Sabbatical Report
Spring Semester 2011

Submitted to the Office of the Provost

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Introduction

During the spring semester of 2011, I was given the opportunity to take a sabbatical leave to work at a university in India. I served as a guest researcher and lecturer at the Indian Institute of Technology - Kharagpur. Kharagpur is a city with a population of about 370,000 in the state of West Bengal. It is about 100 km from Kolkata (Calcutta) on the east side of India.

IIT – Kharagpur (IIT-KGP) is the oldest university in the IIT system, which has become recognized as a world-class system (see the 2008 World University Rankings, The Times, London, UK, http://www.paked.net/higher_education/rankings/times_rankings.htm). IIT – Kharagpur is significantly larger than UW – Platteville, but they share many of the same focus areas: both have strong programs in engineering, science, agriculture, education, business, humanities and social sciences.

![Main Building, Indian Institute of Technology – Kharagpur.](image)

My main activities included teaching a short course as well as working with students in India and Wisconsin to collaborate on a research project. I taught a short course to undergraduate and graduate students and faculty members on “Renewable Energy: Ocean Wave-Energy Conversion”. I worked with two UW-Platteville students in the Renewable Energy minor.
program and one IIT-KGP student to collaborate on a project to develop a wave-tank test for an American ocean wave energy conversion device. I was also able to learn more about how renewable energy technologies are being developed for use in India, through attending presentations and visiting universities and sites.

Acknowledgments

I am grateful to the University of Wisconsin – Platteville for the opportunity to engage in this sabbatical experience. My colleagues in the Mechanical and Industrial Engineering Department took on extra teaching load to make this possible. I am grateful to Professor Baidurya Bhattacharyya, my primary host and advocate at IIT-KGP. Mostly, I am grateful to my wife Theresa, who did most of the hard work of keeping our family healthy through all of the challenges of this rewarding experience.

Goals

I set out to accomplish three main goals:
1) Learn about renewable energy programs in India, so that I can work towards developing new curriculum for the UW – Platteville program in Renewable and Sustainable Energy Systems,
2) Investigate the possibility of expanding UW – Platteville’s international study programs to make study in India available to our engineering students, and
3) Facilitate undergraduate students in Platteville and India collaborating on a design project for the UW – Platteville course “ENERGY 4920 Research and Design Projects in Renewables”.

While I had to adapt to opportunities and challenges there, I was able to address and make progress toward each of these three goals. In general, I adjusted my focus toward my own research, while I was able to work with a small team of students from India and Platteville collaborating on a renewable energy project.

Goal Progress

Progress towards these goals is described below.

1) I set out to learn about renewable energy programs in India, so that I can work towards developing new curriculum for the UW – Platteville program in Renewable and Sustainable Energy Systems. This directly supports the University of Wisconsin System Board of Regents’ emphasis on Interdisciplinary Activities.

I attended the Workshop on Renewable Energy at IIT-KGP given by Dr Prabha Kant Sinha on 11 February 2011.
I was the Featured Speaker at the IIT-KGP Departmental Research Scholars Day, 5 March 2011. I gave a brief description of my research activities to faculty members and graduate students. I listened to and evaluated poster presentations from the graduate students in the department.

I was a keynote speaker at the IIT-KGP Green Earth Day seminar on 23 April 2011, in conjunction with Earth Day celebrations worldwide. I gave a talk about the possibilities of ocean wave-energy conversion to undergraduate and high school students.

I attended a talk given by a researcher the Indian division of John Deere describing their efforts to develop a low-cost solar-powered drip irrigation system on 31 May 2011.

I was able to visit different renewable energy sites in India, from large-scale wind farms, to small solar-thermal heaters, to a small low-technology anaerobic digester at a rural orphanage.
On 3 June 2011, I visited the Gopali Ashram orphanage in Kharagpur, West Bengal, India. They have a simple anaerobic digester installed there (see Fig. 5). The digester allows for capturing methane cooking gas from livestock manure. In the USA, anaerobic digesters are considered not economical for small dairies up until the number of cows milked is measured by thousands. This digester, on the other hand, has no moving parts, no electrical demands, and supplies methane cooking gas for boiling rice. The gas is piped directly to the kitchen where it runs a gas stove nearly nonstop.
Figure 5. Simple anaerobic digester for capturing methane cooking gas from livestock manure at the Gopali Ashram orphanage outside Kharagpur, West Bengal, India.

Figure 6. Left: gas burner connected directly to anaerobic digester; right: boiling rice at Gopali Ashram orphanage.

I attended the TEDxIIT KGP talks on 6 February 2011, an international extension of the famous TED lecture series. Among the talks was one by some IIT students who have developed a method for generating electricity from sewer wastewater.
At the Indian Institute of Science (IISC) in Bengaluru (Bangalore), India’s premiere graduate research institution for science and engineering, I visited their laboratory where they are developing advanced biomass combustion techniques.

![Advanced biomass combustion research laboratory at IISC.](image)

Figure 7. Advanced biomass combustion research laboratory at IISC.

2) I set out to investigate the possibility of expanding UW – Platteville’s international study programs to make study in India available to our engineering students. This directly supports the University of Wisconsin System Board of Regents’ emphasis on **International Education**.

Currently, UW – Platteville does not have any direct programs for undergraduate study in India. I believe that there is a large demand for Indian undergraduate students to study in America. Donna Anderson, director of International Education at UW-Platteville and Mohammad Amin from Admissions conducted a tour of India in November 2012. They are working to open up a path for Indian undergraduate students to enroll as full-time students here at UW-Platteville. I will continue support their efforts.

I do not anticipate a large number of UW – Platteville students wanting to travel all of the way to India; however, it is one of the most exotic English-speaking countries on the planet, so there would certainly be some interest. I recently attended a workshop on Short-Term Faculty-Led Study Abroad Programs, and I continue to explore that possibility.

