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OCEAN CURRENT POWER GENERATOR

FINAL REPORT
For the Period June 2001 - June 2002

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SUMMARY

The Ocean Power Generator as researched and developed under the U S Department of Energy SBIR Grant is both technically and economically feasible for deployment in the Gulf Stream off the southeastern coast of Florida. The U S Navy South Florida Test Facility at Dania, Florida, has been identified as the ideal location for a prototype installation, which will be 17 km east of Dania where the water velocity is relatively constant. William Venezia, Ph.D., prepared a site evaluation plan as part of the Phase I effort, and the Oceanography report of Thomas Lee, Ph.D., University of Miami, addresses the problems of installation at Dania. Both of these reports are summarized in Section 5. of this report.

The present status of the Phase II work is that all of the research and design is complete, and the electronic assemblies, speed increaser gears, and alternators are built and tested. UEK Corporation, subcontractor for the Underwater Electric Kite (UEK™), has completed most of the fiberglass components and has received all of the purchased components and parts. To be completed are the remaining fiberglass parts, painting, assembly and factory test.

To complete the Phase II tasks, the prototype dual hydroturbine UEK with the Abacus Controls Inc Transmission Regulator on board will be launched in the harbor at Baltimore, Maryland, for calibration testing in the Chesapeake Bay. By pulling the UEK behind a tug boat with a 600' tether, a complete set of curves for variable water velocity and variable electric load will verify that the UEK and the Abacus electronics can provide the calculated power. The cost to complete the prototype manufacturing and perform the tests in Chesapeake Bay is $127,837.

Early in the Phase II program it was determined that a lift force is necessary to maintain the Ocean Power Generator at a desired depth. In order to accomplish this lift, a redesign of the underwater vessel was undertaken that incorporated ballast tanks as an integral part of the design. The tanks form pontoons that also provide stability in the direction of water flow as well as in the vertical plane. By including four hydroturbines, the power is doubled to 240 kW at the vessel and 200 kW on shore. Doubling the power virtually cut the cost of the cable installation in half.

One of the technical benefits from the SBIR Grant is the invention of a method for extracting the maximum power from flowing water. By transmitting flow and power information over the same two wires that transmit power to shore at a regulated 5000 Vdc, the Abacus Turboverter®, an inverter that inserts three phase ac power into the utility grid, computes and delivers the maximum power available from the hydroturbines operating in the existing water flow.

The projected cost for a 10 MW installation consisting of 200 Ocean Power Generators is $33.8 million or $3.38 per watt. Following the price history of wind energy after ten to twenty years development and product improvement, the price by the year 2012 can conservatively be expected to be below $1.40 per watt. The Gulf Stream flows reliably 24 hours per day, and water flow is environmentally and ecologically the most attractive of the renewable energy sources. No real estate is required, a consideration often ignored when costing other energy sources. You cannot see, hear, smell or touch an Ocean Power Generator. And little fish can easily swim between the slow moving blades (16 rpm).

ABSTRACT

The Ocean Power Generator is both technically and economically suitable for deployment in the Gulf Stream from the U S Navy facility in Dania, Florida. Yet to be completed is the calibration test in the Chesapeake Bay with the prototype dual hydroturbine Underwater Electric Kite. For the production units a revised design includes two ballast tanks mounted as pontoons to provide buoyancy and depth control. The power rating of the Ocean Power Generator has been doubled to 200 kW ready for insertion into the utility grid.

The projected cost for a 10 MW installation is $3.38 per watt, a cost that is consistent with wind power pricing when it was in its deployment infancy, and a cost that is far better than photovoltaics after 25 years of research and development. The Gulf Stream flows 24 hours per day, and water flow is both environmentally and ecologically perfect as a renewable energy source. No real estate purchases are necessary, and you cannot see, hear, smell or touch an Ocean Power Generator.

1. INTRODUCTION

The Phase II Project as originally proposed and renegotiated from $750,000 to $700,000 was not completed as planned. Shortly after the project started, William Venezia, engineer with the U. S. Navy at the South Florida Test Facility in Dania, Florida, who performed the site selection work and consulted on the mechanical design during Phase I, pointed out to the Principal Investigator that the UEK vessel requires a vertical force to maintain a constant depth and a ballast vessel or some other source for a lift force is necessary. There was no allowance for this in the Phase I design or the Phase II Proposal.

The magnitude of the vertical force changes with the angle of the vertical position with respect to the anchor and with the drag force on the UEK, which in turn has two components, the first due to the resistance to the amplitude of the Gulf Stream velocity and the second due to the mechanical equivalent of the electric power generated by the hydroturbines, speed increaser gears and alternators. With reference to drawing 45534 in Section 4.1 below, the lift force equals the drag force times the tangent of the angle between the tether and the true horizontal, and the stress force on the tether is equal to the drag force divided by the cosine of the same angle.

The work completed in Phase II is described below in **4. PROJECT OBJECTIVES AND RESULTS OBTAINED.** These include all of the systems and electronic design, electronic manufacturing and test results that prove that the prototype equipment is ready for the Chesapeake Bay tests. Basically, the remaining work is the completion of the UEK manufacturing and the Chesapeake Bay tests. These are described in the next Section, 1.1.

After learning that a ballast force must be added to the underwater power generator, a conceptual design for a Phase III effort was added to the scope of work because it was realized that simplicity of design and the economics of manufacture dictated that the ballast tank should be integral to the Ocean Power Generator. This design is illustrated in **2. TECHNICAL FEASIBILITY** and supported in **3. ECONOMIC FEASIBILITY.**

The important site location work completed by Dr. Thomas Lee of the University of Miami and Dr. William Venezia of the U.S. Navy in Phase I is included in **5. SITE LOCATION** so that this report presents the total program effort.

