# *Key Engineering Issues for Economically Viable Ocean Wave Energy Conversion*

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# Agenda

- Survivability is Paramount
  - Deployment Challenges
  - Operational Challenges
  - Deployment Techniques
- Stevens' Research Goals
  - Focus on Commercial Production
  - Simplify Deployments & Recovery
  - Tune Waves to Expand Viable Regions
  - Perform Hydrodynamic Research
  - Perform Extreme-Wave Scale Model Testing
- Appendix

# Survivability is Paramount

- Deployment, maintenance, and recovery logistics, redundancy, fail-safes, mooring loads, and buoyant integrity must lead design hierarchy
- Review deployment sinking of the Applied Research Technology Ltd.(ART)/Wavegen-OSPREY (1996) and Trident Energy DECM (2009)
- Review operational sinking of Finavera-AquaBuOY (2007)

# Deployment Challenges

- Commercial systems must deploy and maintain maximum plate capacity per ship day to be economically viable
- High energy regions have short deployment windows
- Large units (100 ton +) are required for commercial viability
- Two large-scale devices have sunk during deployment

# ART-Wavegen OSPREY 2MW OWC

http://www.wave-energy.net/Library

# OSPREY Aug 1996

# OSPREY

- Sank in August 1996 off Clyde, Scotland
- 2-3 meter seas ruptured unfilled ballast tanks during deployment
- Ballast tanks required sand for structural stability

# Trident Energy 20 kW-DECM

http://www.tridentenergy.co.uk/index.php

# Trident Energy - DECM

- 20 Sep 2009 unit overturns during deployment
- 5 Oct 2009 unit recovered and returned to Lowestoft Harbor, Suffolk, England to assess damages

# Operational Challenges

- Wave energy provides a low frequency (<1 Hz), high density input which causes dead band issues
- Extreme waves typically have 100x the power of average wave conditions
- Moving arrays to avoid storms is not economically viable or realistic
- Commercial systems must operate unmanned for years to be viable
- The Finavera-AquaBuOY sank after 51 days of operation due to a bilge pump failure
- Buoyant integrity is critical

# Finavera AquaBuOY 250 kW

# AquaBuOY Deployment

- 7 Sep 2007 Deployed off Reedsport, Oregon
- 27 Oct 2007 Sank due to bilge pump failure
- The unit did not have a redundant bilge pump and was negatively buoyant with a flooded buoyancy compartment

- http://www.theregister.co.uk/2007/11/09/aquabuoy_wave_power_renewable_sinks/

# Deployment Techniques

- Anchors are placed prior to unit deployment, integrated into unit, or placed by towing or support vessel
- Units are loaded on the deck or towed to sea by service vessels
- Commercial scale units require seafloor cable installation to shore

# RME- AirWEC$^{tm}$ 2 kW Deployment Jan 2009


*Courtesy Resolute Marine Energy, Inc.*

# AirWEC Deployment Details

- AirWEC and anchors were loaded on deck and transported to site by service vessel (Lisa Ann II)
- One sortie
- Designed with data transmission capabilities to monitor performance from shore
- Small scale fish farm application

# Oregon State University 10kW SeaBeav I Deployment Oct 2008

*Courtesy Oregon State University*

# SeaBeav I Deployment Details

- SeaBeav I was towed to sea by service vessel (Pacific Storm) and connected to an independent mooring system
- Power cable was routed to service vessel to monitor performance

# Pelamis 750 kW Deployment

*Courtesy Pelamis Wave Power, Ltd.*

# Pelamis Deployment Details

- Location: Aguçadoura, Portugal
- Project boundary markers installed
- Mooring spreads installed
- Subsea power cables installed
- Latch assemblies installed
- 3 units towed to sea and connected
- Various vessels used
- Numerous sorties