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I was able to observe classroom lectures at IIT-KGP, and I had the opportunity to interact with several students there, both undergraduate and graduate students.

Figure 8. Classroom observations and student interactions.

Professor Prathivati Ravikumar at UW – Platteville has worked to establish a partnership with the R.V. College of Engineering (RVCE) in Bangalore, India. Unfortunately, I was unable to connect with any faculty members at RVCE.

I visited the offices of DAR, an international civil engineering firm in Pune, on 11 June 2011.
I was a technical judge for the engineering contest final presentations during Kshitij, IIT-KGP’s national student-run festival of technology and management on 28 January 2011. Kshitij included international expert speakers from companies across the globe, as well as technology exhibits and engineering contests for students from across India.

I was able to observe school classrooms in India, which will further my ability to relate to students coming to the USA from India. My son was the only Westerner in his second-grade class in an elementary school on the IIT-KGP campus. Furthermore, I had the opportunity to visit a school in a small rural village near Kharagpur.

Figure 9. Offices of DAR engineering firm, Pune, India.

Figure 10. School classrooms in an elementary school on campus, and a rural village school near Kharagpur.
In my travels, I was able to visit Kolkata (Calcutta), Delhi, Agra, Jaipur, Shimla, Goa, Bangalore, Kochi (Cochin), Hyderabad, Pune, Ajanta, Ellora, Kottayam, Chengannur. I traveled by train, mostly, as well as by automobile and commercial aircraft. I experienced India up close, from tourist destinations to small towns, and I rode the crowded trains in between. These experiences give me a certain level of understanding of India which will help me to relate to potential students as we expand our recruiting efforts to attracting Indian undergraduate students.

3) I set out to facilitate undergraduate students in Platteville and India collaborating on a design project for the UW – Platteville course “ENERGY 4920 Research and Design Project in Renewables”. This directly supports the University of Wisconsin System Board of Regents’ emphases on **International Education, Collaboration, Interdisciplinary Activities, and Application of Technology to Instruction and Distance Education**. Projects in the Renewables Project course are inherently interdisciplinary. These projects involve investigation of technical, scientific, economic, sociological, and business issues by students in majors from across the campus.

Two UW-Platteville students, Vincent Hoffman and Brian Applequist, worked with me on a research project. We collaborated with IIT-KGP student Dripta Sarkar, and IIT-KGP Professor Nisith Mandal, both of the Department of Naval Architecture. Vincent and Brian completed the UW – Platteville course “ENERGY 4920 Research and Design Projects in Renewables” as a guided independent study course, completing the final report and presentation in August 2011.

The project involved the investigation of an ocean wave-energy conversion device. The Wave Energy Converter (WEC) is a device that is proposed by the Wave Energy Conversion Corporation of America (WECCA), a small startup company based in Potomac, MD, USA. WECCA. The WEC consists of three barges hinged together (see Figure 11). In the presence of waves, the pitching motions of the barges are used to drive generators which produce electricity.
Figure 11. Wave Energy Converter prototype.

Figure 12. Wave-Energy Converter diagram.
I was able to work with the two UW-Platteville students by having Skype videoconferences, sometimes with the IIT-KGP student as well. Internet connectivity was difficult for me; while the IIT-KGP campus is a research institution with fast internet connections, my connections at my office and home were problematic for the first month before technical issues were resolved.

I worked with Dripta Sarkar, student in Naval Architecture at IIT-KGP, to construct a model to test in the IIT-KGP wave tank (see Figure 13). The model in progress is shown in Figure 14. Unfortunately, due to constraints on the model builders, Dripta and I were not able to see this model completed.

Figure 13. The 150 meter wave / towing tank at IIT-KGP.
Figure 14. Wave-energy converter system model in progress at IIT-KGP.

In parallel to the model-building efforts, I supervised the efforts of Mr Sarkar in creating a simulation using the Matlab computing environment. This will be used to compare with experimental results from wave tank testing.

**Research**

I wrote some computer programs in the Python computer language to investigate the phenomenon known as impedance matching. Analytical equations predict that the power output from a dynamic system (such as a buoyant ocean wave-energy converter) will be maximum when the power take-off damping coefficient is equal to the coefficient of the system’s inherent damping.

Figure 15 shows the power take-off (PTO) output plotted versus changing frequency ratio and also versus changing PTO damping coefficient. The plot shows that the power is maximized when the input frequency is close to the undamped natural frequency of the system, a phenomenon called resonance. The plot also shows a peak in the power when the PTO damping coefficient matches the system’s damping coefficient, which confirms the impedance matching prediction.
At the Indian Institute of Science (IISC) in Bengaluru (Bangalore), India’s premiere graduate research institution for science and engineering, I was invited to give a talk on 17 June 2011 to the Civil Engineering department. I discussed my renewable energy research. I visited their mechanical system dynamics lab and learned some techniques for multi-degree-of-freedom dynamics experiments (see Fig. 17).
Figure 16. Main building at the Indian Institute of Science, Bangalore.

Figure 17. Multi-degree-of-freedom structural dynamics apparatus, and six-degree-of-freedom shake table at IISC.

I had the chance to visit the laboratories of IIT-KGP’s mechanical engineering department. I saw how they use low-cost open-source microcontrollers, such as the Arduino boards, to control student robotics projects.
Teaching
I taught a short course entitled “Renewable Energy: Ocean Wave-Energy Conversion”. This course was taught over the course of two months to faculty members, graduate students, and undergraduate students in the Civil Engineering and Naval Architecture departments at IIT-KGP. The course covered linear wave theory, the basic mathematical description of ocean water waves, ocean wave-energy conversion device classification, and design issues, including temporal resonance, power take-off impedance matching, and wavelength compatibility.
Conclusions

This sabbatical project was of great benefit. The opportunity for me to lecture in India and interact with the students would has been an invaluable experience. I believe the experience would make me a more valuable member of my department, my college, and my university.