1.1 - Completion of Phase II

Philippe Vauthier, President of UEK Corporation, will manage the completion of the Phase II tasks. UEK Corporation has performed the manufacturing of all tooling necessary to complete its assignment in this program and is in the middle of the parts production. Some of the subassemblies have been completed and are ready for finishing and painting. The work to be completed includes:

1. Complete fabrication of UEK fiberglass parts
2. Assemble metal canisters with speed increaser gears, alternators and Abacus Transmission Regulator

3. Prepare assemblies for deployment in the Chesapeake Bay from a launch site in Baltimore
4. Prepare test vessel for Chesapeake Bay tests
5. Perform calibration tests in the Chesapeake Bay
6. Analyze test results and write test report

While an improved design is recommended for ocean deployment, completion of the Chesapeake Bay tests is important because the test results will provide calibration data on the 22 feet diameter hydroturbine and prove the overall concept of the underwater Ocean Power Generator. The present hydroturbine design, which is central to the mechanical design completed under the SBIR Grant, will be used in the four hydroturbine design described below. UEK Corporation will again be the major subcontractor for both the design and manufacture of the underwater vessel.

The cost to complete the design and perform the Chesapeake Bay tests is $127,837. This is a small additional effort after the U.S. Department of Energy Grant for Phase I and Phase II was $800,000 and the contribution of Abacus Controls Inc was $8,000 in Phase I and $148,000 in Phase II.

2. TECHNICAL FEASIBILITY

With the addition of the ballast vessel, the proposed Phase II design in its exact configuration is neither technically nor economically feasible. In redesigning into a technically feasible design, it was decided to retain as much of the proposed design as possible without sacrificing the overall objective of achieving an Ocean Power Generator that is reliable, economic, easy to install and can withstand the environment to which it will be subjected.

Given that a lift force is necessary to maintain the power generator at the desired depth, two approaches were considered. The first is to join one or more ballast tanks with mooring to a weight at the bottom of the ocean as an integral part of the hydroturbine assembly. With this design, the need for varying the lift force is eliminated as long as the pull down force of the weight on the bottom exceeds the minimum lift force, which for safety reasons is designed for zero and therefore cannot be a problem.

A second possible design is to use a wing structure for lift. This is the approach followed by Dehlsen in U.S. Patent 6,091,161[1] and by others [2]. Depth control is complicated compared to a ballast tank design. For ocean currents with the velocity in the Gulf Stream, cost of construction and simplicity in control are the deciding factors for Abacus and UEK to choose the integral ballast tank approach. This design approach also follows nature, since fish have ballast for movement in water and birds have wings for movement in air.

Since the cost of installation is high, operating at a higher power level is also a goal for the new design. After extensive studies a catamaran type construction has been selected. Two ballast tanks serve as pontoons for a simple deck plate that holds two hydroturbines above the deck and two hydroturbines below the deck. The power is doubled to 240 kW at the vessel, 200 kW into the utility grid on shore. With this design, the basic UEK hydroturbine design is retained as are the gear assembly, alternator and basic concept for the onboard Transmission Regulator and the shore based electronics.

Figure 1, Ocean Power Generator, shows a front and bottom view. The two ballast tanks provide stability to the vessel during construction, installation and service. Final assembly will be carried out at a boat yard in the harbor at Fort Lauderdale, Florida, where easy access to the Atlantic Ocean exists on several canals. Each of the four hydroturbines, manufactured by UEK, is secured to the deck plate.

Note that the electronic assembly is located in the center under the deck plate and is directly connected to the winch that controls the vessel depth. Connections to the electronic assembly from the four hydroturbines are through fiber glass conduit. Thus, the only connection to the electronic assembly that must withstand water pressure is the power cable, whose multipurpose service is described below.

Figure 2, Section A-A from Figure 1, shows the electronic compartment with the winch for depth control directly underneath. With the electronic compartment separated from the hydroturbine assemblies, the four hydroturbines are symmetrical with two turning clockwise (upper left, lower right) and two turning counterclockwise (upper right, lower left). The hydroturbine designs have been retained from the Phase II program and represent 75% of the mechanical design.

