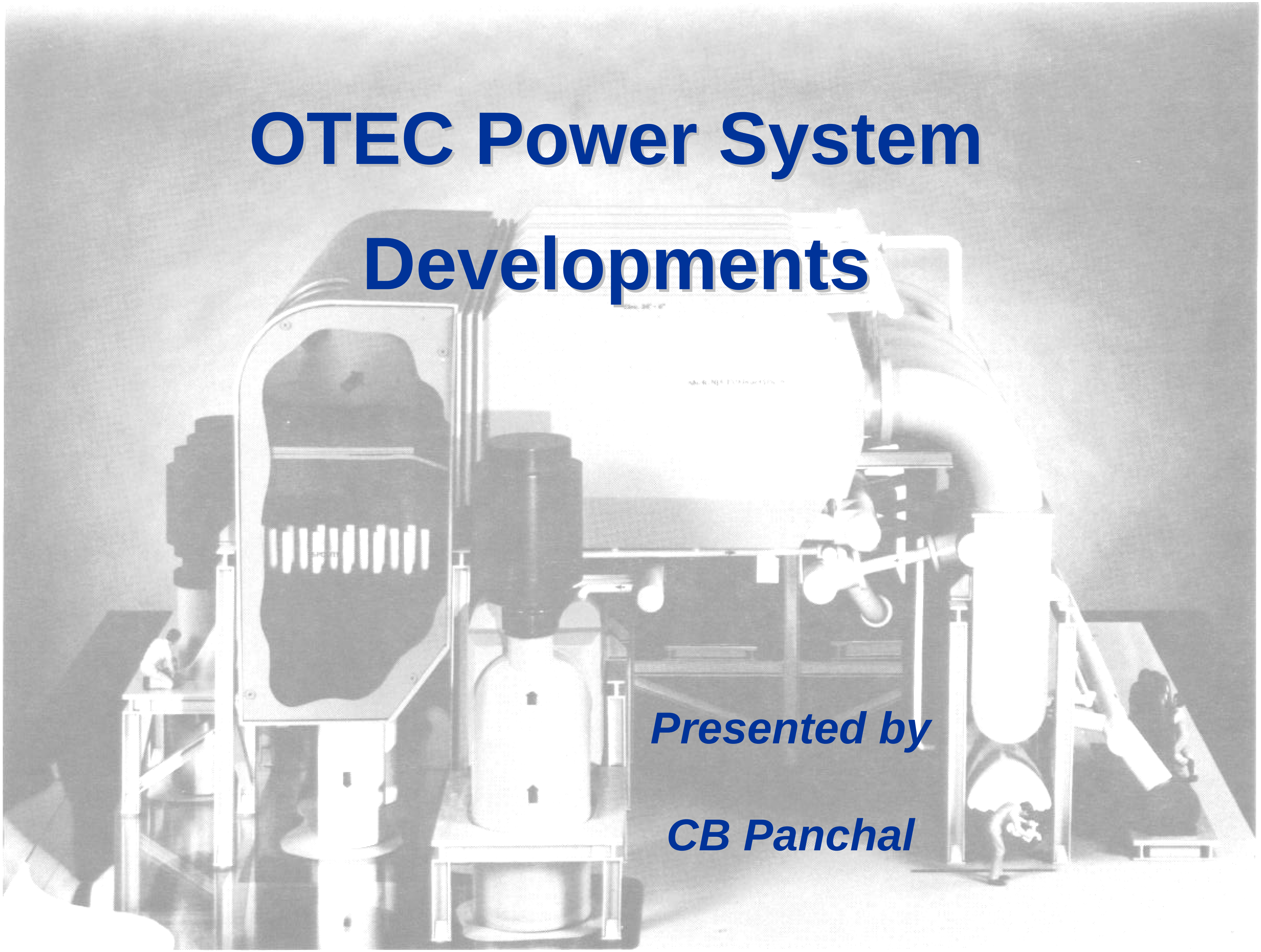
OTEC Power System Developments



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

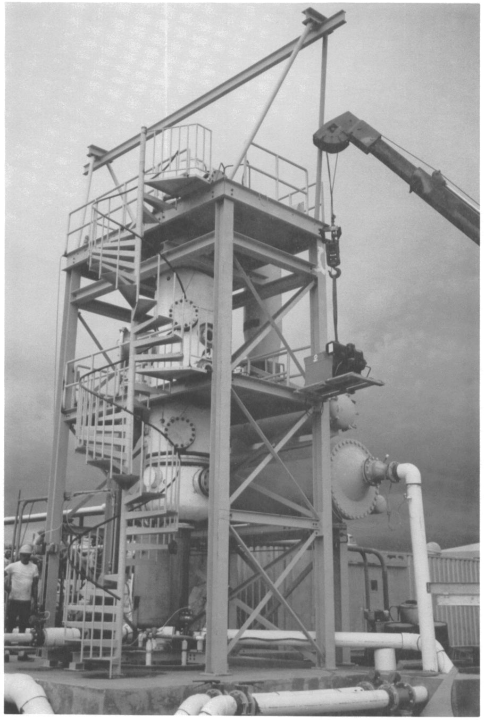
? **On-Going Project of OTEC Plantships**

? **Bottoming Cycle**

? **Energy-Water Nexus**

Overview of OTEC Program at ANL

ANL the Lead Lab for Closed Cycle OTEC Power System



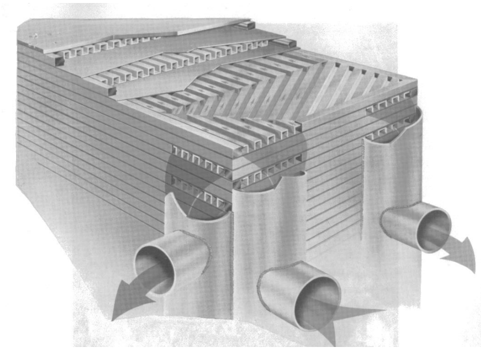
- **Development of Closed and Hybrid Cycle OTEC Power Systems**
  - **Heat exchanger developments**