This project would benefit the Mechanical Engineering program at UW – Platteville. Having access to the 150 meter wave tank at IIT - Kharagpur may enable me to perform experiments to compare with the numerical simulations that I have conducted for design improvements to a particular ocean wave-energy conversion system. Furthermore, access to the laboratory equipment will enable me to bring back experience with sensors and systems that are unavailable in our laboratories in Platteville.

This project would benefit the University of Wisconsin – Platteville. International collaboration by undergraduate students on open-ended projects could be implemented across all majors. I hope to use my experience to help facilitate implementation of international undergraduate remote collaboration by other faculty members at our university.
Continuing Work
Update (17 Dec 2012):

Model testing of the WECCA wave-energy conversion device has been completed at the US Naval Academy in Annapolis, MD. I used the planning done by Hoffman and Appelquist as I worked with Sarah Mouring, Professor of Ocean Engineering at the USNA, in setting up these tests.

I have been working with students at UW-Platteville on two projects this semester:
1. Two students have fabricated a model of the Wave Energy Converter that is designed to test the device’s ability to submerge to escape the excessive forces of extreme storm events.
2. Three students have learned how to use a new software package called TDyn / SeaFEM which will be used to calculate the hydrodynamic force coefficients for the WEC system. These force coefficients will be used as inputs to the Matlab simulation programs that were written with Dripta Sarkar from IIT-KGP.
Previous Leaves of Absence

None.

External Funding Sources

IIT – Kharagpur 5-month housing on campus

Dissemination to University Community

On 13 Nov 2011 I gave a talk to the UW-Platteville Catholic Newman Club about my experiences with different religions in India.

I presented my sabbatical experience to the UW-Platteville and the community with a lecture in the Nohr Art Gallery on 15 Nov 2011. This was incorporated into the university’s International Education Week, and it was well attended.

On 19 January 2012 I delivered a talk to the UW-Platteville College of Engineering, Mathematics, and Science about my research during my sabbatical in India.

I gave a talk to the UW-Platteville Society of Women Engineers chapter on my experiences in India on 8 March 2012.
Appendix

Report from Brian Appelquist and Vincent Hoffman

Submitted as part of the requirements for ENERGY 4920 Research or Design Project in Renewables:

(All were submitted as external attachments.)

Final report: Appelquist and Hoffman report.pdf
Final presentation: Appelquist and Hoffman presentation.pdf
Model testing calculations: Appelquist and Hoffman testing plan.xlsx
Model submergence calculations: Appelquist and Hoffman submergence calculations.xlsx

Simulation program written with Dripta Sarkar, IIT-KGP

Matlab WEC simulation program sim4.pdf
Ocean Wave-Energy Conversion

Optimization of a Wave-Energy Conversion System (WECS) in Operation and Submergence Survivability

Vincent Hoffmann
Brian Appelquist
Outline

- Introduction
- Proposed Site of Operation
- Test Facility
- Initial Model Scaling
- Wave Scaling
- Experimental Calculations
- Submergence Testing
- Conclusion
Introduction

- WECS (Wave Energy-Conversion System)
Introduction

- Harnesses energy available from the ocean waves
  - Electricity Production
- Experiments
  - Ratio of ocean wavelength to WECS barge length
    - Forward and aft length
    - Will allow maximum available energy to be harnessed
Introduction

- WECS (Wave Energy-Conversion System)
Introduction

• Harnesses energy available from the ocean waves
  • Electricity Production

• Experiments
  • Ratio of ocean wavelength to WECS barge length
    • Forward and aft length
    • Will allow maximum available energy to be harnessed
  • Submergence
    • Increase survivability in severe weather
Introduction

- Submergence
  - Weather
    - Uncontrollable
    - Harsh
Proposed Site of Operation

- Irish West Coast
  - On average, waves with
    - Heights of 2.5 meters
    - Periods of 8 seconds
Test Facility

- Indian Institute of Technology – Kharagpur
  - Kharagpur, West Bengal, India
  - 150 meters long
  - 4 meters wide
  - 2.5 meters deep
- Wave generator
  - Regular or irregular waves
  - Max height of 0.3 meters
  - Max amplitude of 0.15 meters
  - Periods ranging from 0.75 to 4 seconds
Initial Model Scaling

- Limited by facility specifications
  - Width
    - $1/10^{th}$ of facility
  - Interference due to reflection of waves from facility apparatus
Wave Scaling

- Varying ocean wavelength to WECS barge length
  - Barge Length
    - Multiple models
  - Ocean wavelength
- Linear Wave Theory
  - Approximation of wave characteristics
Wave Calculations

- Linear Wave Theory

\[ \lambda = \frac{g \cdot T^2}{2 \cdot \pi} \left( \tanh \left( \frac{h \cdot \left( \frac{2 \cdot \pi \cdot g}{T} \right)^{\frac{3}{4}}}{\pi} \right) \right)^{\frac{1}{3}} \]

- Variables
  - Water depth (h)
  - Period (T)
**Experiment**

- **Model Sizing and Test Matrix**

The image contains two tables, which are likely related to the experiment's methodology and results. The tables are not fully visible, but they appear to be related to wave properties and possibly experimental data. The tables are set up to compare different variables, which are typical in technical experiments to analyze and validate models.
Experimental Calculations

- Expected outcome
  - Maximize energy extracted
  - Capture Ratio
    - Greater than 1.6

\[ \varepsilon = \frac{P_s}{P_{ww}} \]
Experimental Calculations

McCormick, M.E., & Murgtagh
Submergence Testing

- Protection the WECS unit from severe weather
  - Height of 14 m
  - Period of 15 s
- Scaled model generated
  - Scale factor dependent on facility depth
  - Neutral buoyance
    - Volume above waterline
Submergence Testing

- Orbital Particle Motion Under Waves
  - Reduced forces
  - Reduced vertical movement
Submergence Testing