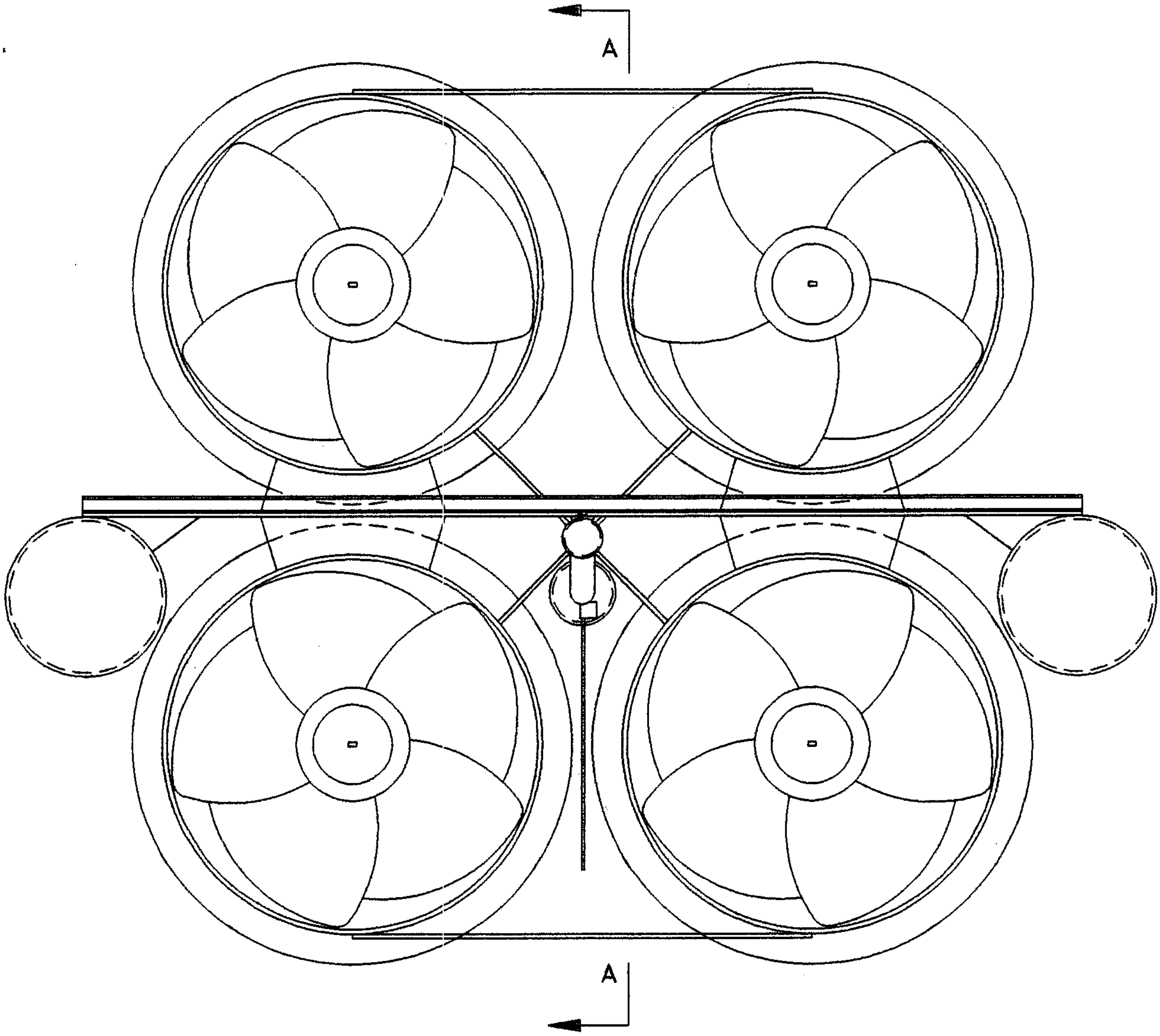
The tether attachment joint is shown in Figure 2. The joint is flexible and permits the Ocean Power Generator to rotate the 11° determined to be the expected tolerance of the water velocity direction as determined in the Oceanography study by Dr. Thomas Lee. See **5. SITE LOCATION** below.

Drawing 45644, Ocean Power Generator, shows the generator installed at 19 km east of Dania, Florida, where the water depth is 300 meters. Note that the center of the upper hydroturbines is set at 25 meters below the surface. Figure 3, Ocean Power Generator with bridle, presents a three dimension view. The ballast tanks provide the stabilizing effect of a catamaran and hold the Ocean Power Generator perpendicular to the water flow.

3. ECONOMIC FEASIBILITY

A detailed cost analysis was performed as part of Task 5, the results of which are reported below in Section **4.5 - Task 5 - Finalize Cost Estimating.** Two conclusions can be drawn: First, the Phase III design is economically feasible and more attractive than the original conceptual design. Second, taking power from the Gulf Stream with the Ocean Power Generator in a 10 MW park is potentially more attractive economically than other renewable energy sources that are receiving large grants and widespread applications.

The detailed cost analysis, the result of Task 5, is also shown on page 8 so that the analysis and conclusions of this section can be better understood.



