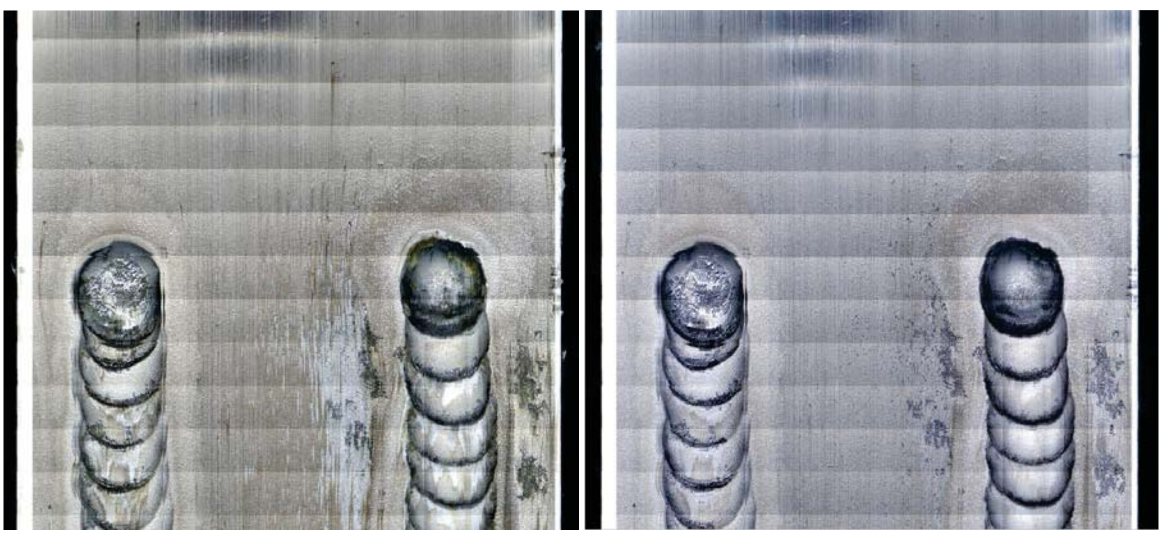


Figure 23: 674m deep seawater nitric acid treated sample after 19 days of exposure, before treatment (left) and after treatment (right).

Figure 24: Nitric acid flushed coupon (left) compared to baseline coupon (right) in 674m deep seawater after 8 months exposure.

Figure 25: Pitting on the nitric acid flushed coupon in surface seawater after 11 months exposure.

Figure 26: Images of the nitric acid baseline coupon exposed 8 months. This coupon was 3003 alloy that had undergone Chart Industries braze heating cycle.

Futures Pit Mitigation testing

In learning that nitric acid is overly corrosive to the alloying elements 2 mild acid cleaners were chosen for future testing.

Sulfamic acid cleaners are commonly used to descaler aluminum in industry and are readily available. Its attack on the alloying element composing aluminum is more uniform than other acids. Scale remover 3100 from DB water technologies was selected as the sulfamic acid based cleaner.

Citric acid descalers are another commonly used descaler product. The main disadvantages of this cleaner over the sulfamic acid is price however citric acid based cleaners have a reputation of being environmentally friendly and effective. Hubbard-Hall's Emerald acid clean LF was selected as the citric acid based cleaner. This product is an inhibited version that will decrease the level of attack on alloying elements and the base metal after the corrosion product is removed.

Siloxel Coating

The Siloxel coated coupons were removed from both warm and cold seawater sources. It appears that the coating supplied some protection early in the testing, but after one year, showed little to no protection to the coupons. These coatings were tested on 2024 aluminum as this alloy is very susceptible to pitting allowing the coating to be evaluated quickly. Both the coated and baseline samples were heavily pitted in CSW. The coated warm seawater sample had a few large pits, suggesting that the coating cannot fully protect the sample. Testing of Siloxel coating has been stopped. Refer to Figure 27 and Figure 28 for images related to Siloxel testing.

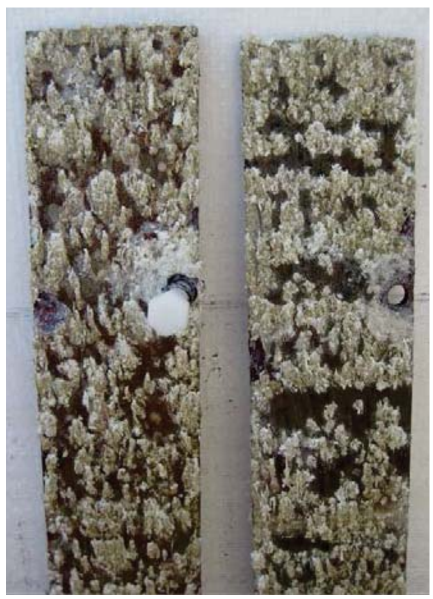


Figure 27: Comparison between the Siloxel coated sample (left) and the baseline (right) after 1 year of exposure in 674m deep seawater.

Figure 28: Siloxel coated sample after 1 year exposure in surface seawater.