  - **Testing of prototype heat exchangers at ANL test facility**
  - **OTEC-1 heat exchanger testing**
  - **Interactions with industry for the power system developments**
  - **Hybrid cycle OTEC cycle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

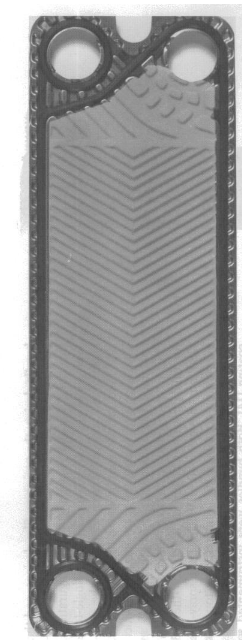


Figure 4 Typical plate enhanced with a porous surface for ammonia evaporator applications.

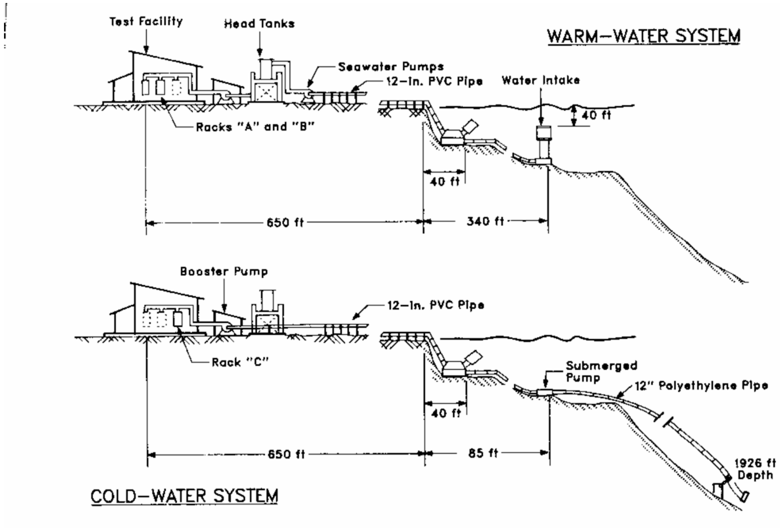
Modular Aluminum Heat Exchangers Ideally Suited for OTEC Power Systems