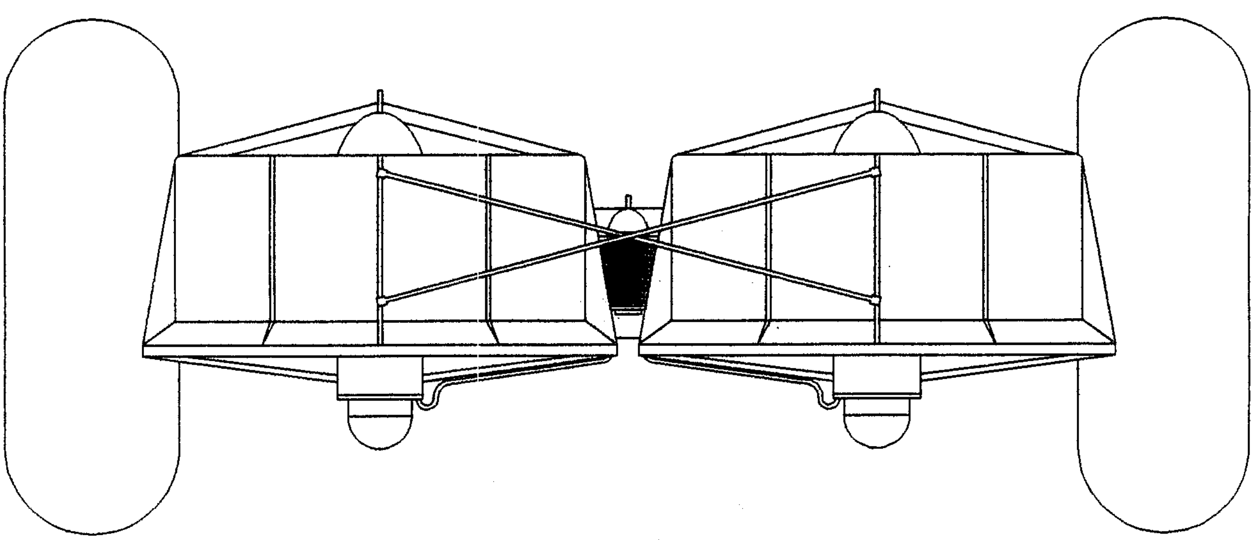
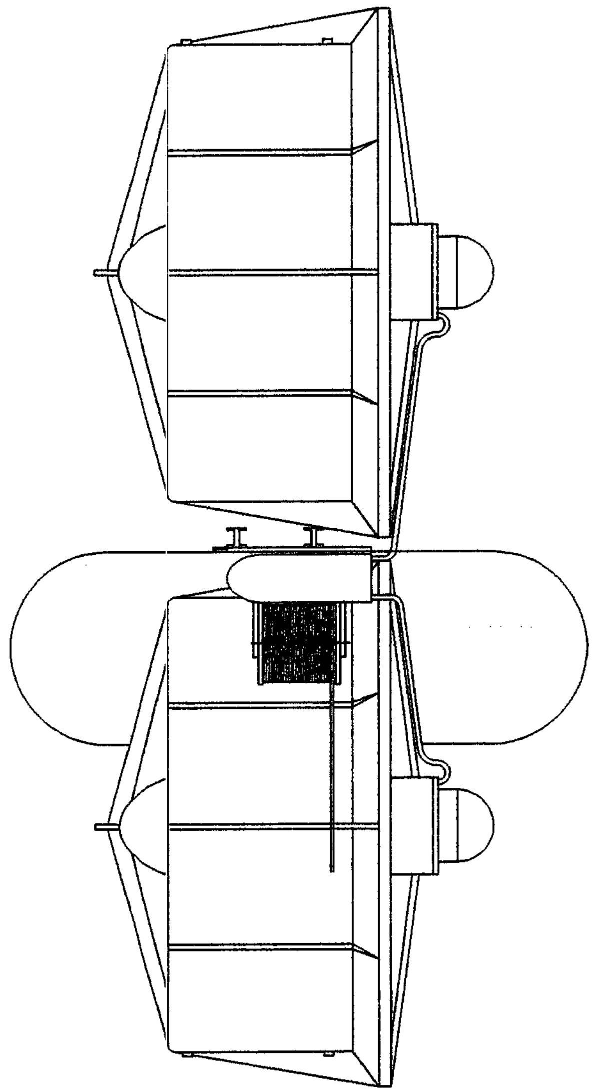
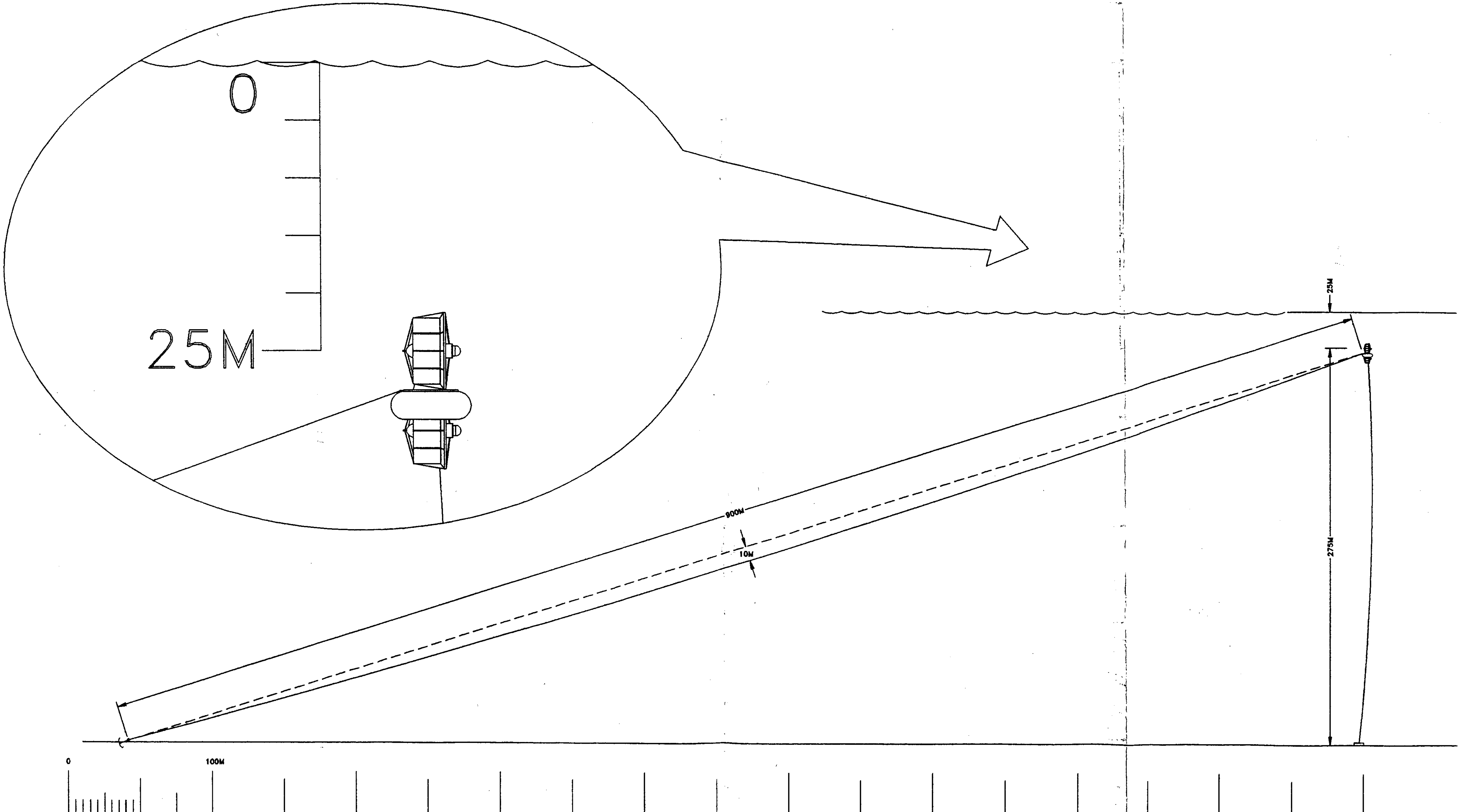


