

# Opportunities for Marine Sequestration of Carbon Dioxide

**Presented by Christopher D. Barry**  
**SNAME, Panel EC-15**

*The opinions expressed in this paper are those of the author and do not necessarily reflect the opinions or official policy of the United States Coast Guard or the Department of Homeland Security.*



# Overview

- Physical Options
- Biological Approaches
- The Opportunities
  - Lots of “Moving Parts”
  - Economics, Carbon Credits / Taxes
  - Major Marine Infrastructure Is Needed
  - Innovation
- Conclusion: *“It’s Up to You”*

“Who am I, why am I here?”

VADM James Stockdale, USN

# Coal

- Huge Amounts of Carbon Sequestered During Carboniferous Period (290 MYA – 354 MYA – 64 MY)
- Trees Evolved to Produce Lignin (A Biopolymer of Phenol, Not Sugar)
- Bacteria Couldn't Break Down Lignin
- Lignin Was Buried, Became Coal
- A Potential Lesson?
- World Consumption:
  - 5,537 Mtce ~  $5.54 \times 10^{12}$  kg ~ 5.5 km<sup>3</sup>



*Paul R. Tregurtha* downbound from Duluth/Superior seaport w/ 63,000 LT of coal, to be burned in an Indiana power plant in 48 hours at nameplate rating. Part of a five ship rotation.

## The “Hail Mary” Option

- Sequestration Isn't Necessarily The Best Option
- But
- Decarbonization Isn't Coming On Line In Time
- May Be More Economical Than Some Renewables
- Climate Change May Be Proceeding Too Fast
- Probably Will Be Part Of A Mix Of Solutions
- Some Renewables May Include Sequestration

Current Projections Require Negative Emissions To Meet  
Maximum 2°C Warming (Net Zero ~ 15 GTONNE)

- The Ocean Holds 50x More Carbon Than Total in The Atmosphere
- About 30% - 40% of Anthropogenic Carbon Taken Up By The Ocean

# Physical Options

- Deep Ocean Liquid or Clathrate / Hydrate Injection
- Oil Reservoir Injection (*Sleipner* Sequestered 1 Mtonne / yr)
- Basalt Injection
- 1<sup>st</sup> Problem Is Separating CO<sub>2</sub> From The Atmosphere (Ongoing Research)
- May Use Power Plant Emissions Directly
- May Need Pipelines, Requires Energy, Generally Expensive
- Powered By Ocean Renewable Energy?
- Making Fuel At Sea (“e-Fuels”) From Ocean Renewable Energy
- CO<sub>2</sub> is More Concentrated in Seawater
- Solves The Problem of Stranded Energy – Only Carbon Neutral – Feed Stocks?
- Ocean Energy + Mineral Take-up (“Ocean Liming – Plus”)

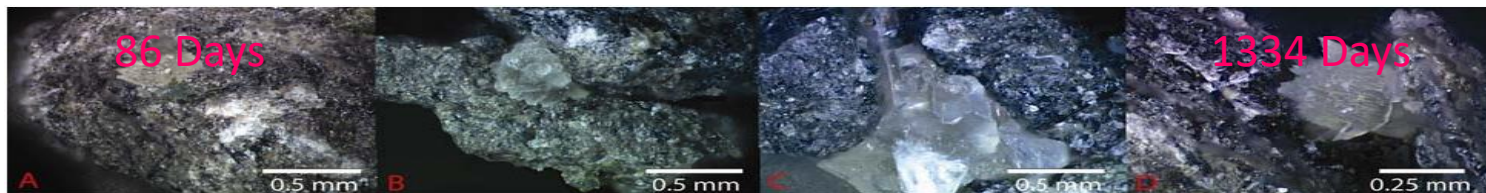


# Basalt Injection

- Basalt: Volcanic Ca, Na, K Silicates & Quartz
- Basalt + Seawater + CO<sub>2</sub> + Pressure = Carbonate Minerals: Calcite (CaCO<sub>3</sub>) + Heat
- Successful Test in Iceland: 250 tonnes CO<sub>2</sub>,
- 95% Became Calcite in 2 Years
- Deep Sea Basalt = Seawater & Pressure
- Much Less Depth, Much Less Energy Required
- Doesn't Leak: Locked In Mineral Form