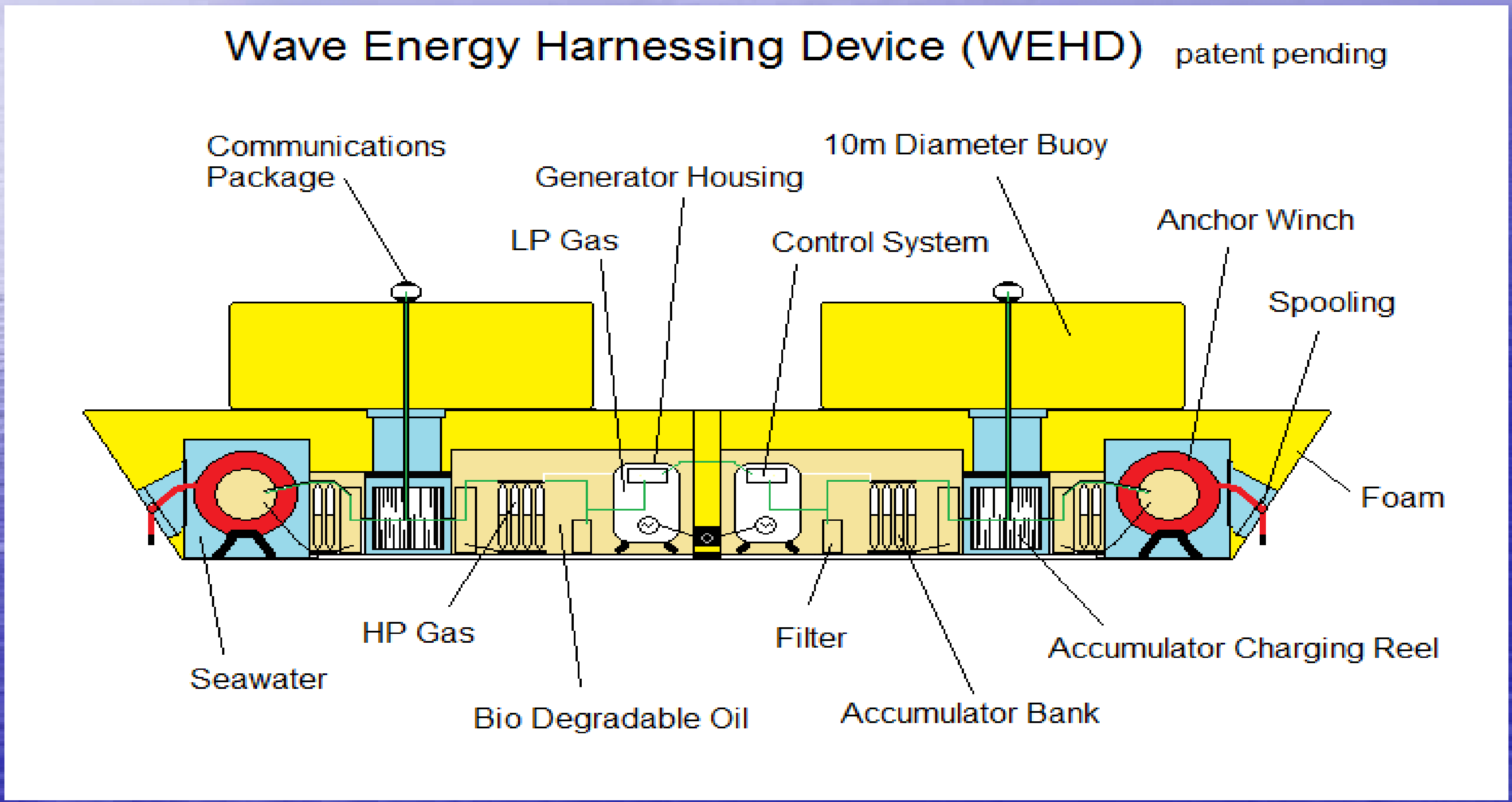
http://www.pelamiswave.com/

# Stevens' Research Goals

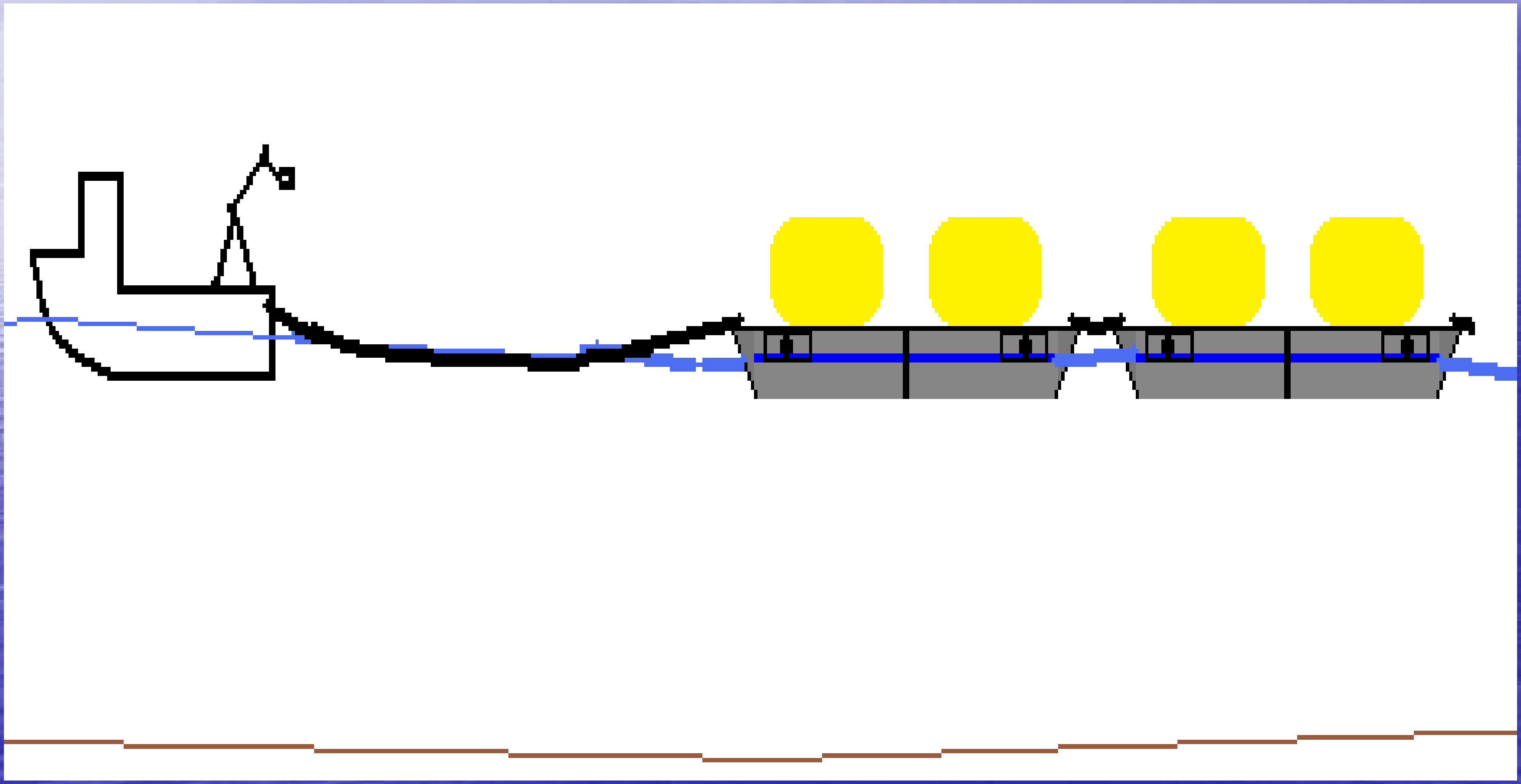
- Focus on Commercial Production
- Use a Barge Based Platform
- Develop Redundancy, Fail-Safes, Wave Tuning, Storm Avoidance, and Energy Storage Features
- Quantify Mooring Loads and Wave Tuning Limits
- Perform Hydrodynamic Research
- Perform Extreme-Wave Scale Model Tests