FIGURE 1
OCEAN POWER GENERATOR



SECTION A–A

FIGURE 2
SECTION A–A FROM FIGURE 1



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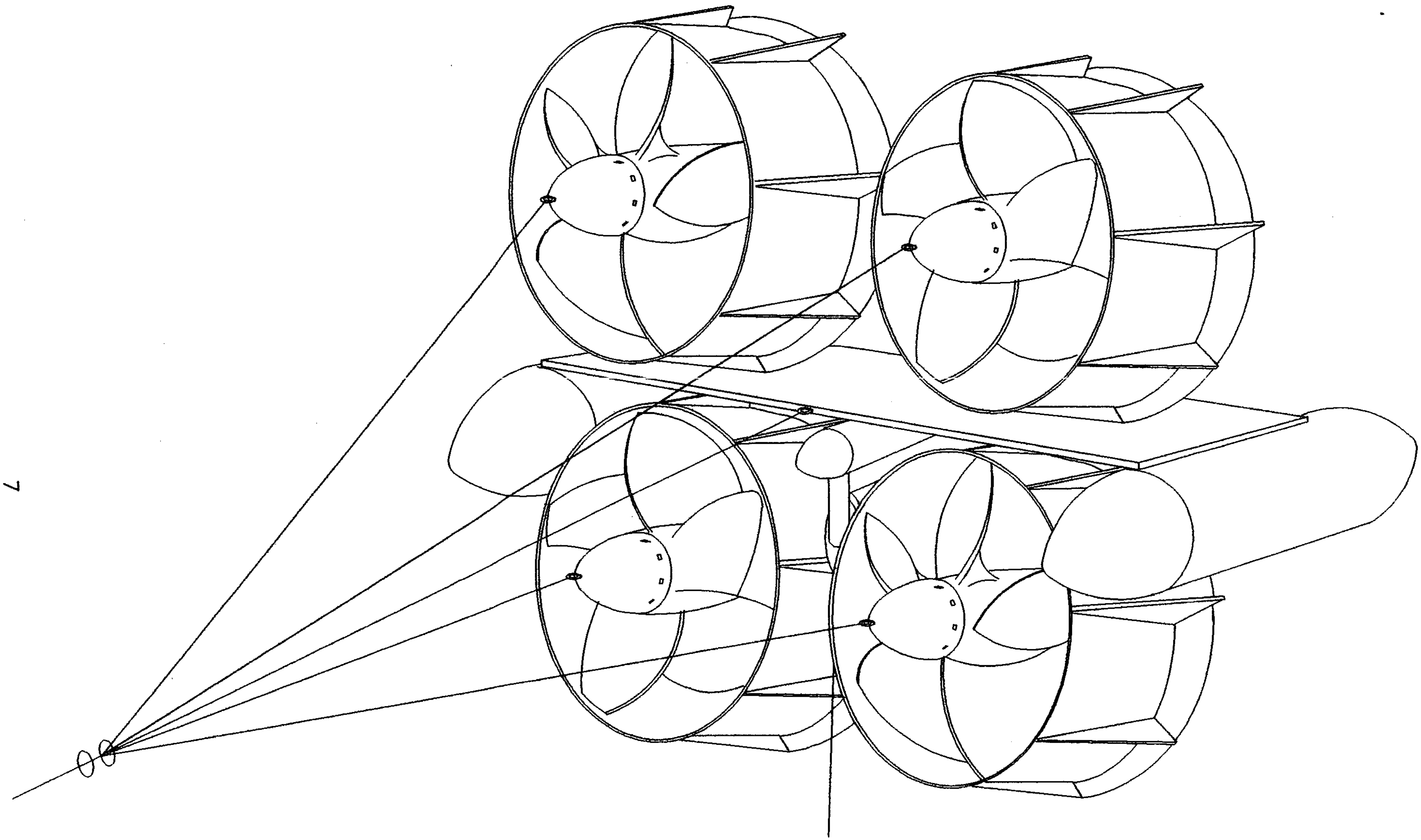


FIGURE 3
OCEAN POWER GENERATOR
WITH BRIDLE

June 14, 2002

OCEAN POWER GENERATOR
COST ANALYSIS
FOR 200 kW, 1 MW, 10 MW

Description	Supplier	Unit cost	Qty	200 kW	Unit Cost	Qty	1 MW	Unit Cost	Qty	10 MW
Hydroturbines	UEK	45,000	4	180,000	41,500	20	830,000	29,800	200	5,960,000
Final Assembly	Abacus & UEK	28,000	1	28,000	25,200	5	126,000	18,900	50	945,000
Ballast tank	Composites USA	34,075	2	68,150	32,710	10	327,100	28,030	100	2,803,000
Gear assembly	Fairfield	19,550	4	78,200	17,250	20	345,000	12,900	200	2,580,000
Alternator	Fisher Electric	18,000	4	72,000	13,000	20	260,000	10,000	200	2,000,000
Transmission Regulator	Abacus	55,000	1	55,000	37,000	5	185,000	21,600	50	1,080,000
Winch assembly	TBD	7,600	1	7,600	6,400	5	32,000	3,900	50	195,000
Anchor and chain	Park City Supply	5,000	1	5,000	4,000	5	20,000	2,900	50	145,000
Tether to anchor	Kulkoni Inc	48,000	1	48,000	43,200	5	216,000	38,000	50	1,900,000
Concrete mooring	TBD	22,000	1	22,000	20,500	5	102,500	18,800	50	940,000
Tether to mooring	Kulkoni Inc	16,000	1	16,000	14,400	5	72,000	12,700	50	635,000
Support items	Misc	5,000	1	5,000	4,500	5	22,500	3,000	50	150,000
Electric cable 15 kV	Oakonite	107,000	1	107,000	6,000	5	30,000	6,000	50	300,000
Electric cable 35 kV	Oakonite				205,000	1	205,000	140,000	10	1,400,000
Ocean central station	Abacus				246,000	1	246,000	124,000	10	1,240,000
Installation - OPG	T BD	18,000	1	18,000	6,000	5	30,000	3,000	50	150,000
Installation - cables 15 kV	TBD	200,000	1	200,000	1,200	5	6,000	1,100	50	55,000
Installation - cables 35 kV	TBD				450,000	1	450,000	110,000	10	1,100,000
Installation - central station	TBD				150,000	1	150,000	55,000	10	550,000
G&A + Profit	Abacus	28% above		326,000	28% above		1,310,000	23% above		5,550,000
Transmission Conv 200 kW	Abacus	44,800	1	44,800						
Tansmission Conv 1 MW	Abacus				178,000	1	178,000	151,000	10	1,510,000
Inverter 200 kW	Abacus	65,600	1	65,600						
Inverter 1 MW	Abacus				289,000	1	289,000	259,000	10	2,590,000
TOTAL				1,346,350			5,432,100			33,778,000
Cost per kW				6,732			5,432			3,378