- Tethered mass
Submergence Testing

- Free Body Diagram

\[ \rho V_{\text{BelowWaterline}} g \]

\[ M_{\text{Barge}} g \]

\[ M_{\text{Weight}} g \]
Submergence Testing

Operational State
1: \( 0 = (M_{\text{System}} + M_{\text{Weight}} - \rho \cdot V_{\text{Below Waterline}}) \cdot g \)
\( M_{\text{System}} \): mass of system \( M_{\text{Weight}} \): mass of tethered weight \( V_{\text{Below Waterline}} \): volume of water below waterline at steady state

Submerged State
2: \( 0 = (M_{\text{System}} + M_{\text{Weight}} - \rho \cdot [V_{\text{Below Waterline}} + V_{\text{Above Waterline}} - V_{\text{Flooded}}] - M_{\text{Weight}} \cdot x\%) \cdot g \)
\( x\% \): percent of the required mass to submerge system
\( V_{\text{Above Waterline}} \): volume of water above waterline

Flooded Volume
3: \( V_{\text{Flooded}} = M_{\text{Weight}} \cdot x\%/\rho + V_{\text{Above Waterline}} \)
\( V_{\text{Flooded}} \): volume of water to flood barges
Submergence Testing

- Tethered mass
Submergence Testing

- Submerged State

Zimmer
Submergence Testing

- Inserts
Conclusion

- Amplification
  - Current amplification versus experimental
  - Is it suitable?
- Submergence
  - What is the survivability?
  - Is this method feasible?
Works Cited

Ocean Wave-Energy Conversion
Optimization of a Wave-Energy Conversion System (WECS) in Operation and Submergence Survivability
August 2011

Introduction

Wave-energy conversion is the transformation of the energy of waves into another form of usable energy, normally electricity. Harnessing this motion allows for a clean, renewable energy source that has minimal negative effects on the surrounding environment. A model of a wave-energy conversion system (WECS), otherwise known as the McCabe Wave Pump (MWP), is to be scaled from an existing prototype. This system is a means of generating electricity from the motion of ocean waves.

M. E. McCormick had conducted an experiment in which he was able to measure the power capturing efficiency of a WECS in regards to the variation of the length ratio. The length ratio is the ocean wavelength versus the WECS barge length. He never found the maximum output obtainable due to the variation in this ratio. We will inspect the length ratio and assess the amplification produced, and should it ever reach a maximum value. Should there be a maximum, this is the point where the maximum available power will be produced by the WECS.

One issue with the WECS is the uncontrollable inclement weather it is subjected to. There are multiple methods that can be utilized that would assist the WECS apparatus in its survivability and overall lifespan during undesirable weather. We will test one method, a form of submergence that will descend the apparatus below the waves to increase its survivability.

Proposed Operation Site

The wave properties simulated in the study will be representative of those from the intended location of the actual WECS. This location is the Irish west coast, which provides, on average, waves with heights of 2.5 meters and 8 second wave periods.¹

Test Facility

The facility in which the model will be tested is located in Kharagpur, West Bengal, India at the Indian Institute of Technology - Kharagpur. The scale of the model will be dependent on the size on the wave tank testing facility. This facility is 150 meters long, 4 meters wide and 2.5 meters deep. The wave generator is capable of producing regular or irregular waves with periods ranging from 0.75 to 4 seconds with a maximum height of 0.3 meters. In testing, the model will be held stationary relative to its position in the tank while being subjected to the waves that are produced. The forward barge will be

¹ (Cunningham & Morley)
mounted to a stationary brace, shown here as the center pontoon, on which it the barge can pitch vertically up and down.

Figure 1: Barge System

Model Scaling

Limited by the facility specifications, the maximum allowable size of the model is determined and limited by the width of the testing facility. The model width should be less than one tenth the width of the testing facility, due to the effect that wave interference would have on the test results. This interference will either cause the measured values to be amplified or reduced. This interference is due to the reflection of waves from the testing facility apparatus. By having the model sufficiently smaller than the testing facility, most interference will be negligible. Since the width of the prototype is known, the model scale factor can be determined by using:

\[ \eta_L = \frac{W_{\text{model}}}{W_{\text{prototype}}} \]

(Cunningham & Morley)
The height and length of the model are then determined using the model scale factor.

**Wave Scaling**

In varying the ocean wavelength vs. WECS barge length, only one variable will be adjusted. Since varying the scaled WECS barge length requires the construction of multiple models, the scaled ocean wavelength will be varied. Determining the wavelength of ocean waves can be quite complex and in order to describe their wavelength and motion, linear wave theory can be applied. Linear wave theory gives a reasonable approximation of wave characteristics and a range of wave parameters. Due to the dispersion relation, a reasonable wavelength can be determined in linear wave theory, using the assumption of deepwater. The assumption of deepwater can be assumed if the water depth is at least half the wavelength. “There is a very good approximation for the wavelength given the water depth and wave period that does not require numerical iteration due to Fenton and McKee (1989) as quoted by Fenton, The Sea, vol. 9, A, 1990.”

\[
\lambda = \frac{g \cdot T^2}{2 \cdot \pi} \left( \text{tanh} \left( \frac{h \cdot \left( \frac{2 \cdot \pi \cdot T^2}{g} \right)^{\frac{3}{4}}}{\frac{3}{2}} \right) \right)
\]

The water depth (h) and period (T) of the model testing are the only variables that can be varied, given that we are unable to manipulate gravity (g). Since the apparatus’ position does not vary greatly relative to the coastline, the water depth is assumed to be constant, thus h is constant. To vary the wavelength in the model testing, only the period will be varied. The waves were scaled to those of typical waves from the proposed operation site. The scaled wave height was determined using the ratio of wave height divided by wavelength. Scaling time required the use of a different scale factor. The scaled period was calculated from the following equation:

\[
\eta_T \equiv \frac{T_{\text{model}}}{T_{\text{prototype}}} = \eta_L^{1/2}
\]

**Power Output Experiment**

The expected outcome of this experiment is to find the efficiency of the WECS system vs. ocean wavelength divided by the WECS overall barge length. Doing so will allow the apparatus to maximize the energy extracted from the waves. The efficiency is defined as power output of the system divided by the wave power available.