# Barges- Simple, Proven Platforms

# Integrate Power Take-Off



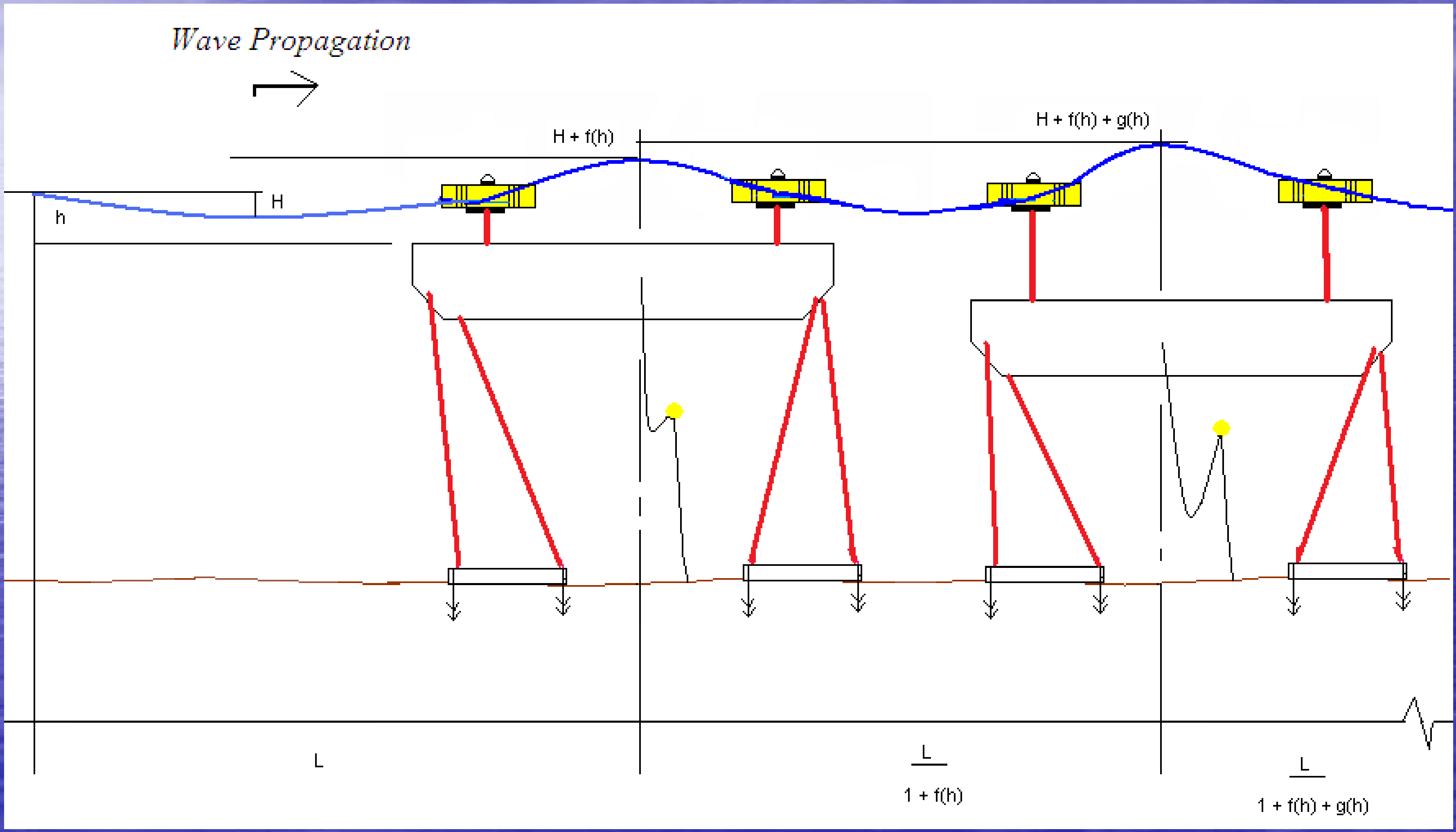
# Towed to Mooring Site



# Prototype Design Features

- Variable Depth Platform
- Redundant Data and Power Systems
- Power Take-Off Decoupled from Electricity Generation
- 100 kWh Energy Storage (240-4500psi cylinders)
- Data Cables Integrated with Strength Cables
- Foam-Filled Compartments
- Bulkhead Fittings for Generators (No shaft seals)
- Pressure Compensated Winch Shaft Seals
- Components Submersed in Bio Degradable Oil Reservoir

# Wave Tuning & Storm Avoidance



# Mooring Loads

- Determine probable extreme waves
- Calculate hydrostatic and hydrodynamic loads
- Use a four-point mooring
- Design each mooring leg to hold design load

# Extreme Wave Height Predictions

| Westhampton, NY 1994 - 2000 | |
|---|---|
| **Return Period (years)** | **Extreme Wave Height (m)** |
| | |
| 1 | 5.2 |
| 2 | 6.1 |
| 3 | 6.6 |
| 5 | 7.3 |
| 7 | 7.7 |
| 10* | 8.2 |
| 20* | 9 |
| 25* | 9.3 |
| 50* | 10.2 |