For the prototype installation, the first of a kind, the cost per watt, ignoring the nonrecurring engineering, is $1,346,350.00 divided by 200,000 watts or $6.73 per watt, a figure now being achieved with photovoltaics (PV) at remote locations after twenty-two years of experience. PV produces electricity on the average of eight hours per day. So, hydropower in the Gulf Stream, which produces twenty-four hours per day, has a three to one advantage, even for the prototype. A PV system requires a battery backup for twenty-four hour service, and is far more costly.[3]

A cluster of five Ocean Power Generators has a total cost of $5,432,100.00 for 1,000,000 watts or $5.43 per watt. At a projected $0.10 per kW hour, the payback for unattended service is 54,300 hours, or allowing three weeks per annum for maintenance, seven years. After seven years, the electricity is free.

A 10 MW Ocean Current Power Generator Park has a total cost of $33,778,000.00 or $3.38 per watt. This is better than wind power was ten years ago when it was in its initial stages of installation. Payback using the three weeks per annum for maintenance is four years two months.

The advantage that hydropower has over PV and wind is that the power is steady and, therefore, can be used as base load twenty-four hours per day. There is a second hidden advantage, and that is that the 10 MW park does not use any real estate, a cost factor conveniently ignored when PV and wind energy are promulgated. The hidden advantage is that the hydropower source is hidden deep in the ocean beneath the shipping lanes where there is no scenic disturbance or land taken from any other use.

With the natural evolution of cost improvements as the volume of production and the addition of innovative technology take place, it can be projected that hydropower will achieve the same cost reductions that have been experienced with wind power.[4] Wind power is now at $1.60 per watt at a multi-megawatt volume. With the proper support, hydropower can have a two-to-one cost reduction and be practical for utility distribution.

Do you like looking at oil rigs? Wind generators on a hill top? Fields of solar panels? Lets get started building hydropower and converting the natural flow of water to ready-to-use electricity!

4. PROJECT OBJECTIVES AND RESULTS OBTAINED

The Phase II Project naturally followed the accomplishments of the Phase I Project with the same team in place. The revised technical specifications are listed below as part of the Work Plan. There are five Project Objectives, and these form the Tasks in the Work Plan.

1. Complete the research on the system design. Subsystems not covered in Phase I are communication between shore and the UEK and the method of extracting maximum power from the UEK.
2. Manage and monitor the subcontract with the UEK Corporation This is subdivided into several tasks.
3. Complete the research and detailed design of the electronic subsystems.
4. Manufacture the onboard and shore based electronics.
5. Continue cost estimates and determine ideal cluster size.

The work plan was divided into five tasks that matched the five project objectives.

4.1 - Task 1 - Complete System Design

The specifications for the system design were established at the conclusion of the Phase I research and development work tasks. These have been modified to accommodate the four hydroturbine design and are restated here as the guide for the Phase III effort.