Maybe We Can Just Bury It

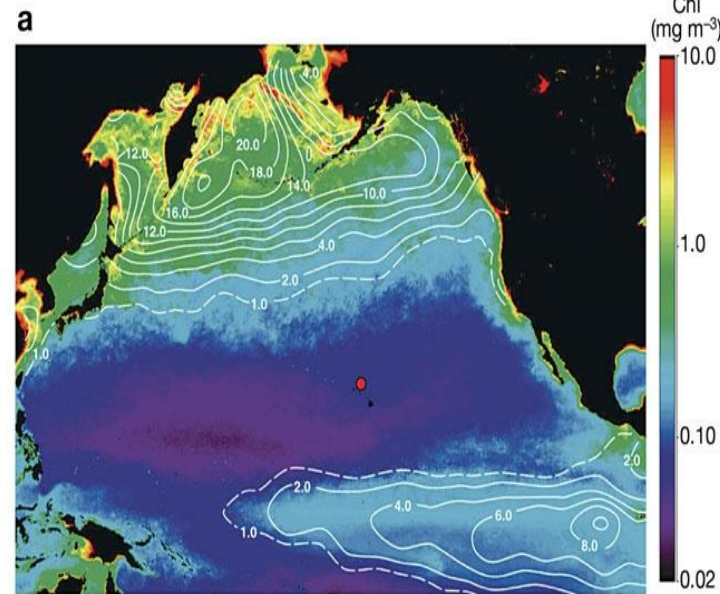


# Biological Sequestration

*...and the fishes of the sea shall declare unto you...*

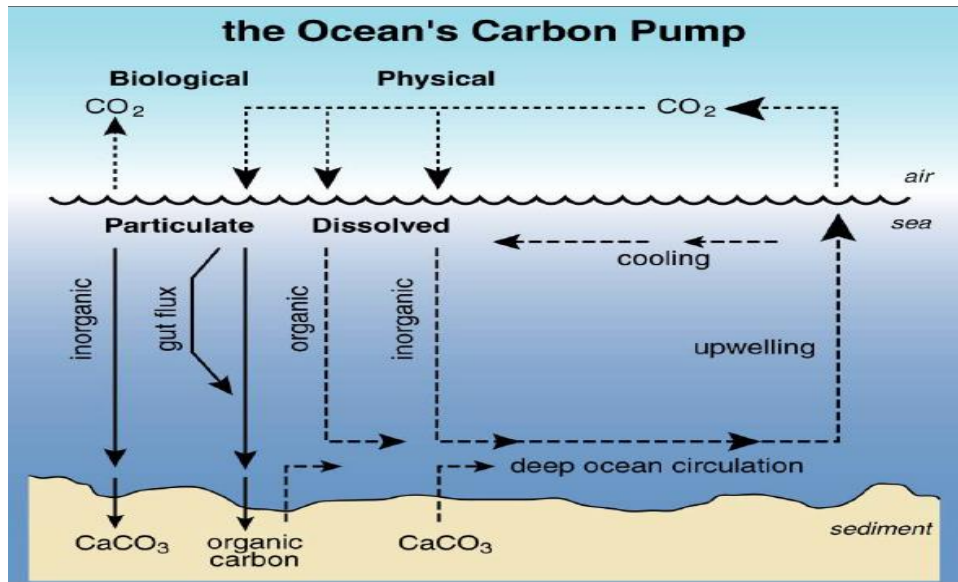
*Job 12:8*

- Ocean Is The Major Sink For CO<sub>2</sub>
- Biological Uptake Is The Conduit
  - Mainly Via Sedimentation Of Zooplankton, Etc.
  - The Redfield Ratio (N, P; May Limit Takeup)
- Tropical Ocean Fertility Very Small
  - 100 mg Carbon Takeup / m<sup>2</sup> / yr
  - Tropical Water Is Nutrient Poor: Deep Cold Water Traps Nutrients
  - Nitrates, P, Fe(?) Limited
- Approaches:
  - “Geritol Option” – Iron Fertilization
  - Upwelling: Lovelock & Rapley (*Nature*, 09/07)
  - “Blue Forests” / “Blue Carbon”
  - Kelp Farming / Kelp Forest Restoration
  - Littoral Aeration