http://sandbar.wes.army.mil/public_html

# Extreme Wave Duration

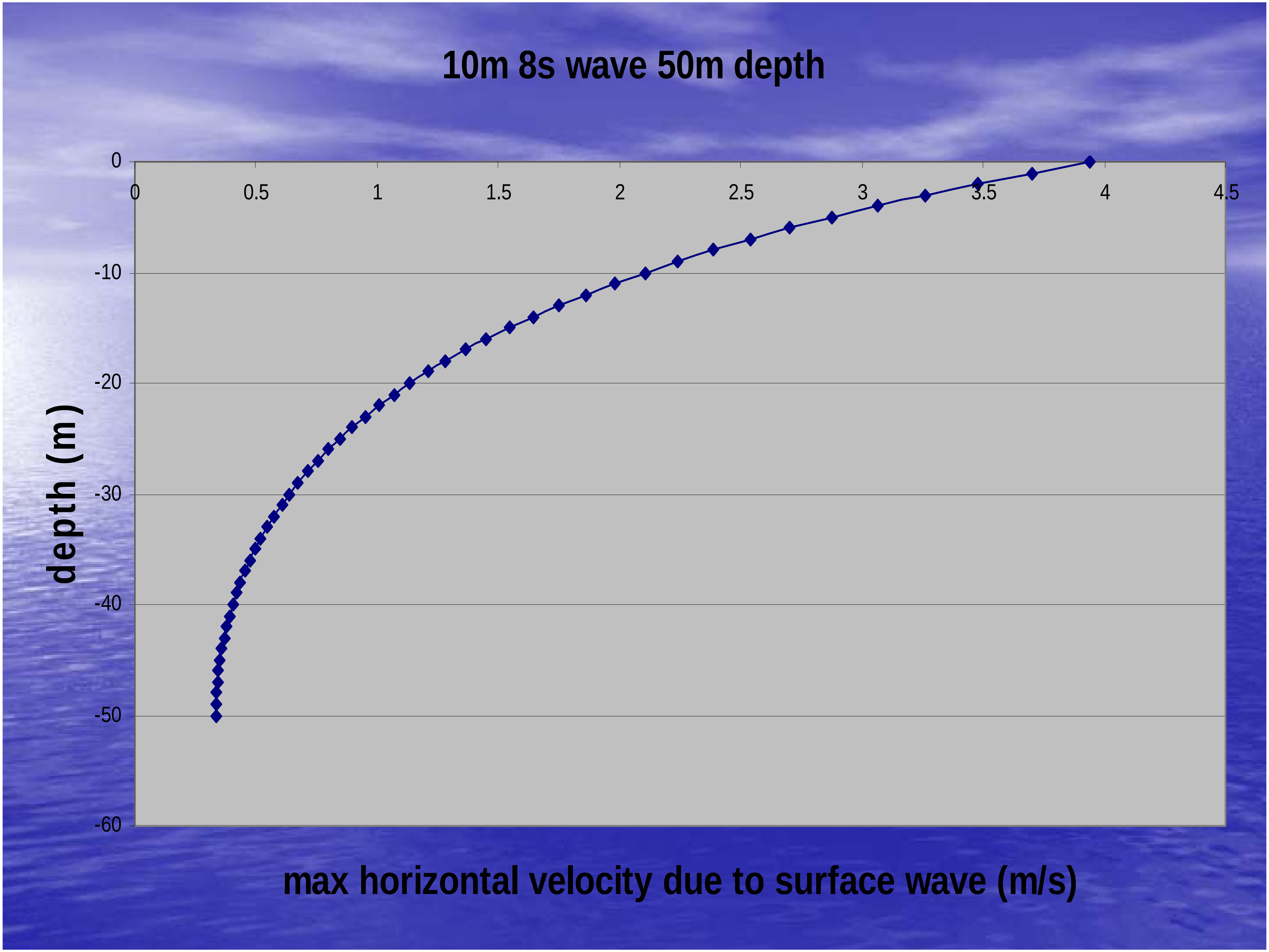
| Year | Month | Day | Hour | Wind Direction | Wind Speed (m/s) | Gust | Wave Height (m) |
|---|---|---|---|---|---|---|---|
| 91 | 10 | 30 | 17 | 25 | 17.6 | 22 | 5.2 |
| 91 | 10 | 30 | 18 | 29 | 19.5 | 24.2 | 5.9 |
| 91 | 10 | 30 | 19 | 30 | 18.9 | 23.8 | 6.2 |
| 91 | 10 | 30 | 20 | 28 | 19.6 | 25.6 | 6.9 |
| 91 | 10 | 30 | 21 | 28 | 19.6 | 24.2 | 7.6 |
| 91 | 10 | 30 | 22 | 25 | 19.2 | 23.2 | 7.7 |
| 91 | 10 | 30 | 23 | 27 | 20.8 | 25.6 | 7.8 |
| 91 | 10 | 31 | 0 | 27 | 20 | 25.2 | 7.7 |
| 91 | 10 | 31 | 1 | 29 | 22.5 | 28.1 | 8.2 |
| 91 | 10 | 31 | 2 | 29 | 22.7 | 26.4 | 9.1 |
| 91 | 10 | 31 | 3 | 25 | 19.6 | 24.2 | 7.6 |
| 91 | 10 | 31 | 4 | 32 | 20.3 | 25.1 | 7.7 |
| 91 | 10 | 31 | 5 | 37 | 19.1 | 23 | 7.6 |
| 91 | 10 | 31 | 6 | 32 | 19.5 | 22.8 | 6.8 |
| 91 | 10 | 31 | 7 | 36 | 18.2 | 22.6 | 7 |

Buoy Data from NDBC 44013, 16 Nautical Miles East of Boston, MA during the “Perfect Storm”