Representative Heat Exchanger Coupons

Representative heat exchanger coupons are currently being installed in the new rooms that were added during the recent lab expansion. These coupons consist of a set of tubes approximately 12" long with a tubesheet on both ends. The tubesheet on each end allows the samples to be mounted with standard flanges. These coupons were fabricated such that the tube/tubesheet joint mimics that of the full scale OTEC style heat exchanger. The following coupons have been installed:

Surface seawater:

- Expanded 7-tube- flow started on 8/1/12 – no noticeable pitting to date
- Multi-hollow extrusion- flow started on 8/1/12 – no noticeable pitting to date

674m deep seawater:

- Expanded 7-tube- flow started on 8/1/12
  - Pitting started on the water exit tube sheet and inside the expanded portion of the tubes in October, shown in Figure 30.
- Multi-hollow extrusion- flow started on 8/1/12
  - -Pitting started on the water exit tube sheet and on the end of the multi-hollow extrusions in the un-stirred portions in October, shown in Figure 31
- 3 tube knurled – flow started on 12/9/12 – no noticeable pitting to date
- 3 tube baseline - flow started on 12/9/12 – no noticeable pitting to date

Figure 29: Multi-hollow extrusion and 3 tube coupons installed in the 674 meter deep cold seawater room.

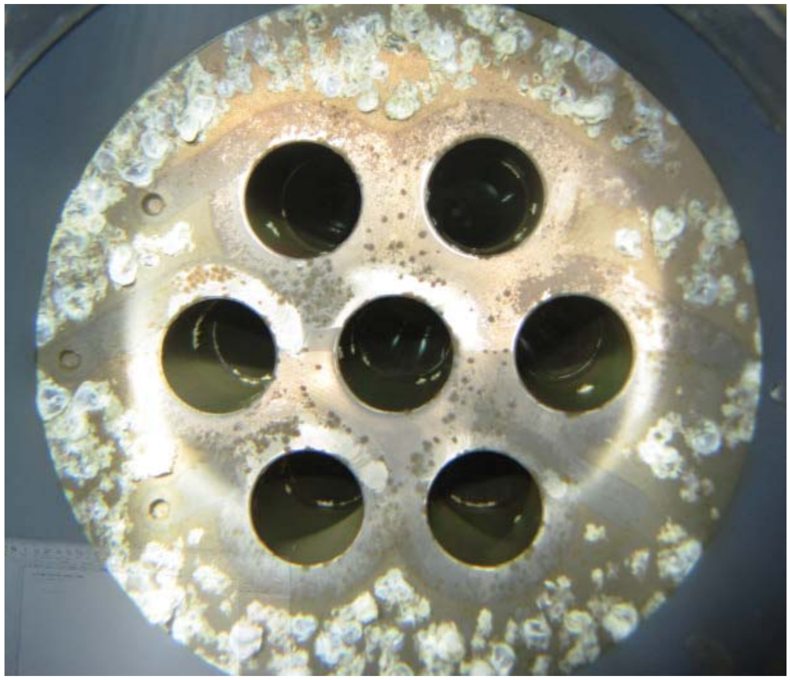


Figure 30: Expanded 7 tube water exit tube sheet after 5 months of exposure to 674m deep seawater.

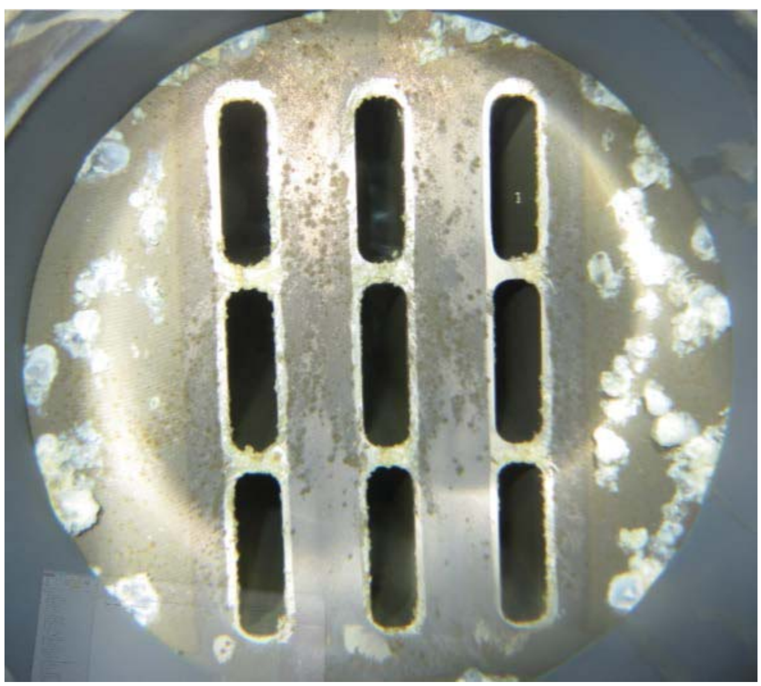


Figure 31: MHE coupon water exit tube sheet after 5 months of exposure to 674m deep seawater.