Chlorophyll Levels In The Pacific

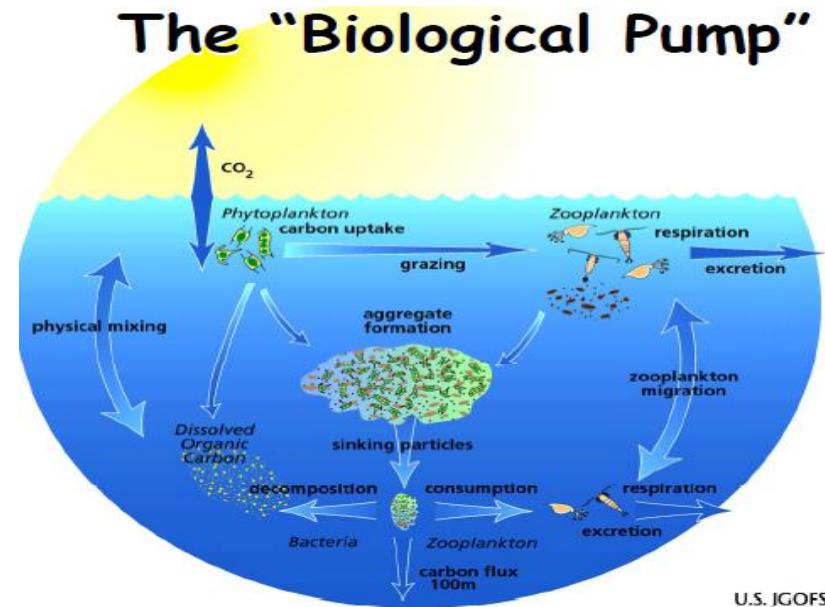
# Ocean Carbon Pump



“Improving the Efficiency of the Ocean’s Biological Carbon Pump” David M. Karl and friends

University of Hawaii

8



U.S. JGOFS

One common aggregating phytoplankton is *Botryococcus Brauni*, which may be the major contributor to fossil oil as well as a source for biofuels.



## “Geritol” Option

- Theory Is That Lack Of Trace Amounts of Iron Is The Problem
- Early Experiments In Iron Fertilization Not Clear Regarding Ultimate Sequestration (Sinking)
  - 50% or 5% Carbon Sequestered?
  - “Political Issues” From Early Efforts
  - “Large Scale” Experiments Banned

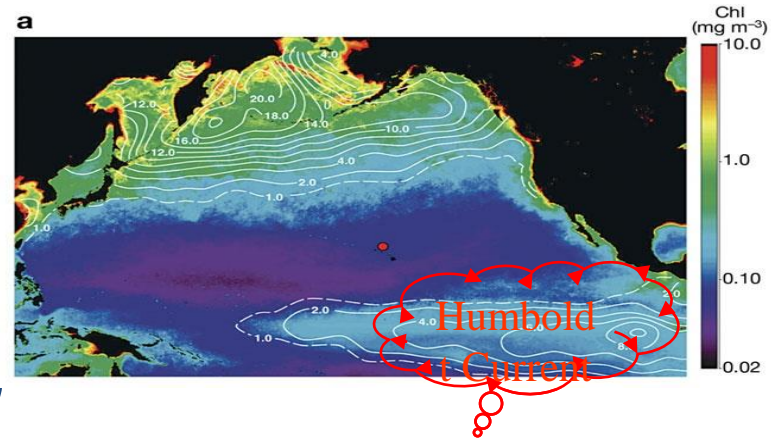


*“The Iron Hypothesis isn’t wrong, but it’s much more subtle than usually stated.*

*Achieving optimum carbon sedimentation from plankton growth may require the right “recipe” of iron and other trace nutrients to grow the right kind of phytoplankton, ... “You can grow a lot of Brussels sprouts, but kids won’t eat it. The same appears to be the case with diatom phytoplankton and zooplankton. It’s the zooplankton community that determines carbon sedimentation.”*