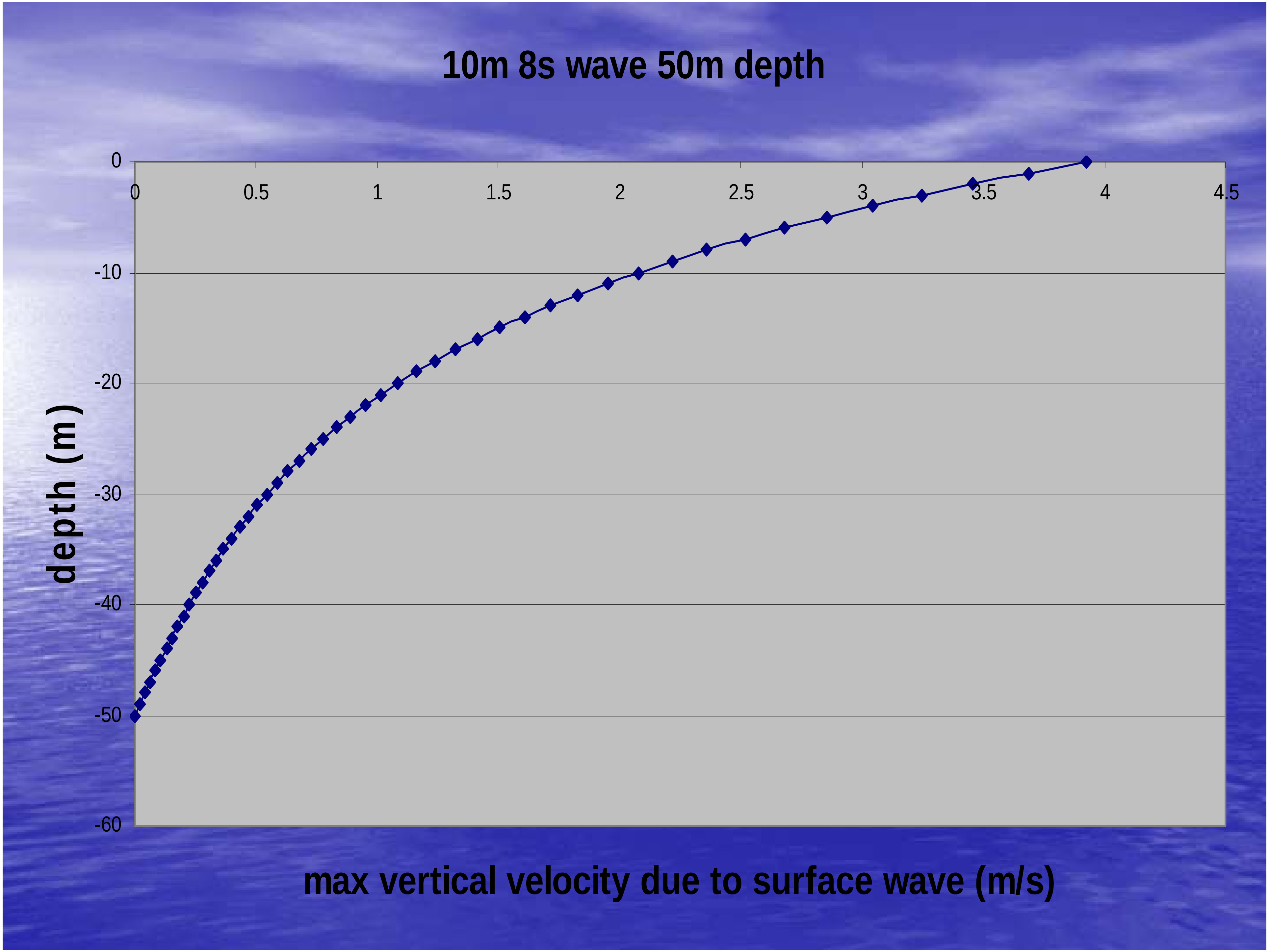
# Water Particle Velocities

$$u = -\frac{\partial \phi}{\partial x} = \frac{H\omega}{2} . \frac{\cosh\ k(h+z)}{\sinh\ kh} \cos(kx - \omega t)$$

$$w = -\frac{\partial \phi}{\partial z} = \frac{H\omega}{2} . \frac{\sinh k(h+z)}{\sinh kh} \sin(kx - \omega t)$$



10m 8s wave 50m depth
depth (m)
max horizontal velocity due to surface wave (m/s)
0
-10
-20
-30
-40
-50
-60
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5


10m 8s wave 50m depth
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-20
-30
-40
-50
-60
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
depth (m)
max vertical velocity due to surface wave (m/s)

# Calculating Loads

- For wave energy conversion systems, mooring loads are functions of device displacement, drag, weight (mass), water particle velocities, damping, and device geometry

# Displacement

- A fully submerged, 10m diameter, 2m high cylindrical buoy will displace ~160,000 kg of seawater (1025 kg/m3)
- Or ~80 kg per mm of draft

# Added Mass/ Drag Force

- $M_a = \rho \pi a^2 H$
- where a is the cylinder radius and H is the cylinder height.
- = 1025 x 3.14 x 25 x 2 ~ 160,000 kg
- Cylinders and Flat plates have the potential for added mass equal to total displacement depending on the direction of water particle acceleration

# Buoy Design Load

- 10m diameter, 2m high, cylindrical foam core buoy
- Buoy weight = 47,000 kg
- Added mass = 160,000 kg
- = 160k displacement + 160k added mass – 47k buoy weight
- = 273,000kg vertical load
- Max *w* = 4m/s
- KE = ½ mv^2
- (273,000 kg x 16 m^2/s^2)/2
- = 2,184,000 N max tether/anchor line load
- = 491,000 lb/246 ton required anchor holding power per buoy

# Platform Anchor Load

Submerged, Flooded, Platform Lift = 115 tons

Added Mass:

Ma = $\rho\pi a^2/4$ * b

a is platform width and b is platform length

= 1025 x 3.14 x 36 x 30 = 3,500,000 kg

KE = ½ mv2

= (3.5M x .25)/2 = 437,500 N lift = 50 tons

# Total Design Anchor Load

115 tons static platform lift

50 tons kinetic platform lift

492 tons buoy lift (246 tons x 2)