3 (Dalrymple)
\[ \varepsilon = \frac{P_s}{P_w} \]

\( \varepsilon \) is the efficiency of the system, \( P_s \) is the power in the system, and \( P_w \) is the wave power available to the pontoon over a crest width equal to the beam of the pontoon. If this value is determined to be greater than one, diffractive wave focusing has occurred. This is, when the power obtained by the WECS barge is greater than the energy in the wave the same width of the barge. In McCormick’s experiments, he found values reaching up to 1.6 as seen below.

These experiments never found the peak value of the efficiency, plotted versus the wavelength to system length ratio. By finding this point, the maximum energy extracted by the WECS is determined. Testing the model efficiency requires the system power as well as the wave power. Measuring the system power could be achieved by using a hydraulic cylinder placed between a single barge and a carriage. The barge pivots against a towing tank carriage, displacing the hydraulic cylinder. The flow rate and pressure produced by the cylinder are measured. The power in the system, \( P_s \), is determined by:

\[ P_s = P_t + P_p \]

\( P_t \) is the threshold power, this is the minimum power that had to be overcome before the pump was activated. \( P_p \) is the system power from the pump. The pumping power can be described by:

\[ P_p = p \ast Q \]

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4 (McCormick, Murtagh, & McCabe, 1998)
where \( p \) is the pumping pressure from the hydraulic cylinder, \( Q \) is the flow rate.

The available wave power, \( P_w \), is the amount of energy incident upon the WECS:

\[
P_w = \frac{\rho \cdot g \cdot H^2 \cdot C_g \cdot B}{8}
\]

\( \rho \) is the mass-density of water, \( g \) is the gravitational acceleration, \( B \) is the beam of the WECS, \( H \) is the wave height, and \( C_g \) is the group velocity of the waves. The group velocity, \( C_g \), can be approximated by the deep-water depth. The water depth must be greater than half that of the wavelength of the waves in order for the expression to be true for the group velocity:

\[
C_g = \frac{g \cdot T}{4 \cdot \pi}
\]

For this experiment, the technician will measure wave heights, pump pressures, and pump flow rates from the model while adjusting the period to gather the necessary data. In the experimental spreadsheet supplied to these technicians, the power ratio and efficiency from are calculated and plotted. At this point a peak value should emerge and the optimum ratio is known. This data should be studied to determine if the current WECS system has sufficient amplification in comparison to the power that could be extracted from the waves.

**Submergence Testing Experiment**

Submergence testing is intended to develop a method in which the WECS will have a greater chance of survival in severe weather. The mechanism would move the WECS out of the most destructive part of the wave, submerging the entire system. The system is designed to survive a storm with waves reaching a height of 14m and a wave period of 15 seconds.\(^5\) The further an object is submergent, the greater the reduction in total vertical travel the object is subjected to, thus increasing the survivability, as seen below.

![Figure 3: Orbital Wave Motion\(^6\)](image)

A scaled model can be developed and tested at the IIT-Kharagpur facility. In sizing the model, the scale factor is generated while keeping in mind that the depth of the facility must be greater than half of the wavelength, or the waves will be affected by the bottom of the facility.

\(^5\) (Wu, 2003)
\(^6\) (Zimmer)
The volume above the water level is the volume of water that the barge needs to be filled with to create neutral buoyancy. With the new scaled model, the volume of each barge needs to be calculated, as well as the volume of the barges both above and below the water level in order to enter a submerged state (Figure 5) from normal operation mode (Figure 4) when the tanks are flooded.

There have been discussions about the center barge being left unfilled with water and it being pulled downward by a tethered mass when the outside barges are flooded by water when entering its submerged state. In doing this, the barge system will be slightly buoyant, allowing it to be submerged while preventing it from coming into contact with the ocean floor thus maximizing the depth the WECS when submerged. This will further reduce the forces on the system in severe weather, as shown in Figure 3. The tethered weight should be a bit heavier than needed in order to pull the system down when the volume above the water level is filled. The length between the sea level and the WECS barges is the submergence depth in Figure 6 and 7.

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7 (Zimmer)
8 (Zimmer)
The entire system (The forward barge, center barge, aft barge, and tethered mass) can be simplified into the following free body diagram:

\[
0 = (M_{\text{Barge}} + M_{\text{Weight}} - \rho \cdot V_{\text{Below Waterline}}) \cdot g
\]

To create a neutrally buoyant system, the flooded volume of the barges needs to be equal to the volume of water above the waterline in the floating state. To cause this system sink a volume greater than the neutrally buoyant volume needs to be flooded.

The whole submerged barge system, including the hanging weight, can be described by:
\[ 0 = (M_{\text{Barge}} + M_{\text{Weight}} - \rho \cdot [V_{\text{BelowWaterline}} + V_{\text{AboveWaterline}} - V_{\text{Flooded}}] - M_{\text{Weight}} \cdot \#\%) \cdot g \]

The percentage of the tethered weight is the force maintaining the WECS’s depth in severe weather and currents when submerged. As long as the force from the mass does not exceed the buoyant force of the system in operating state, the mass is acceptable.

The following can be derived from the previous two equations:

\[ V_{\text{Flooded}} = \frac{M_{\text{Weight}} \cdot \#\%}{\rho} + V_{\text{AboveWaterline}} \]

This is the volume required to be flooded to meet the desired specifications. This achieves a submerged state of the overall system and a positively buoyant barge system, accomplishing the desired submergence attributes. A spreadsheet will be supplied to the technicians at IIT-Kharagpur that when the scaled models dimensions are inputted, the necessary flooded volume is calculated.