Gasket Interface Testing

The gasket interface coatings test will rate the relative corrosion performance of both 6061 and 3003 coated with Siloxel, Alodine 1201, 3M 5200 polyurethane sealant, Siloxel with an over coating of 3M 5200, and Alodine with an over coating of 3M 5200 at a gasket interface. Baseline samples of 6061 and 3003 are also included in this test. These various combinations will be tested in both cross and in-line flow. Duplicate tests were started in both surface seawater on 1/17/13 and 674 meter deep seawater on 1/29/13.

Steel Samples

Galvanized steel samples were initially placed in 674 meter deep flowing seawater on 4/6/2011. The galvanizing on these samples was quickly consumed within the first 9 months of exposure. After the galvanizing was gone it was observed that the underlying steel didn't corrode very quickly. So, two samples were removed and weighed to estimate the corrosion rate. To approximate the corrosion rate it was assumed that; the weight loss which occurred from 9 to 14 months was only steel (no galvanizing) and all samples had approximately the same weight of galvanizing prior to being tested. This analysis predicted a corrosion rate of approximately 0.3 mils/year. Another data point was collected at 21 months which confirmed the slow corrosion rate. After these preliminary findings, additional steel coupons were added to the corrosion test. These coupons were tubular and not initially galvanized making them more representative of a steel shell and tube heat exchanger. These samples were placed in 674 meter deep flowing seawater on 12/14/2012. Linear polarization resistance measurements were taken on these samples after 35 days of exposure. Assuming both beta constants to be 0.1 V/decade the average corrosion rate was calculated to be ~0.2 mils/year. This low corrosion rate makes steel a viable candidate for an OTEC condenser. To help support these findings additional corrosion samples will be place in 915 meter deep flowing seawater. Linear polarization resistance data will be periodically collected to help monitor the corrosion rate as a function of exposure time.

VII. Conclusion and Outlook

The second round of heat exchanger testing has been completed. This past year's effort was focused on the condenser, since it poses the largest risk in the development of an OTEC power plant. Results from the Lockheed Graphite Foam Heat Exchanger (GFHX) development showed that it is a high cost, poor performance heat exchanger. The Lockheed Enhanced Tube Shell & Tube Condenser is a moderate cost, medium performance heat exchanger. The graphite foam condenser performed much worse than expected, while the ETHX performed slightly better than predicted. This increase in performance may be attributed to the lack of oxide layer or biofouling buildup that is expected after a period of exposure to seawater. The ETHX will be tested periodically to determine the effects of oxide layer or biofoulant buildup on performance.

At the time of writing, the economics problem of OTEC heat exchangers still exists. The costs for a commercial-scale OTEC heat exchanger are still very high, regardless of the style of construction, considering the physical size that is required in a power plant. An aluminum shell & tube heat exchanger with external enhancements brings considerable capital cost savings compared with a conventional titanium heat exchanger, but the question of durability still exists. As a result, it cannot be known if an aluminum heat exchanger is more economical than one constructed from titanium, primarily because it is still unknown whether or not an aluminum heat exchanger can withstand the 20- to 30-year exposure in seawater without failing due to pitting corrosion effects.

Further corrosion testing will be required to determine the expected life of an aluminum heat exchanger at sea.

This year we were able to find a suitable cost effective enhancement which essentially decreases the total size of the heat exchanger. Although the enhancement comes with an added cost to the tubes, the cost savings from reducing the size is much more dramatic. A reduction in size translates to an equivalent proportional reduction in labor, shell material and fabrication costs, tube material and installation costs, as well as overhead and profit – all cost items which contribute heavily in the total cost of the heat exchanger.

While an incremental improvement has been made toward the OTEC heat exchanger cost problem, much more progress can be made. Makai has plans next year for testing an OTEC-optimized titanium plate frame condenser. This development will serve two main purposes: 1) it will provide a low-risk option for an OTEC condenser in case funding for a power plant becomes available, and 2) it will allow us to obtain real-world performance, rather than theoretical predictions, in order to determine the optimized size (and therefore cost), and help us determine how a titanium heat exchanger compares economically with our previous aluminum versions.

After three years of focusing on aluminum and comparing it with titanium, we have also 'stumbled upon' the idea of building a plain-steel condenser. Most corrosion studies on steel show that a minimum of 2-3mm of corrosion allowance will be required, but none of this data was for deep water. The low oxygen environment changes the corrosion rate, and we discovered this in our galvanized steel corrosion test. Once the galvanizing wore off (rather quickly), it yielded a steel surface which corroded very slowly in the deep seawater loop. We plan to continue our corrosion tests on steel samples in a more controlled manner to determine if steel is a suitable material in an OTEC condenser.

In addition to testing the titanium plate frame condenser and looking further into a steel condenser, Makai may be working on the development of our newest heat exchanger design. We have submitted a provisional patent in hopes that, after carrying out some initial investigations, it will prove to be a very economical design and will justify further development and completing the patent process.