= 657 tons

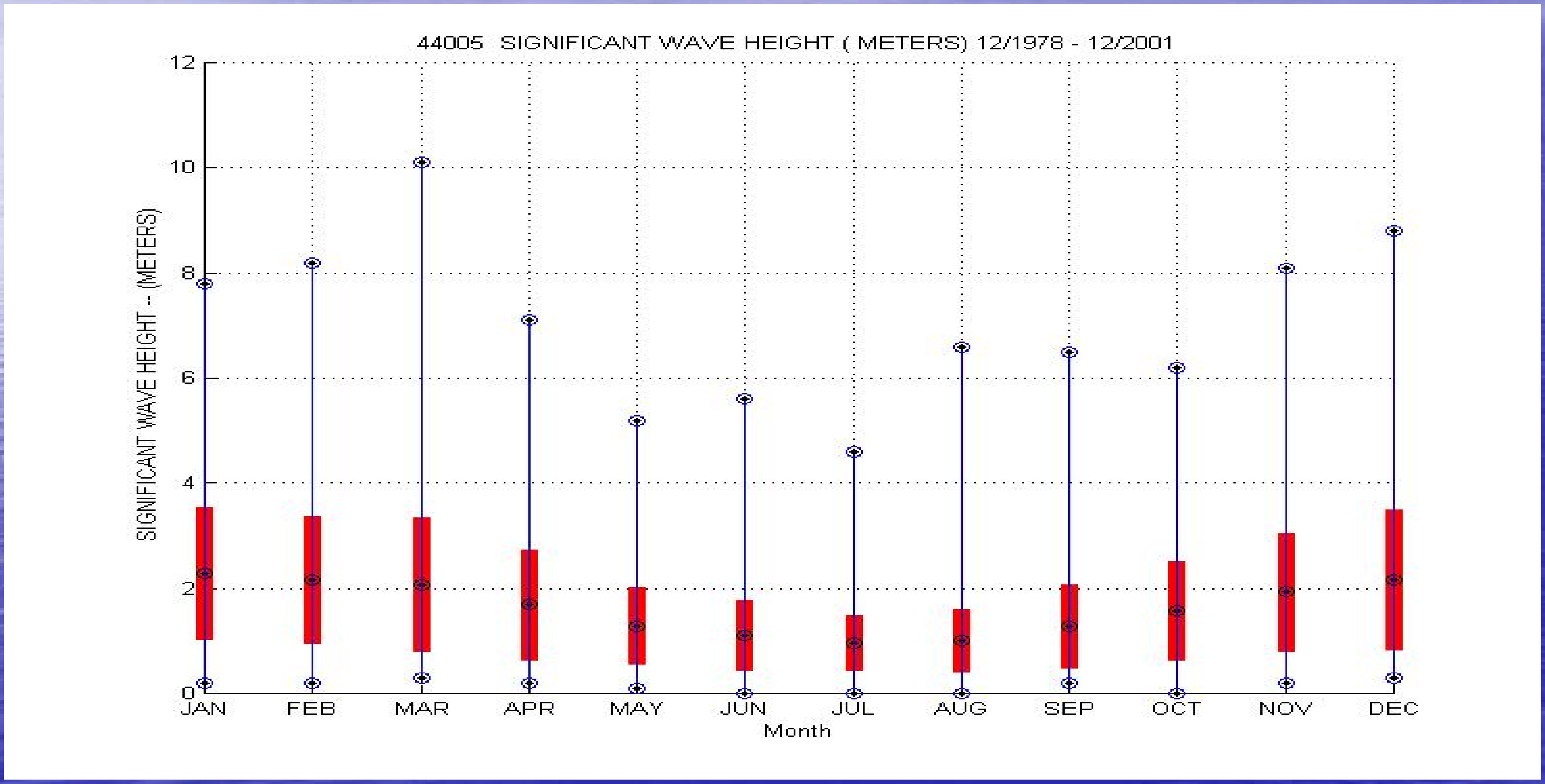
# Wave Tuning

- Determine available wave height, period, and length
- Determine maximum tuning (shoaling) prior to breaking criteria (1:7 slope)