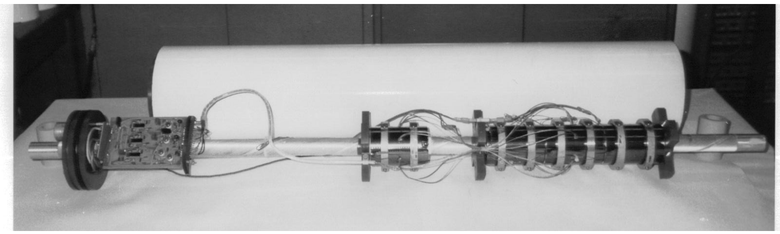
Aluminum plate-fin heat exchanger with extruded water passages and bonded with navy epoxy as a surface condenser in the open-cycle test facility

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

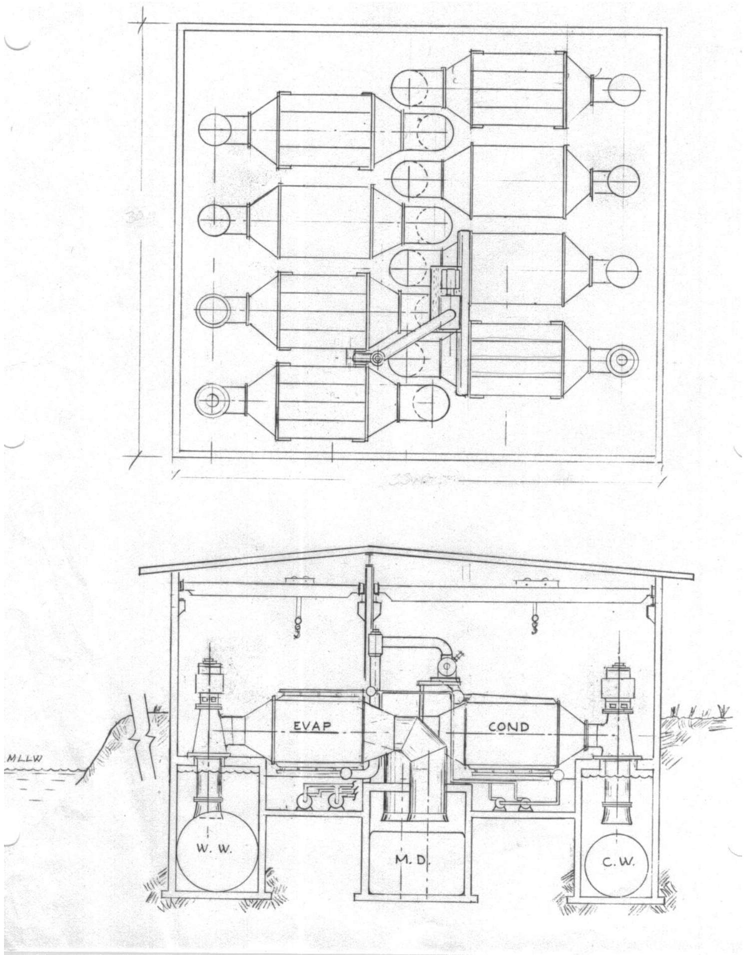
? Technical and Economic Viabilities of Small (~ 10 MWe) OTEC Plants for the Small Island States

? Proven Technologies for Pipe Deployments

? Optimized Power System to Minimize Cold Water Flows

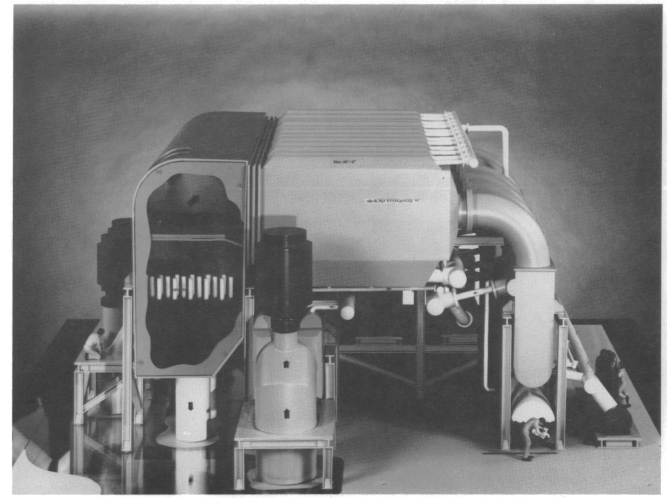
? Evaluation of Three Heat Exchanger Types:

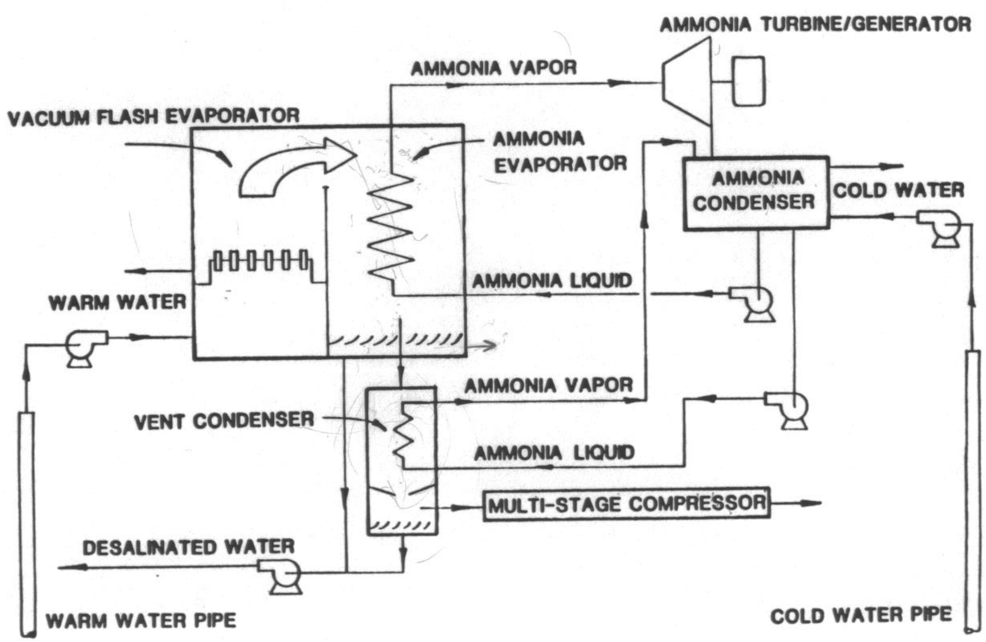
- Shell-and-tube
- Aluminum plate-fin heat exchanger (new design concept)
- Alfa-Laval plate heat exchangers

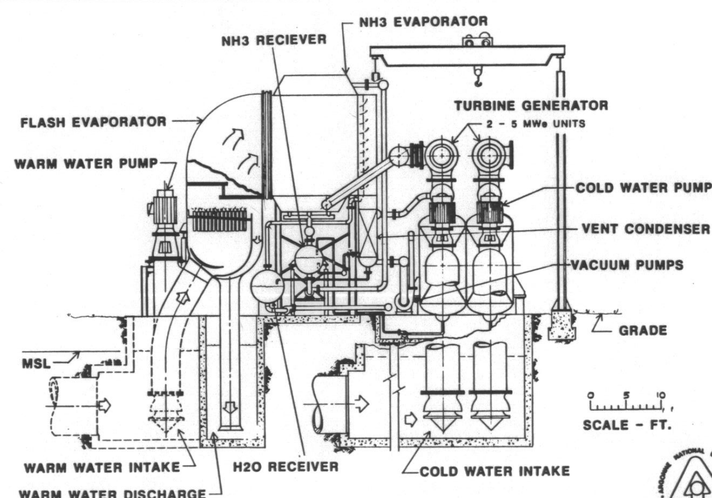


Hybrid Cycle for Co-Production of Electric Power and Fresh Water

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







OTEC Plantships for Co-Production of Ammonia and Desalinated 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

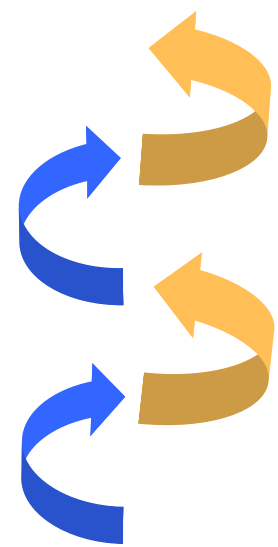
Water pumping, treatment, and distribution require energy