After the volume calculations and mass calculations are completed, the size of an insert that must go in each barge is calculated. The insert will be a partitioned air or foam filled area in the barges so that it will not be filled up when the barge releases its air while in a submerged state. Solid model replicas of the barges are created and the sizes are calculated.

![Figure 9: Barge Cross-section](image)

Using the solid modeling, all of the unknown dimensions are found. An insert was developed with a design that had a top slope deemed suitable for water to run off so that the majority of the water will flow towards the exit valve when pressuring the barges into an operating state. The intent of the insert is a failsafe from over-flooding should something malfunction with the valves or air supply, potentially making the WECS an anchor.
Conclusion

In the ocean wavelength versus WECS barge length testing, the results should be studied to determine if the experimental WECS system has a sufficient amplification gain over the existing design to justify the costs of a redesign. In the submergence testing, no data needs to be recorded as it is mostly a test of feasibility. Should the proposed submergence system be deemed suitable, the WECS system should be scaled up and tested in more real world conditions before being implemented in the production WECS. If it is not suitable, other submergence methods should be developed and researched, otherwise the high risk of catastrophic failure in inclement weather make it a high risk venture.
Works Cited


## Construction Summary

### Forward Barge

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of Model</td>
<td>0.071 m</td>
</tr>
<tr>
<td>Length of Model - End to End</td>
<td>0.1278 m</td>
</tr>
<tr>
<td>Length of Model Bottom</td>
<td>0.1136 m</td>
</tr>
<tr>
<td>Height of Model</td>
<td>0.03195 m</td>
</tr>
</tbody>
</table>

### Forward Barge Inner Construction

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>0.0986 m</td>
</tr>
<tr>
<td>Width</td>
<td>0.069 m</td>
</tr>
<tr>
<td>Height</td>
<td>0.01573562 m</td>
</tr>
<tr>
<td>Inner Construction Incline</td>
<td>3 degrees</td>
</tr>
<tr>
<td>Metal Thickness</td>
<td>0.001 m</td>
</tr>
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</table>

### Center Barge

<table>
<thead>
<tr>
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<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Width of Model</td>
<td>0.071 m</td>
</tr>
<tr>
<td>Length of Model</td>
<td>0.0426 m</td>
</tr>
<tr>
<td>Height of Model</td>
<td>0.03195 m</td>
</tr>
<tr>
<td>Weight To Sink Center Barge</td>
<td>0.03221199 kg</td>
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</tbody>
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### After Barge

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<tr>
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<th>Value</th>
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<tbody>
<tr>
<td>Width of Model</td>
<td>0.071 m</td>
</tr>
<tr>
<td>Length of Model</td>
<td>0.142 m</td>
</tr>
<tr>
<td>Height of Model</td>
<td>0.03195 m</td>
</tr>
</tbody>
</table>

### Forward Barge Inner Construction

<table>
<thead>
<tr>
<th></th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>0.0986 m</td>
</tr>
<tr>
<td>Width</td>
<td>0.069 m</td>
</tr>
<tr>
<td>Height</td>
<td>0.01573562 m</td>
</tr>
<tr>
<td>Inner Construction Incline</td>
<td>3 degrees</td>
</tr>
<tr>
<td>Metal Thickness</td>
<td>0.001 m</td>
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</tbody>
</table>
System Verification Model

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
<th>Units</th>
<th>Additional Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width of Model</td>
<td>0.25 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of Model</td>
<td>0.425 m</td>
<td></td>
<td>From water line to water line</td>
</tr>
<tr>
<td>Length of Model - End to End</td>
<td>0.45 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Height of Model</td>
<td>0.0875 m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ballast Position</td>
<td></td>
<td></td>
<td>At present time, ballast position is unknown</td>
</tr>
</tbody>
</table>

Other notes:

Without solving for the wavelengths in the system, at the moment we are unsure if the current model values are...
be valid for the given testing facility
function simnew4(t,xy,shu)

    global sim1;

    x1=xy(1);
    z1=xy(7);
    o1=xy(13);
    x2=xy(3);
    z2=xy(9);
    o2=xy(15);
    x3=xy(5);
    z3=xy(11);
    o3=xy(17);

    k=6.28/56.19;
    w=6.28/6;
    xcos=[-12:0.01:35];
    zcos=0;
    xwave=xcos;
    zwave= 0.5*cos(k.*xcos-w*t);

    x0new1= [0:0.001:8.25];
    z0new1=1;
    r1=sqrt((x0new1.^2)+(z0new1.^2));
    alpha1=atan(z0new1./x0new1);
    x1newup= x1+r1.*cos(alpha1-o1);
    z1newup=z1+r1.*sin(alpha1-o1);

    x0new2=[-7.25:0.001:-0.01];
    z0new2=1;
    r2=sqrt((x0new2.^2)+(z0new2.^2));
    alpha2=atan(z0new2./x0new2);
    x1newdown= x1-r2.*cos(alpha2+o1);
    z1newdown=z1+r2.*sin(alpha2+o1);

    x0new1a= [0:0.001:7.25];
    z0new1a=-1;
    r1a=sqrt((x0new1a.^2)+(z0new1a.^2));
    alpha1a=atan(z0new1a./x0new1a);
    x1anewup= x1+r1a.*cos(alpha1a-o1);
    z1anewup=z1-r1a.*sin(alpha1a-o1);

    x0new2a=[-7.25:0.001:-0.01];
z0new2a=-1;
r2a=sqrt((x0new2a.^2)+(z0new2a.^2));
alpha2a=atan(z0new2a./x0new2a);
x1anewdown= x1-r2a.*cos(alpha2a-o1);
z1anewdown=z1-r2a.*sin(alpha2a-o1);