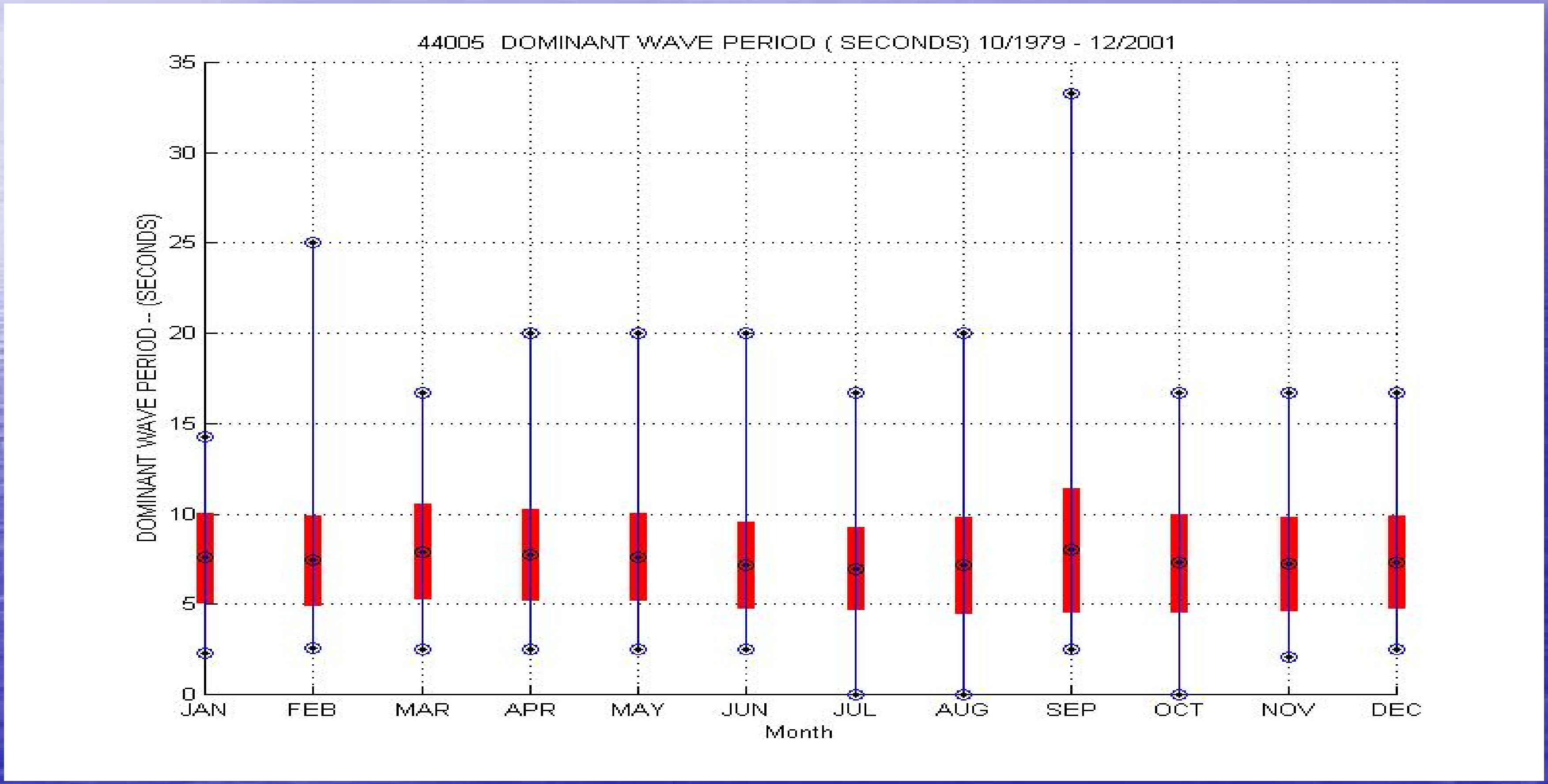
# Buoy Data


Ottawa
Montréal
Maine
Bay of Fundy
Vermont
NDBC 44027
NDBC 44007
New York
NDBC 44005
NDBC 44013
42.346N 70.651W
Fundian Valley
ylvania
Rhode Island
Shelton
NDBC 44018
NDBC 44011
NDBC 44017
New York
NDBC 44025
© 2009 Europa Technologies
© 2009 Google
Image © 2009 TerraMetrics
© 2009 Tele Atlas
Google
Philadelphia
New Jersey
42°51'24.00" N 70°34'50.23" W elev -11 ft
Eye alt 584.49 mi

# NDBC 44005 78NM East of NH



# 44005 Tp 200m water depth



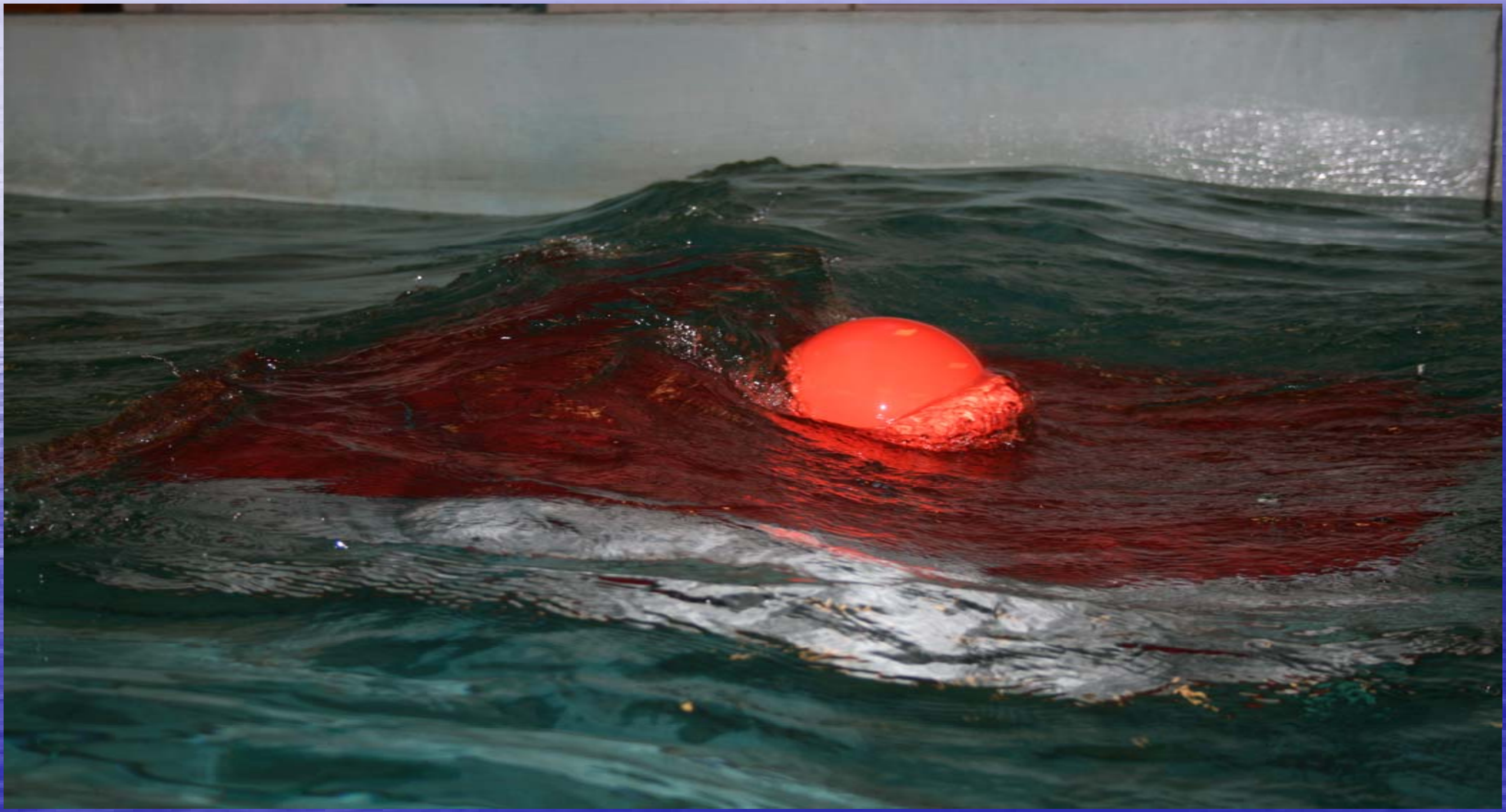
# Tuning July Waves at 44005

- Hs = 1m Tp = 7s
- L= 76m C= 10.9 m/s Cg= 5.46 m/s
- P =6852 W/m
- By conservation of mass:
- Hs = 2.5m L = 30m slope= 1:12
- Cg= 2.18 m/s
- P = 17, 139 W/m

# Tuned Wave Power

- 17 kW/m x 10m diameter x 2 buoys
- = 340 kW wave power acting on buoys
- Conservative, simple, linear approximation without added mass/drag effects