# Artificial Upwelling

- Tropical Upwelling  
(Humboldt / Peru Current)
  - 1.8 kg Carbon / m<sup>2</sup> / yr
  - 6.6 kg CO<sub>2</sub> / m<sup>2</sup> / yr
- Artificial Upwelling (**Lovelock & Rapley**)
- Wave Powered Pumps
- Deep Seawater Has Substantial CO<sub>2</sub> : Upwellings Can Be Sources
- Redfield Ratio: C May Just Cycle Up And Down – No Net Takeup
- Artificial Upwelling Is Also a Controversial Solution
  - One Study Suggests It Might Only Provide 1 GTONne
  - Also Location, Species, Chemistry Dependent

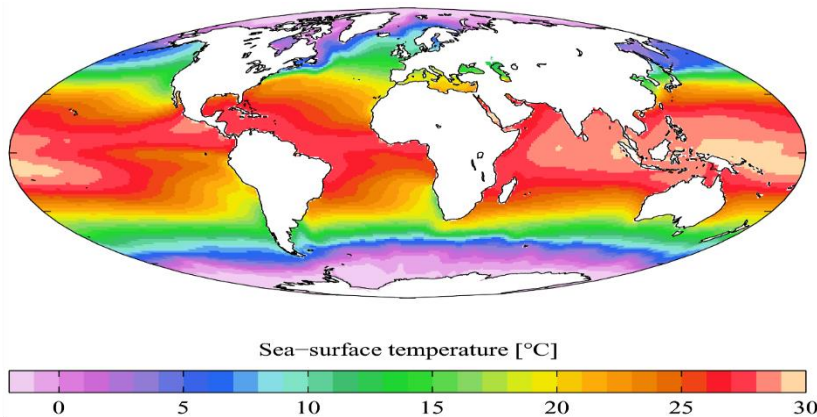


## The Questions

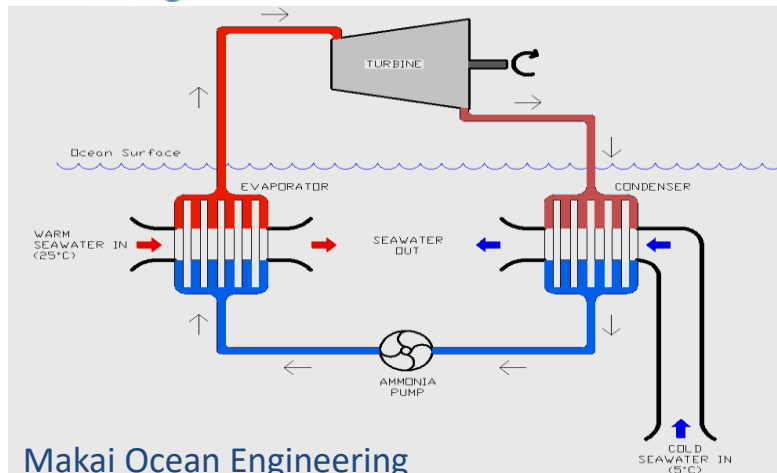
- What Is The Level Of Nutrients Vice CO<sub>2</sub> Release?
- Does This Vary With Depth, Location, Season, Species (Copepods, Diatoms)?
- How Do The Nutrients Mix?
- What Optimizes Biological Takeup?
  - How Much CaCO<sub>3</sub>, Chitin or Lipids, Then RDOM, POM, Accessible Carbon?
  - How Much N, P is Lost to the Depths, Limiting Further Growth?
  - Diatoms Also Need Silicon
- What Other Environmental Effects?
- How Do We Design & Build Equipment?
- How Much Does It Cost?

