OTEC Power System Developments

Presented by CB Panchal
Presentation Outline

- Overview of the OTEC Program at Argonne National Laboratory (ANL)
- Heat Exchanger Developments for Closed-Cycle OTEC
- Biofouling and Corrosion Program
- Design Studies of 10 MWe Land-Based OTEC Plants for the Island Market
  - Closed Cycle
  - Hybrid Cycle for co-production of power and desalinated water
- On-Going Project of OTEC Plantships
- Bottoming Cycle
- Energy-Water Nexus
Overview of OTEC Program at ANL

ANL the Lead Lab for Closed Cycle OTEC Power System

- Development of Closed and Hybrid Cycle OTEC Power Systems
  - Heat exchanger developments
  - Testing of prototype heat exchangers at ANL test facility
  - OTEC-1 heat exchanger testing
  - Interactions with industry for the power system developments
  - Hybrid cycle OTEC cycle for co-production of power and desalinated water

- ANL supported NREL and PICHTR for the Development of Open-Cycle OTEC Power System
  - Designed and installed open-cycle test facility at NELHA

- ANL was also Responsible for Environmental Assessments

- Biofouling and Corrosion R&D to Qualify Aluminum for OTEC Applications
  - Seawater tests at Puerto Rico, Writtesville Beach NC
  - Long-term tests at NTLHA, Hawaii
Heat Exchanger Developments

- Initial Focus on Large Scale Shell-and-Tube Heat Exchangers with Enhanced Tubes
  - Performance measurement of prototype heat exchangers
  - Heat transfer enhancements
  - Biofouling control of enhanced tubes

- Major Findings
  - Heat transfer performance can be enhanced by a factor of two
  - Biofouling can be controlled for enhanced tubes
  - Shell-and-tube heat exchangers for small to medium size (< 100 MWe) OTEC plants would be expensive and occupy significant space
Heat Exchanger Developments

• Further Developments Focused on Compact Heat Exchangers
  - Titanium or stainless steel plate heat exchangers
  - Aluminum brazed plate-fin heat exchangers

• Biofouling
  - Biofouling can be controlled with an acceptable level of chlorination (70 ppb to 100 ppb applied for one hour per day)

• Recommended Design
  - Aluminum plate-fin heat exchangers with modular design
  - Stainless steel plate heat exchangers with semi-welded plates (parallel flow in near term and cross-flow in long term)
Modular Aluminum Heat Exchangers Ideally Suited for OTEC Power Systems

Aluminum plate-fin heat exchanger with extruded water passages and bonded with navy epoxy as a surface condenser in the open-cycle test facility
Biofouling and Corrosion
Unique *Long-Term Experimental Program*

• 10+ Years of biofouling and corrosion tests in Hawaii, Puerto Rico, and N Carolina
• Prototype OTEC seawater: surface warm water and deep-ocean cold water
• Development of highly sensitive biofouling monitoring sensor for early detection of biofouling buildup and determination of effectiveness of low-level chlorination
• Material research for in-depth understanding of corrosion mechanisms to predict the service life of aluminum heat exchangers with high-level confidence
Biofouling and Corrosion

Biofouling Was a Major Technical Barrier

- No significant difference in biofouling behavior for aluminum alloys and titanium or Al-6X stainless steel
- Warm water biofouling is controlled by 70 ppb to 100 ppb applied for one hour per day
- Negligible biofouling is expected for deep-ocean cold water
- Biofouling of non-circular flow passages of plate-fin and plate heat exchangers can be controlled like circular tubes
- Considering variability of biological parameters of seawater, it is advisable to perform validation biofouling experiments (3 to 6 months) at the proposed site in Puerto Rico
Biofouling and Corrosion

Qualification of Aluminum Alloys

• 30 Year loss of metal is < 100 µm for warm water and < 200 µm for cold water, both of which are less than acceptable level of 380 µm for 15+ service life

• Pitting corrosion not a major problem with a good design practice

• Use of aluminum alloys with seamless water flow passages can be recommended for service life of 30 years with replacement/refurbishing of modules after 15 years
  ➢ *warm water has low risk*
  ➢ *cold water does entail some risk and will require proper design and good monitoring practice*