# Tuned Wave



# Tuned Wave (Non-Linear Transition)

# 1:10 Scale Extreme Wave Tests

- Stevens granted $50,000 to research wave energy by DOD (Oct 2009)
- 1:10 Scale wave tuning model being built
- Estimated completion April 2010
- Stevens' wave tank tests April 2010- Sep 2010
- Simulate 10m waves at OHMSETT facility (Fall 2010)

# Appendix

- New England's Electricity Use
- Seafloor Cables
- Wave Power Resource (Non-Directional)
- EPRI Wave Power Estimate (2005)
- Enabling Technologies

# New England’s Electricity use

- 2007 – 1232 trillion Btu for Electric Power
- MA-423, CT-322, NH-234
- ME-127, VT-70, RI-56
- = 225 billion kW-hr
- = 40GW average production
- 1GW = 1 kW-hr every 0.0036 seconds

http://www.eia.doe.gov/emeu/states/sep_sum/html/pdf/sum_btu_eu.pdf

# Seafloor Cables

http://www.3ehabitat.fr/tag/gaz/

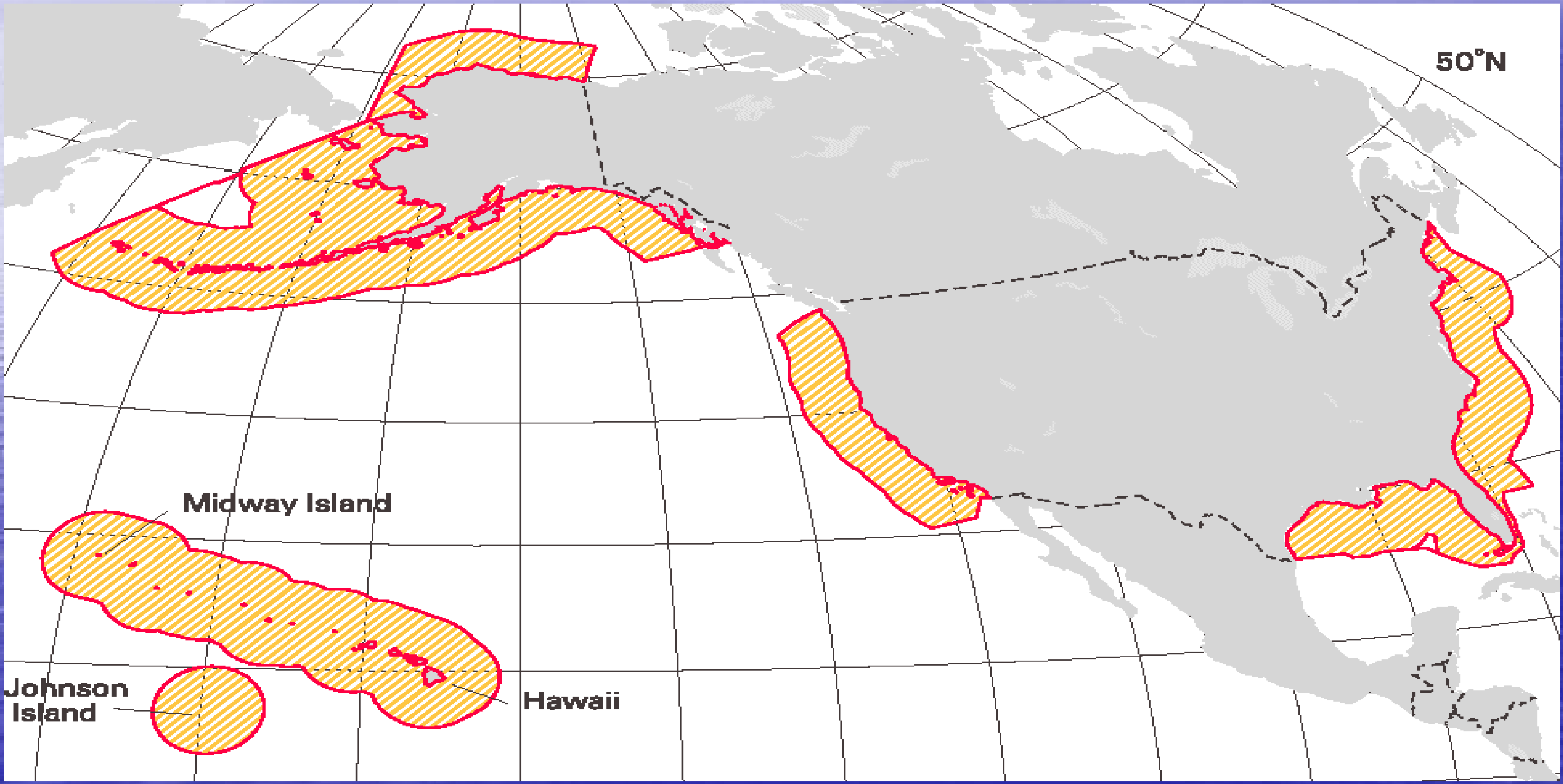
# Wave Power Resource

- Based on regional buoy data, 4.89 trillion watts (4.89TW) of wave power are available between the New England shores and the Continental Shelf (170NM offshore) in average wave conditions
- Harnessing 5% of the resource and converting to electricity at 20% efficiency would produce 49GW of electricity or *more than* New England's use

# Wave Power Calculations

- Average power for New England area:
- 1255 J/m2 x 5.46 m/s = 6852 W/m x 250,000m of wave crest north to south = 1.7GW per wave crest
- 220,000 m of wave travel/76.44m between wave crest = 2878 wave crests propagating through the area
- Total wave power = 1.7GW x 2878 = 4892GW or 4.892TW of wave power propagating through this area in average wave conditions.

# EPRI Wave Energy Assessment 2100 TWh/yr (240GW), Bedard et. al. 2005




http://my.epri.com/

# Enabling Technologies

- Submersible winches- Dynacon Inc.
- Offshore communications- Space Data LLC
- Integrated strength, communications, and power cables- Honeywell, PMI Industries
- Bio-degradable oil- HydroTex
- Anchors- Delmar 700 ton OmniMax
- Load-sensing hydraulics- Bosch-Rexroth