%%%%%% First Barge left side
x0new1b=-7.25 ;
z0new1b=[0.01:0.001:1] ;
r1b=sqrt((x0new1b.^2)+(z0new1b.^2));
alpha1b=atan(-z0new1b./x0new1b);
x1leftup= x1-r1b.*cos(alpha1b+o1);
z1leftup=z1+r1b.*sin(alpha1b+o1);

x0new2b=-7.25 ;
z0new2b=[-1:0.001:-0.01] ;
r2b=sqrt((x0new2b.^2)+(z0new2b.^2));
alpha2b=atan(z0new2b./x0new2b);
x1leftdown= x1-r2b.*cos(alpha2b-o1);
z1leftdown=z1-r2b.*sin(alpha2b-o1);

%%%%%% First Barge Right Side
x0new1c=7.25 ;
z0new1c=[0.01:0.001:1] ;
r1c=sqrt((x0new1c.^2)+(z0new1c.^2));
alpha1c=atan(z0new1c./x0new1c);
x1rightup= x1+r1c.*cos(alpha1c-o1);
z1rightup=z1+r1c.*sin(alpha1c-o1);

x0new2c=7.25 ;
z0new2c=[-1:0.001:0.01] ;
r2c=sqrt((x0new2c.^2)+(z0new2c.^2));
alpha2c=atan(-z0new2c./x0new2c);
x1rightdown= x1+r2c.*cos(alpha2c+o1);
z1rightdown=z1-r2c.*sin(alpha2c+o1);

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%% Second barge
x0new3=[0:0.001:4.3];
z0new3=1.5;
%z0new1=[-1:0.001:1];
r3=sqrt((x0new3.^2)+(z0new3.^2));
alpha3 = atan(z0new3./x0new3);
x2newup = x2 + r3.*cos(alpha3 - o2);
z2newup = z2 + r3.*sin(alpha3 - o2);

x0new4 = [-4.3:0.001:-0.01];
z0new4 = 1.5;
r4 = sqrt((x0new4.^2) + (z0new4.^2));
alpha4 = atan(-z0new4./x0new4);
x2newdown = x2 - r4.*cos(alpha4 + o2);
z2newdown = z2 + r4.*sin(alpha4 + o2);

%%%%%%% second barge down part

x0new3a = [0:0.001:3.3];
z0new3a = -1.5;
% z0new1 = [-1:0.001:1];
r3a = sqrt((x0new3a.^2) + (z0new3a.^2));
alpha3a = atan(z0new3a./x0new3a);
x2anewup = x2 + r3a.*cos(alpha3a - o2);
z2anewup = z2 + r3a.*sin(alpha3a - o2);

x0new4a = [-3.3:0.001:-0.01];
z0new4a = 1.5;
r4a = sqrt((x0new4a.^2) + (z0new4a.^2));
alpha4a = atan(-z0new4a./x0new4a);
x2anewdown = x2 - r4a.*cos(alpha4a + o2);
z2anewdown = z2 + r4a.*sin(alpha4a + o2);

%%%%%%% Second Barge left side

x0new3b = -3.3;
z0new3b = [0.01:0.001:1.5];
r3b = sqrt((x0new3b.^2) + (z0new3b.^2));
alpha3b = atan(-z0new3b./x0new3b);
x2leftup = x2 - r3b.*cos(alpha3b + o2);
z2leftup = z2 + r3b.*sin(alpha3b + o2);

x0new4b = -3.3;
z0new4b = [-1.5:0.001:-0.01];
r4b = sqrt((x0new4b.^2) + (z0new4b.^2));
alpha4b = atan(z0new4b./x0new4b);
x2leftdown = x2 - r4b.*cos(alpha4b - o2);
z2leftdown = z2 - r4b.*sin(alpha4b - o2);

%%%%%%% Second Barge Right Side

x0new3c = 3.3;
z0new3c = [0.01:0.001:1.5];
r3c = sqrt((x0new3c.^2) + (z0new3c.^2));
\[ \alpha_{3c} = \text{atan}(z_{0new3c} / x_{0new3c}); \]
\[ x_{2 \text{rightup}} = x_2 + r_{3c} \cdot \cos(\alpha_{3c} - o_2); \]
\[ z_{2 \text{rightup}} = z_2 + r_{3c} \cdot \sin(\alpha_{3c} - o_2); \]
\[ x_{0new4c} = 3.3; \]
\[ z_{0new4c} = [-1.5:0.001:0.01]; \]
\[ r_{4c} = \sqrt{(x_{0new4c}^2) + (z_{0new4c}^2)}; \]
\[ \alpha_{4c} = \text{atan}(-z_{0new4c} / x_{0new4c}); \]
\[ x_{2 \text{rightdown}} = x_2 + r_{4c} \cdot \cos(\alpha_{4c} + o_2); \]
\[ z_{2 \text{rightdown}} = z_2 - r_{4c} \cdot \sin(\alpha_{4c} + o_2); \]

% Third barge
\[ x_{0new5} = [0:0.001:7.25]; \]
\[ z_{0new5} = 1; \]
\[ r_{5} = \sqrt{(x_{0new5}^2) + (z_{0new5}^2)}; \]
\[ \alpha_{5} = \text{atan}(z_{0new5} / x_{0new5}); \]
\[ x_{3 \text{newup}} = x_3 + r_{5} \cdot \cos(\alpha_{5} - o_3); \]
\[ z_{3 \text{newup}} = z_3 + r_{5} \cdot \sin(\alpha_{5} - o_3); \]
\[ x_{0new6} = [-8.25:0.001:-0.01]; \]
\[ z_{0new6} = 1; \]
\[ r_{6} = \sqrt{(x_{0new6}^2) + (z_{0new6}^2)}; \]
\[ \alpha_{6} = \text{atan}(-z_{0new6} / x_{0new6}); \]
\[ x_{3 \text{newdown}} = x_3 - r_{6} \cdot \cos(\alpha_{6} + o_3); \]
\[ z_{3 \text{newdown}} = z_3 + r_{6} \cdot \sin(\alpha_{6} + o_3); \]