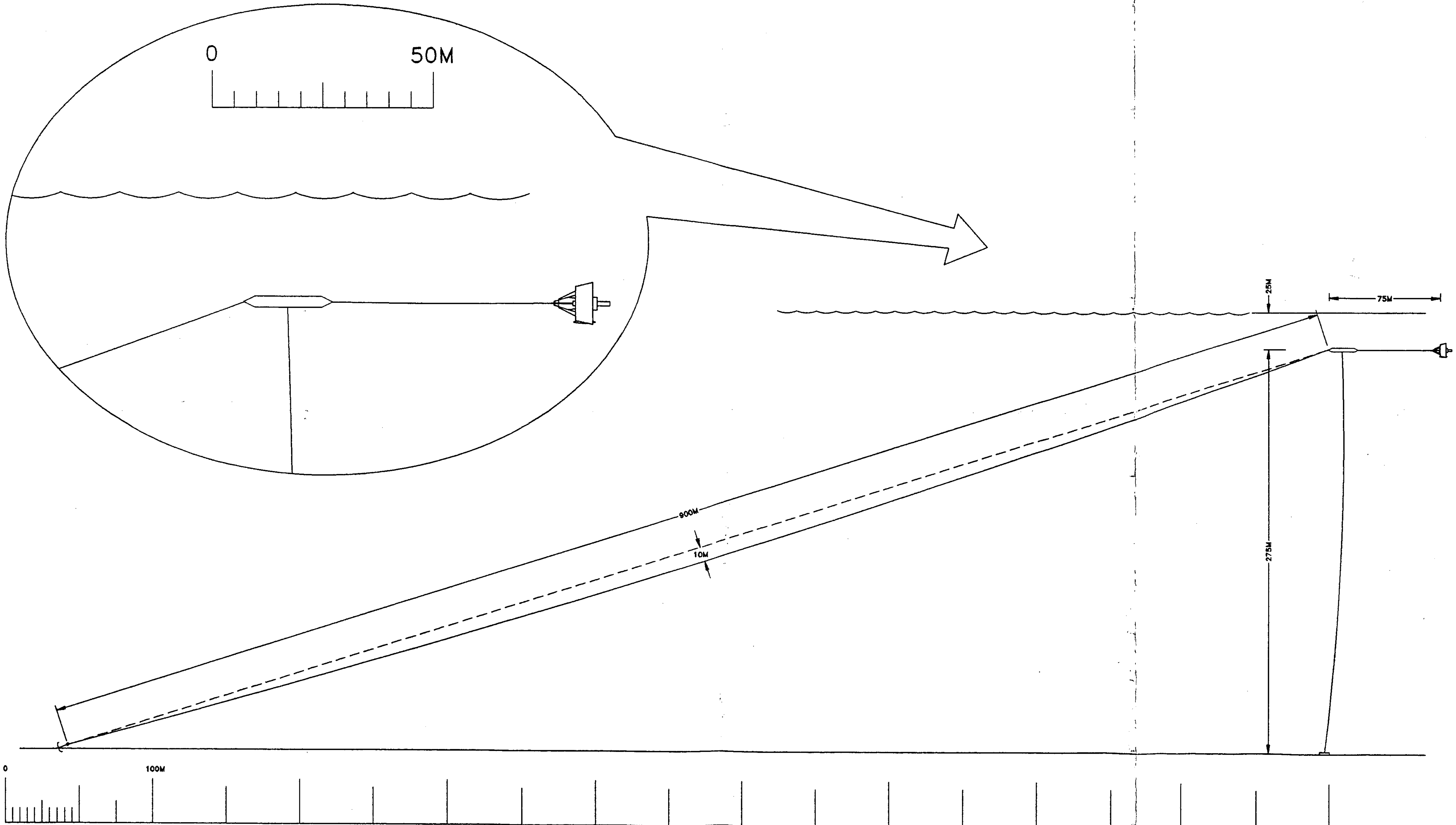
Summary of the critical system design parameters

1. Distance from shore	17 km
2. Depth at selected distance	300 m
3. Operating depth	30 m ± 10 m
4. Transmission voltage	10000 Vdc
5. Cable type	Okoguard 161-23-3069
6. Cable length	20 km
7. Cable resistance	0.315 Ω
8. Tether length	900 m
9. UEK size	46' h x 54' w x 24' 6" d
10. Blade rpm	16.1 rev/min
11. Gear ratio	94:1
12. Brushless alternator power	60 kW each
13. Power delivered to the utility	200 kW
14. Utility voltage	277/480 Vac 60 Hz three phase
15. Turboverter cabinet size	63" h x 46" w x 30" d

A major system design change was the replacement of the Diving Mobile Ballast System with a ballast vessel and simple winch control. The ballast vessel is positioned with a winch and motor; it holds its position with respect to the ocean bottom independent of ocean disturbances and automatically surfaces upon release of a solenoid, its buoyancy force being greater than the ocean forces pulling the UEK downward.

Drawing 45534, Abacus Controls Ocean Current Generator, shows the ocean installation of the UEK trailing 75 meters behind the ballast vessel. The flowing water forces on the symmetrically designed UEK will keep it at the same depth as the ballast vessel and perpendicular to the water flow, thus assuring the production of the maximum power possible.

A 900 meter tether is anchored to the ocean floor and connects to the front of the ballast vessel. A second tether ties the center of the ballast vessel to the ocean floor where it is connected to a heavy concrete weight. The end of the tether at the ballast vessel is on a motor driven drum that is ratcheted down to the desired depth. Releasing the ratchet with a solenoid raises the ballast vessel by allowing the ballast force to unwind the tether on the drum. The ocean depth at the place of installation is approximately 300 meters. A secondary safety advantage of the ballast vessel is that there is little risk that the UEK will ever see a depth, and hence, water pressure, lower than the depth of the ballast vessel.



ABACUS CONTROLS
OCEAN CURRENT GENERATOR
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Communication Subsystem

The communication subsystem is a low frequency information exchange between the UEK and the shore based Turboverter that uses the same two wires as the main power in order to minimize the cost of the cable. From shore to UEK, it is necessary to instruct the vertical position controller to surface when maintenance is required, to dive deeper when a hurricane is expected and to return to normal depth when the hurricane has passed.

From the UEK to shore, it is necessary to inform the Turboverter what the generator frequency is so that the Turboverter can compute the maximum power operating point. Emergency alarms must also be communicated, and these include:

1. water level sensors in each power module housing
2. over-temperature in an alternator
3. over-temperature in a speed increaser
4. over-temperature in the Abacus power converter
5. imbalance in the power from each alternator
6. depth too high
7. depth too low

Details of the modulation technique have been designed and tested in the laboratory at Abacus as reported below under Task 4. The cable resistance, inductance and capacitance were properly simulated in the tests.

Maximum Power Tracking

It is a natural objective in any renewable energy system to extract the maximum possible power from the energy source under all operating conditions. For the UEK, there is a unique relationship between water velocity, alternator frequency and power. Since the Abacus Transmission Regulator located in the UEK holds the output voltage on the cable at 5000 Vdc, the unique relationship also exists between water velocity, alternator frequency and cable current.

By transmitting alternator frequency information in the Communication Subsystem, the maximum power tracker can set the cable current to the maximum power point by means of a lookup table in the Turboverter micro controller. A patent has been applied for and has been duly reported to the U.S. Department of Energy.

4.1.1 - Consultant Reports

Abacus retained Baxley Ocean Visions, Inc. of Hollywood, Florida, to provide calculations and design assistance for the Gulf Stream considerations of the project. William Baxley, P.E., is experienced in underwater vessel design, drag forces and other related mechanical engineering topics. He provided the Principal Investigator with the technical information needed to integrate the components in the system design.

