



MAKAI OCEAN ENGINEERING

**Ultra-Compact Heat Exchangers
for Northrop Grumman**

17 December 2018

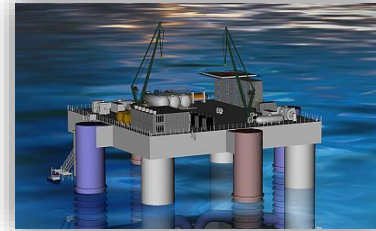
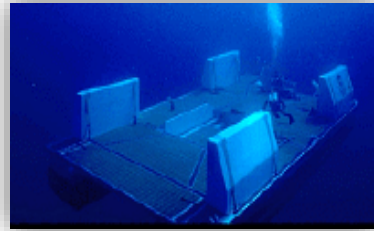
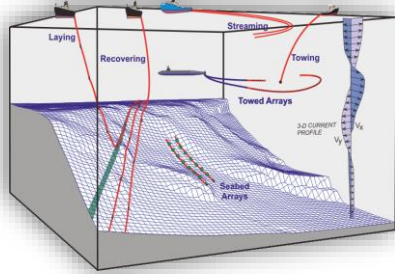
PROPRIETARY

Who is Makai?



Innovative Ocean Technology Company • Founded 1973 • 34 employees (and growing!)

Turning Concepts into Capability for 45 years



**Subsea
Cable Software**

**DoD S&T,
Ocean Engineering**

**Ocean
Energy**

**Oceans Multiple
Award Contract
(OMAC)**

- World's #1 cable software
- Navy underwater vehicles
- Pioneers of SWAC/OTEC
- Broad Ocean Engineering
- Installed +600,000 km
- Subsea sensor networks
- World's largest OTEC plant
- Competitive IDIQ

Heat Exchanger Technologies

Marine Heat Exchanger Testing



- Testing at OTEC facility in Kona
 - ~12,000 gal/min seawater
 - High accuracy instrumentation
 - Fully automatic controls
- HX Performance
 - Heat transfer coefficients
 - Pressure drop
 - Design optimization



Makai Proprietary Information – DISTRIBUTION STATEMENT D

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Marine Heat Exchanger Development



- Manufacturing Laboratory at OTEC facility in Kona
- 100kW Test Station
 - Rapid prototyping
 - Air/liquid/refrigerant
- Performance predictions and data based models

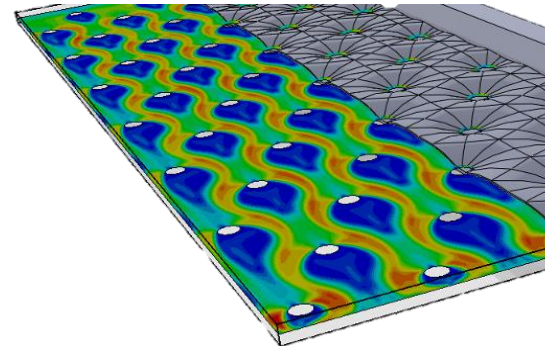


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- Ultra-compact Heat Exchangers
 - Applications include
 - Airborne
 - Subsea
 - Industry
 - Ongoing ONR funding
 - ONR funded since 2009
 - Advanced Manufacturing Lab
 - 100kW test facility
 - USAF Phase I SBIR
 - Phase II anticipated in 2019-2021

OPPORTUNITY: Traditional Plate Frame HXs are $100 \text{ m}^2/\text{m}^3$. Radiators generally limited to approximately $6,000 \text{ m}^2/\text{m}^3$ heat transfer area, utilizing large fin effectiveness to compensate for low air-side convection. These designs do not allow for step-change improvements in compactness.