• Infrequent brush cleaning is recommended to avoid local biofouling buildup which may cause localized corrosion
Design Studies of OTEC Plants

- Design Studies of 10 MWe Land-Based OTEC Plants
- Hybrid OTEC System for co-production of power and water
  - Hybrid cycle with separate power and desalinations systems based on commercial multi-stage flashing technology
  - Integrated hybrid OTEC power system
- Review of 40 MWe Pilot OTEC Plants
  - Man-made island based OTEC plant by Ocean Thermal Corporation (OTC) and
  - Tower-mounted OTEC plant by GE
Small Land-Based OTEC Plants

- Technical and Economic Viabilities of Small (~ 10 MWe) OTEC Plants for the Small Island States
- Proven Technologies for Pipe Deployments
- Optimized Power System to Minimize Cold Water Flows
- Evaluation of Three Heat Exchanger Types:
  - Shell-and-tube
  - Aluminum plate-fin heat exchanger (new design concept)
  - Alfa-Laval plate heat exchangers
Hybrid Cycle for Co-Production of Electric Power and Fresh Water

- Design incorporates R&D results from the OTEC program
- Aluminum heat exchangers
- Biofouling totally eliminated
- Optimum production of power and fresh water
Ammonia as the hydrogen energy carrier

- Infrastructure for distributing, storing and delivering hydrogen is non-existent
- Existing infrastructure for transporting, storing, and distributing ammonia
- Ammonia has higher energy density (kWh/liter) than hydrogen
- Ammonia being evaluated for distributed power generation and in IC engines (particularly for farm equipment and irrigation pumps)

On-going DOE project at Argonne

- Phase I focuses on updating the Applied Physics Laboratory design of 40 MWe Pilot Plantship by incorporating plate-fin heat exchangers
- Phase II focuses on co-production of ammonia, as the hydrogen carrier, and desalinated water using hybrid cycle OTEC Plantship
**What is the Energy~Water Nexus?**

*Energy and Water are Fundamentally Linked*

Energy production and generation require water:

- Water pumping, treatment, and distribution require energy.

As water availability decreases, cost increases:
- As water cost increases, energy cost increases.
- As energy cost increases, water cost increases.
- And so on.....
Water Consumption by Energy Systems: OTEC co-produces power and fresh water

- Utility Plants
  - 20 gallons per kWh electricity produced
  - In some states, future plants and expansion of the capacity will require closed-loop (cooling tower or cooling ponds, which requires makeup waters) OR dry cooling

- Petroleum Refineries
  - 65 to 90 gallons per barrel (42 gallons) of crude oil processed

- Ethanol Production
  - 10 to 15 gallons per gallon of ethanol in processing plus irrigation water

- Hydrogen
  - 70 gallons per kg of hydrogen (equivalent of one gallon of gasoline)
Ammonia Bottoming Cycle:
*OTEC Technology to Enhance Power Plant Capacity*

**Advantages:**

- Optimum LP back pressure to maximize efficiency
- Steam condenser material can be carbon steel, ammonia condenser can be stainless steel plate or aluminum plate-fin heat exchangers
- Impact of biofouling significantly reduced
- By utilizing the colder deep ocean seawater, the overall capacity increases (higher kWh/fuel consumed)
- Deep ocean cold water can be from an intermediate depth ~ 300 m
- Pure ammonia or binary fluids (ammonia-water or hydrocarbon mixtures can be used as working fluids)
Ammonia Bottoming Cycle: OTEC Technology to Enhance Power Plant Capacity
Path Forward

- Established technology base of the OTEC Power System for the first generation of commercial OTEC plants with guaranteed power system performance
- Further improvements of the power system will improved performance and cost reduction
- Co-production of desalinated water will significantly improve the economics of OTEC plants for near-term commercialization
- In many respects year 2030 has been set for alternate energy supply; therefore, there is a window of opportunity to commercialize OTEC
Path Forward
Mini-OTEC to OTEC-1 to OTEC Plants