? **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 stetas, 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:

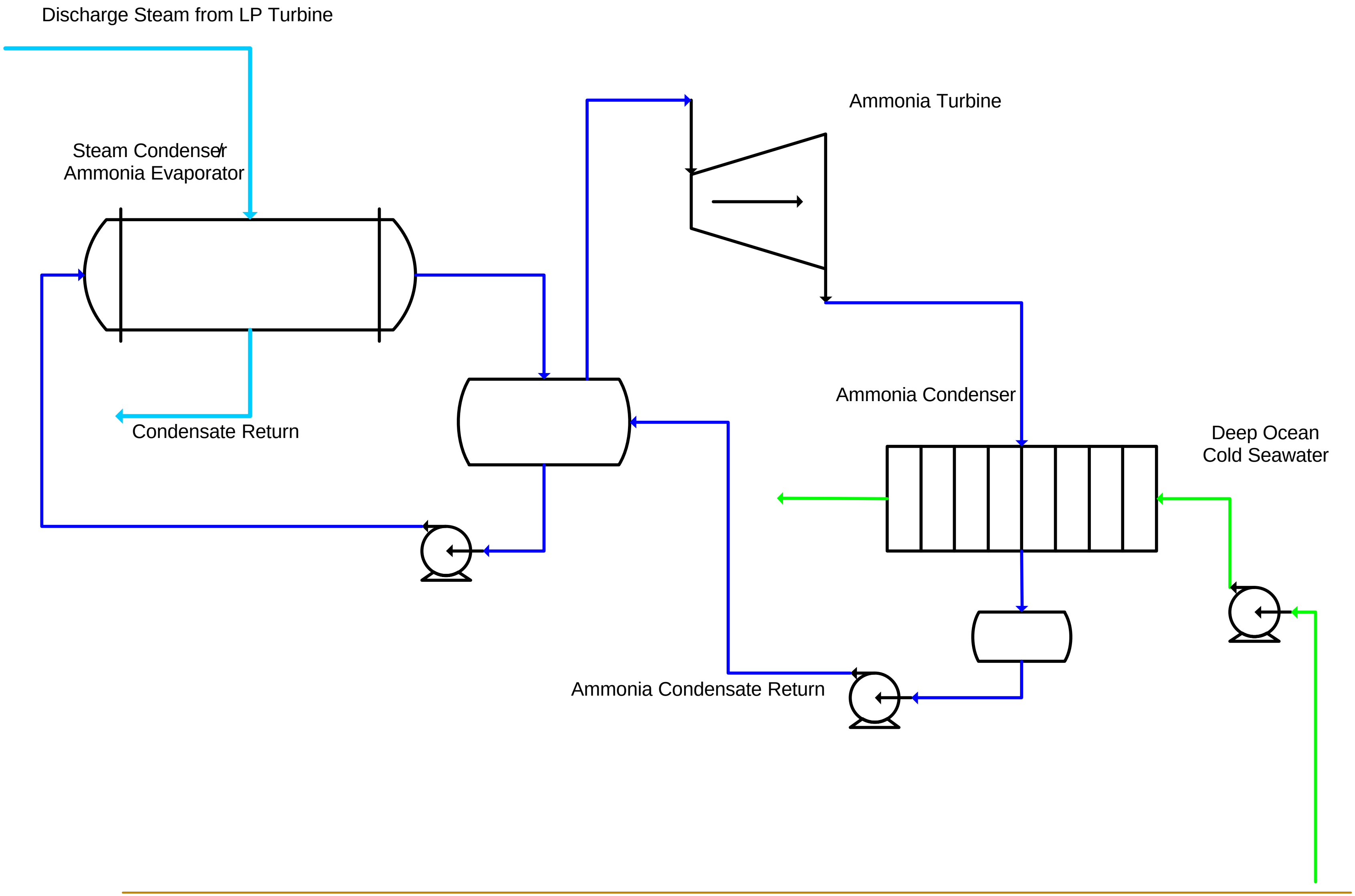
OTEC Technology to Enhance Power Plant Capacity

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 enenrgy supply; therefore, there is a *window of opportunity* to commercialize OTEC**

Path Forward

Mini-OTEC to OTEC-1 to OTEC Plants