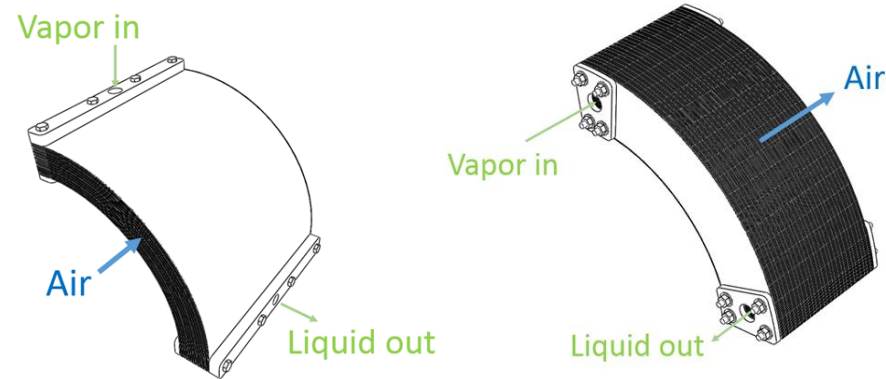
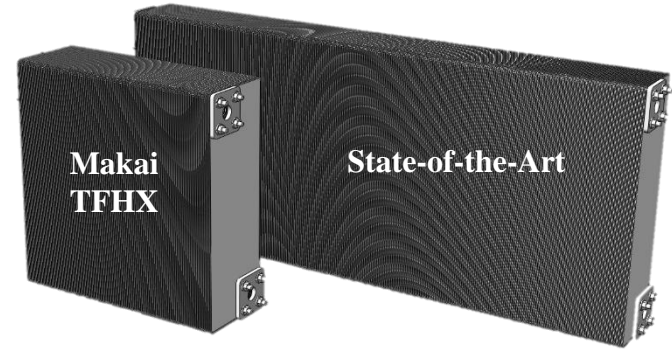


Makai's Thin Foil Heat Exchanger (TFHX)



U.S. Air Force SBIR

- Titanium foil construction
 - Lightweight
 - Corrosion Resistant
- Rapid, advanced manufacturing
- ***Form fitting***
- Custom, Optimized flow & convection
- Holds internal pressure
 - Tested to >500 psi



Up to 3x more compact than leading state-of-the-art COTS for air-cooled condenser applications.

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Makai's TFHX – Air-Cooled Performance Metrics



Air Heat-Transfer Coefficient	250 – 500 W//m² K*
Refrigerant Condensation Heat-Transfer Coefficient	1500 - 2000 (W/m ² K)**
Internal Pressure Expected	> 500 psi
Heat Transfer Area Density	2000 to 4000 m²/m³
Flow Channels	0.1 – 2.0 mm
Plate Dimensions	1cm to 1m scale
Flow Channel Roughness	< 4 μm
Material Consumption	80% less

*Operating with 20-60 m/s air speed **Representative of R-245 refrigerant / similar

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Makai's Thin Foil Heat Exchanger (TFHX)

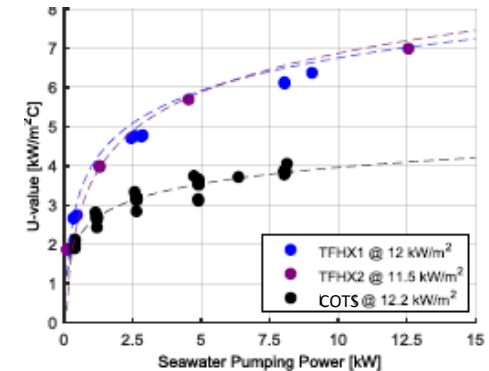
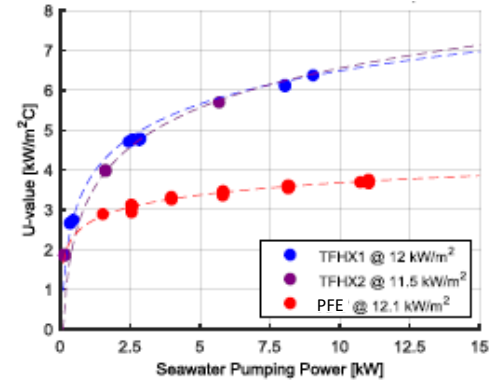


Liquid Cooled Applications

- Titanium foil construction
 - Lightweight, Corrosion Resistant
- Holds internal pressure
 - Tested to >500 psi
- >4x more compact than COTS plate-frame or brazed-fin HXers
- Optimized convection – 2x heat transfer performance



Up to 6-8x more compact than leading state-of-the-art COTS for liquid-cooled condenser applications.



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Makai's TFHX – Liquid-Cooled Performance Metrics



Water Heat-Transfer Coefficient	15 -60 kW/m ² K*
Refrigerant Condensation Heat-Transfer Coefficient	1500 - 2000 (W/m ² K)**
Internal Pressure Expected	> 500 psi
Heat Transfer Area Density	400 - 2000 m²/m³
Flow Channels (mm)	0.5 – 4.0 mm
Plate Dimensions	1cm to 1m scale
Flow Channel Roughness	< 4 μm
Material Consumption	80% less

*Operating with 20-60 m/s air speed **Representative of R-245 refrigerant / similar

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MAKAI OCEAN ENGINEERING

MAHALO!

*Manager Sales and Business Dev: Hermann.Kugeler@makai.com
Director of Marketing and Strategies: Ingrid.Hillhouse@makai.com
Director of Engineering: Greg.Rocheleau@makai.com*