% Third barge down part
\[ x_{0new5a} = [0:0.001:7.25]; \]
\[ z_{0new5a} = -1; \]
\[ r_{5a} = \sqrt{(x_{0new5a}^2) + (z_{0new5a}^2)}; \]
\[ \alpha_{5a} = \text{atan}(-z_{0new5a} / x_{0new5a}); \]
\[ x_{3 \text{anewup}} = x_3 + r_{5a} \cdot \cos(\alpha_{5a} + o_3); \]
\[ z_{3 \text{anewup}} = z_3 - r_{5a} \cdot \sin(\alpha_{5a} + o_3); \]
\[ x_{0new6a} = [-7.25:0.001:-0.01]; \]
\[ \begin{align*}
z0new6a &= -1; \\
r6a &= \sqrt{(x0new6a^2) + (z0new6a^2)}; \\
alpha6a &= \tan(z0new6a / x0new6a); \\
x3anewdown &= x3 - r6a \cdot \cos(\alpha6a - o3); \\
z3anewdown &= z3 - r6a \cdot \sin(\alpha6a - o3); \\
\end{align*} \]

%%%%%% Third Barge left side 
\begin{align*}
x0new5b &= -7.25; \\
z0new5b &= [0.01:0.001:1]; \\
r5b &= \sqrt{(x0new5b^2) + (z0new5b^2)}; \\
alpha5b &= \tan(z0new5b / x0new5b); \\
x3leftup &= x3 - r5b \cdot \cos(\alpha5b + o3); \\
z3leftup &= z3 + r5b \cdot \sin(\alpha5b + o3); \\
\end{align*} 

\begin{align*}
x0new6b &= -7.25; \\
z0new6b &= [-1:0.001:-0.01]; \\
r6b &= \sqrt{(x0new6b^2) + (z0new6b^2)}; \\
alpha6b &= \tan(z0new6b / x0new6b); \\
x3leftdown &= x3 - r6b \cdot \cos(\alpha6b - o3); \\
z3leftdown &= z3 - r6b \cdot \sin(\alpha6b - o3); \\
\end{align*} 

%%%%%% Third Barge Right Side 
\begin{align*}
x0new5c &= 7.25; \\
z0new5c &= [0.01:0.001:1]; \\
r5c &= \sqrt{(x0new5c^2) + (z0new5c^2)}; \\
alpha5c &= \tan(z0new5c / x0new5c); \\
x3rightup &= x3 + r5c \cdot \cos(\alpha5c - o3); \\
z3rightup &= z3 + r5c \cdot \sin(\alpha5c - o3); \\
\end{align*} 

\begin{align*}
x0new6c &= 7.25; \\
z0new6c &= [-1:0.001:0.01]; \\
r6c &= \sqrt{(x0new6c^2) + (z0new6c^2)}; \\
alpha6c &= \tan(-z0new6c / x0new6c); \\
x3rightdown &= x3 + r6c \cdot \cos(\alpha6c + o3); \\
z3rightdown &= z3 - r6c \cdot \sin(\alpha6c + o3); \\
\end{align*} 

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% Connecting Rod 
\begin{align*}
x0rod &= -0.01; \\
z0rod &= [-8:0.001:-1.5]; \\
rrod &= \sqrt{(x0rod^2) + (z0rod^2)}; \\
alpharod &= \tan(z0rod / x0rod); \\
\end{align*} 

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
x2rod= x2-rrod.*cos(alpharod-o2);
z2rod=z2-rrod.*sin(alpharod-o2);

%%%% Inertial Plate
x0plate1=[0.01:0.001:4.5];
z0plate1= -8 ;
r1plate=sqrt((x0plate1.^2)+(z0plate1.^2));
alpha1plate=atan(-z0plate1./x0plate1);
x1plate= x2+r1plate.*cos(alpha1plate+o2);
z1plate=z2-r1plate.*sin(alpha1plate+o2);

x0plate2=[-4.5:0.001:-0.01];
z0plate2=-8;
r2plate=sqrt((x0plate2.^2)+(z0plate2.^2));
alpha2plate=atan(z0plate2./x0plate2);
x2plate= x2-r2plate.*cos(alpha2plate-o2);
z2plate= z2-r2plate.*sin(alpha2plate-o2);

asd=mod(shu,2);

%if shu>400
%if (asd==0)

figure(9);              %figure(shu);
plot(x1newup,z1newup,'b',x1newdown,z1newdown , 'b', x2newup,z2newup, 'b',
x2newdown,z2newdown, 'b', x3newup,z3newup, 'b',
x3newdown,z3newdown,'b', .......
x1anewup,z1anewup , 'b', x1anewdown,z1anewdown , 'b', x2anewup,z2anewup,
' b', x2anewdown,z2anewdown, 'b', x3anewup,z3anewup,'b',
x3anewdown,z3anewdown , 'b', .......
x1leftup,z1leftup , 'b', x1leftdown,z1leftdown , 'b', x2leftup,
z2leftup , 'b', x2leftdown,z2leftdown , 'b', x3leftup, z3leftup , 'b',
x3leftdown,z3leftdown , 'b', .......
x1rightup, z1rightup , 'b', x1rightdown, z1rightdown , 'b', x2rightup,
z2rightup , 'b', x2rightdown,z2rightdown, 'b', x3rightup,z3rightup , 'b',
x3rightdown, z3rightdown, 'b', .......
x2rod, z2rod, 'b', x1plate,z1plate , 'b', x2plate,z2plate , 'b' ,
xcos,zwave , 'b' );

%plot(xy(1),xy(7),'*');
axis([-12 35 -10 3]);   % axis([-12 35 -22 22]);
%axis off;

%end
%end
%sim1(shu)=getframe; check structure
%movie(sim1);

simnew=0;