# Wave Powered Artificial Upwelling

- Most Artificial Upwelling Schemes Use Wave Power
  - Relatively Unsophisticated Devices Tested So Far - Haven't Survived
  - Limited Amounts of Water Pumped
  - A Specific Opportunity for Engineers
  - State of the Art Wave Energy Devices, State of the Art Pumps Upwelling Cold Water Pipe May Provide Reference For WEC
  - Solve The Problem of Exporting Stranded Energy?
  - May Be Combined With Other Energy / Cold Water Uses
  - BitCoin Mining / Server Farms at Sea + *Carbon Credits*
- Can Google, Microsoft and Amazon Save The Earth?*



## OTEC



- Ocean Thermal Energy
- Heat Engine Running Between Surface Water (30° +C) and Deep Cold Water (2° +C)
  - Poor Thermal Efficiency  $\eta_{\text{Carnot}} = (T_{\text{hot}} - T_{\text{cold}}) / T_{\text{hot}}$  (In Kelvin)  
( 303° K – 275 ° K ) / 303° K = 9% (At Best); Everything Has To Be Near Perfect
  - Engineering Issues: Cold Water Pipe, Biofouling, Pumps, Turbines, Heat Exchangers ...
  - Ongoing Research and Trials



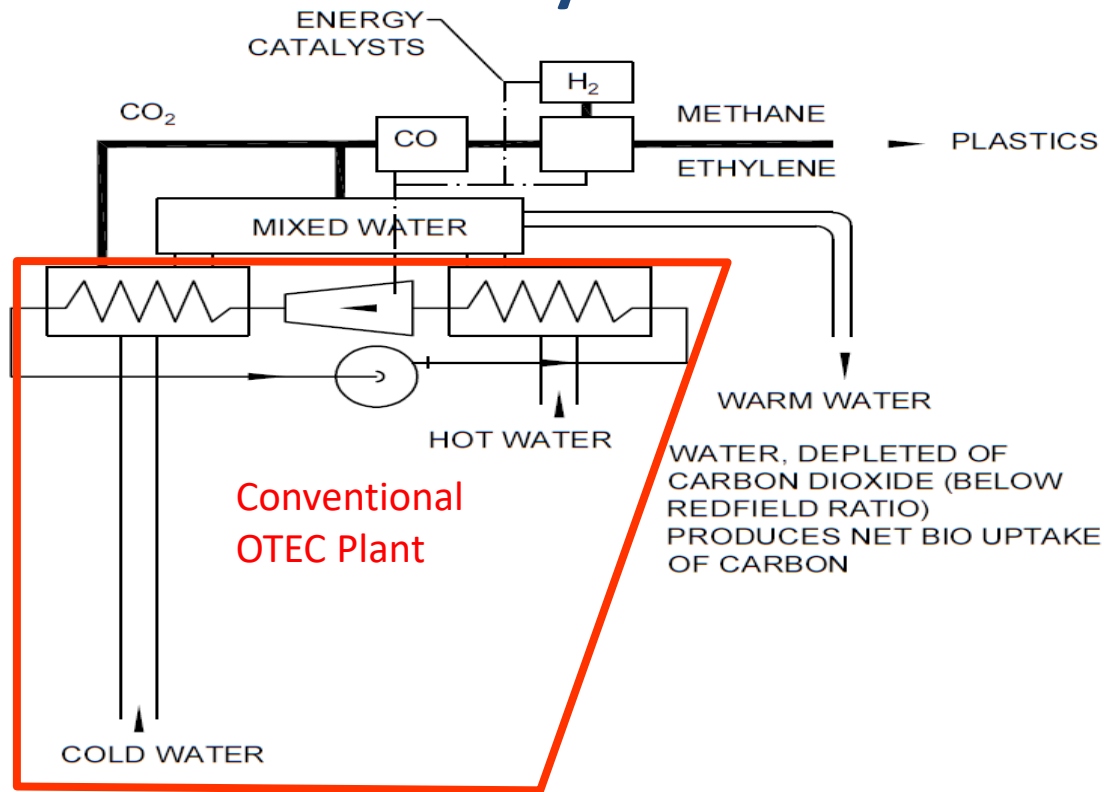
## OTEC Upwelling - If Upwelling Alone Works

- Prodigious Amounts Of Cold Water:  $15 \text{ m}^3 / \text{s} / \text{MW}$
- Depending On Dilution Scenarios, Etc. (Best Case)  
Sequesters  $10,000 \text{ Tonnes } (1 \times 10^7 \text{ kg}) \text{ CO}_2 / \text{MW} / \text{yr}$
- $1 \text{ Gtonne } C_e = 3.6 \text{ Billion Tonnes CO}_2 / \text{yr For } 360,000 \text{ MW}$
- OTEC Plant  $\sim \$5,000,000 / \text{MW}$  (Very Best case)
- Alternate Uses For Stranded Energy: BitCoin Mining, Server Farms

*If Upwelling Effect Is Sufficient*

- $\text{NH}_3$  Fertilizer, and Fish – “Solve World Hunger”
- Does Upwelling Work In Tropic Waters?
- Trade Offs Between Sequestration and Economics?

# Hybrid OTEC

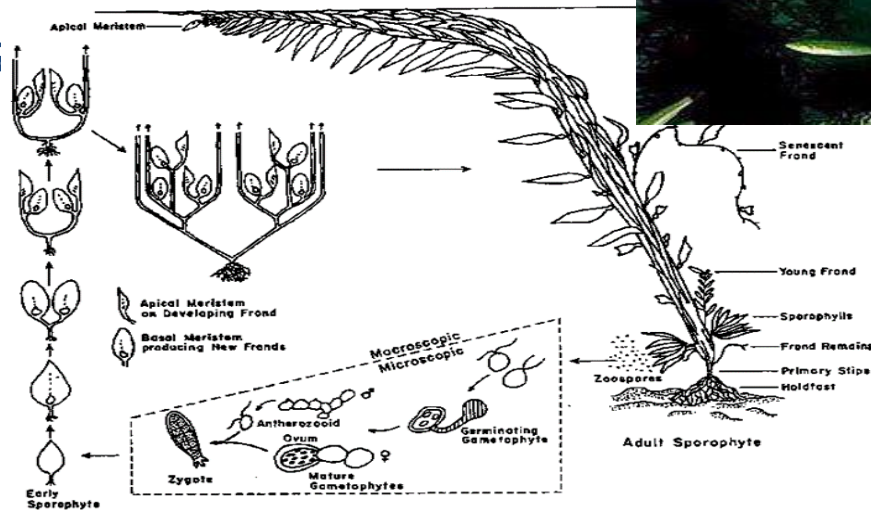


*Plastics; Like coal, inert in the environment for centuries.*

*Hopefully disposed of sustainably.*

# Kelp (Macroalgae)

- “Blue Forests”, “Blue Carbon”
- *Macrocystis spp.*
- Cooler Temperate or Arctic Waters, High Nutrients, (From Upwelling?)
- Need Substrate
- Annual and Perennial Species
- Perennials: Fronds Grow From The Holdfast
- Fronds Grow 1’ 2’ Ft / Day



## Kelp Farming

- Kelp Is a Substantial Carbon Sink
- Farming: Theoretically: 15 G/Tonne
- Artificial Kelp Farming Proven
- Ongoing Tests, Trials For Deep Water: “The Ocean Food and Energy Project” (1976)
- Current Ongoing DoE Work
- May Help With N, P Pollution From Shore Sources
- Bioengineered Kelp?
- Not Proven How Much Is Sequestered Long Term
- Will Require Artificial Structures In Deep Water
- What Other Environmental Impacts?
- Kelp to Fuel Is Somewhat Carbon Negative, Not Carbon Neutral
- Cattle Feed: Some Kelp Species Reduce Methane Generation



## Natural Kelp Forests; Sea Otters

- Restore Natural Pacific Kelp Forests
- Sea Urchins Eat Holdfasts, Kelp Dies
- Hunting Sea Otters Decimated Kelp Forests
- Currently Otters Sequester 4 – 8 Mtonne C
  - Perhaps 1% - 10% Of “Natural” Population;  
Historic Otter Populations 1 GTONne?
- Low Cost Compared to Credits
- Otter Threats; Pollution, Feline Diseases, Nets / Oil Spills, New Predators
- Not Exactly Sure How To Promote Otter Recolonization
- Artificial Otter Homes / Kelp Ranches?



Marshall Hedin [wikimedia.org](https://www.wikimedia.org/)



# Littoral Aeration

- Use Marine Renewable Energy To Aerate Dead Zones
  - Wave Powered Pumps Surprisingly Effective
- Increased Biological Activity Sequesters Carbon
  - Consider The Carbon Taken Up By The Historical Chesapeake Oyster Harvest; 10,000,000 40 Lb Bushels/Yr, 1900s  
Now Less Than 1% of Historic Yields
- Plenty of Nutrients Due To Pollution
  - But, Will RDOM, POC In Dead Zone Become CO<sub>2</sub>?
  - Will Aerated Zones No Longer Reduce N Pollution?
- New Finding: Dead Zones Produce Methane
  - Much More Powerful Greenhouse Gas Than CO<sub>2</sub>
- Need More Science, Study, Research, Carefully Monitored

# Artificial Floating Wetlands?



- Sea Otters Shelters?
- Protection From Predators
- National Aquarium Project In Baltimore Harbor Since 2010
- Wetlands: Substantial Carbon Sinks



# Opportunities For The Marine Industry

- Research Vessels: / Manned / Autonomous / Buoys
- Injection Schemes: Standard Oil Patch Operations:
  - Injection Platforms, Big Pipelines At High Pressure
  - Where Does The Energy Come From?
  - Injection Platforms With Wind Turbines / Wave Harvesters?
- Standard Opportunities For OSV Fleets, Drilling Rigs,
- Biological Schemes:
  - Lots Of Small Units (To Be Designed, Built, Installed, Etc.)
  - Big OTEC Plants / Maybe Product Carriers
  - Wave Energy Harvesters, Upwelling Pumps, Aeration Pumps
  - Kelp Farm Structures, Harvesting Ships, Auditing Systems ...

## Economics

- Carbon Taxes, Carbon Credits, Tax Credits, Cap And Trade
- Depends On Competing Source Costs And Carbon Emissions
- Price Of Oil, Natural Gas, Nuclear, Other Alternative Energy
- Prices For Carbon Credits:

**New IRS 45Q CCS Credit: \$50 / Tonne (CO<sub>2</sub>)**

- Stiglitz: \$40 Required by 2020 To Decarbonize Energy
- Canada: To Set \$ 50 CDN / Tonne By 2020
- One GTONne = \$45 – \$120 Billion
- Many Sequestration Schemes Probably Very Expensive
- Think About Business Models: Tax vs. Credits vs. ?
- Verifying Carbon Sequestration

## Lots of Moving Parts

- Need More Research, Awareness; Marine Biology, Chemistry
- Need to Work With Scientists, Oceanographers
- Need Developments In Chemical Engineering (Catalysts)
- Need More Ideas on Possible Schemes
- Need To Work With Environmentalists
- Need Supporting Public Policy (Talk to Activists)
- Need Supporting Economics / Business Models
- Need Lots of Engineering Details
- Need Fuller Understanding of Environmental Impacts

*“It seemed like a good idea at the time.”*



# Innovation

The Breadth of Disciplines Involved In Ship Design, Construction, and Operations Requires Wide Knowledge to Integrate the Whole Ship; Teaches Interactions and Connections

Innovation Comes From Seeing Interactions and Connections and Bringing Them Together.

- Example: Purple Sea Urchins Destroying Kelp Forests: Autonomous Sea Urchin Hunter UUV Robots?
- Example: Restore/Protect Whales (*The Deep Range*, Clarke, 1957)

# Summary

*Don't stop thinking about tomorrow...*

*Fleetwood Mac*

## Marine Carbon Sequestration

### May Be Help Prevent Catastrophic Climate Change

- Not A Silver Bullet – Need Alternative Energy, Efficiency
- May Be Opportunities For The Marine Industry
- Depends On Carbon Credit Economics, Tax, Policy
- Depends On Better Science, Engineering Details
- Keep Thinking, Keep Alert For New Ideas; It's Up To You

*"Be alert; America Needs More Lerts"*

*Popular Tee-Shirt*

Thank You For Listening

[cdbarry12@yahoo.com](mailto:cdbarry12@yahoo.com) / [www.sname.org](http://www.sname.org)