Mr. Baxley's two reports are part of this Final Report in the appendices:

Appendix A - UEK Drag Force Calculations and Project Review
Appendix B - UEK Follow-on System Analysis

The primary conclusion from Appendix A is that the tether design and ballast vessel design should be based on a drag force of 100,000 lbs. Appendix B served as an analytical check on the tether design and a recommendation on a bridle design.

4.2 - TASK 2 - Subcontract with UEK Corporation

Philippe Vauthier, President of UEK Corporation, is the technical and business manager of the UEK subcontract. The UEK Corporation tasks were:

1. Complete detailed parts drawings
2. Design detailed parts tooling
3. Purchase tooling
4. Subcontract parts
5. In-house manufacturing
6. Assembly
7. Test

During the detailed design of the UEK, it was realized that the stress on the main shaft for the sixteen feet diameter turbine is a potential point of failure, especially when the UEK is hanging from a crane or sloshed by waves at sea prior to its reaching its operating position in the Gulf Stream. The design improvement to overcome this condition is to add a front end support. See the figure below.

The front conditioning vanes and shaft holding frame not only are necessary to correct the lack of support of the runner in the initial design but also will improve the efficiency of energy extraction from the water flow. Another advantage in adopting this design is that it will also help and probably suppress ovalization of the augmentor ring (outside housing).

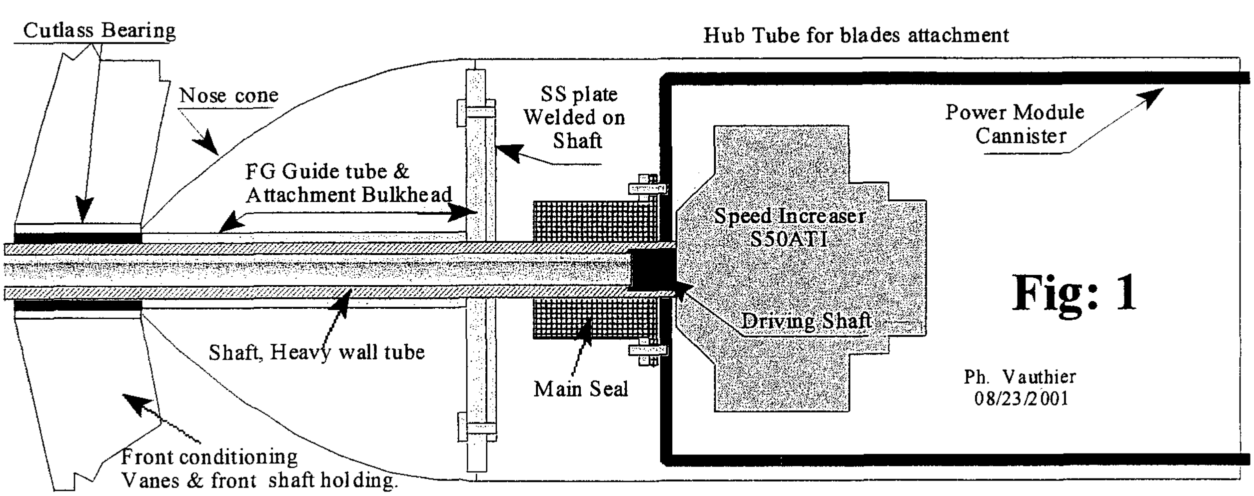


Fig: 1

Hydraulic Seal

Guidance for the critical design of the hydraulic seal for deep ocean submergence was provided by William Hofmann, U.S. Navy, Philadelphia Naval Business Center. After learning of the required shaft power and low rotating shaft velocity, he recommended Chesterton Products as a possible vendor.

The outside pressure resistance of the Chesterton seal is 10,000 psi static at a linear velocity of 100 ft/min maximum. At 17 rpm and 5 inch shaft diameter, the design velocity is 23 ft/min. The triple seal design will hold any pressure, including a catastrophic sinking that can be encountered at the selected site of installation. The seal closest to the canister holds the static inside pressure at 70 psi. The middle seal is a safety seal designed to back up the front seal from the operating water pressure.

Tether Design

The design of the tether connection is illustrated in Figures 4 and 5. Figure 4, Vertical View of the Tether Connection, is a cross section view of the UEK showing the tether connection in the center of the two shrouds. Figure 5, Tether Connection Detailed Drawing, shows the two tether plates bolted to the fiberglass web of the UEK.

Thermal Analysis

A detailed computerized thermal analysis by James Durham, P.E., consultant to UEK, revealed that at the 60 kW power level in each gear assembly and alternator housing, a six element heat exchanger is required for continuous safe operation. The details can be seen on reduced drawing 105107. The heat exchangers extend behind each canister that houses the gear assembly and alternator. Cooling is by conduction with the ocean water flowing past the heat exchanger tubes.

All of the designs for the UEK have been completed and approved for manufacture. See **1.2 Completion of Phase II** for details of work and cost to finish the Phase II effort.

Testing in Chesapeake Bay, Maryland

Following is the proposed test protocol subject to review and approval.

The UEK will be shipped in pieces to Baltimore Harbor and reassembled at Pier 6. This pier has a water depth greater than 22 feet and has access to the main harbor channel which is maintained at a legal depth of 55 feet for commercial shipping.

At the time of insertion into the harbor, the buoyancy and water tightness tests will be performed. The UEK is then towed to a position below the Key Bridge in Chesapeake Bay where the cable and tether will be installed. The tow line is 600 feet long to avoid propeller wash. To assist and maintain an acceptable depth of the turbine under towing operation, the UEK test vessel will hold the towing cable below the water surface at about 20 feet in front of the UEK.

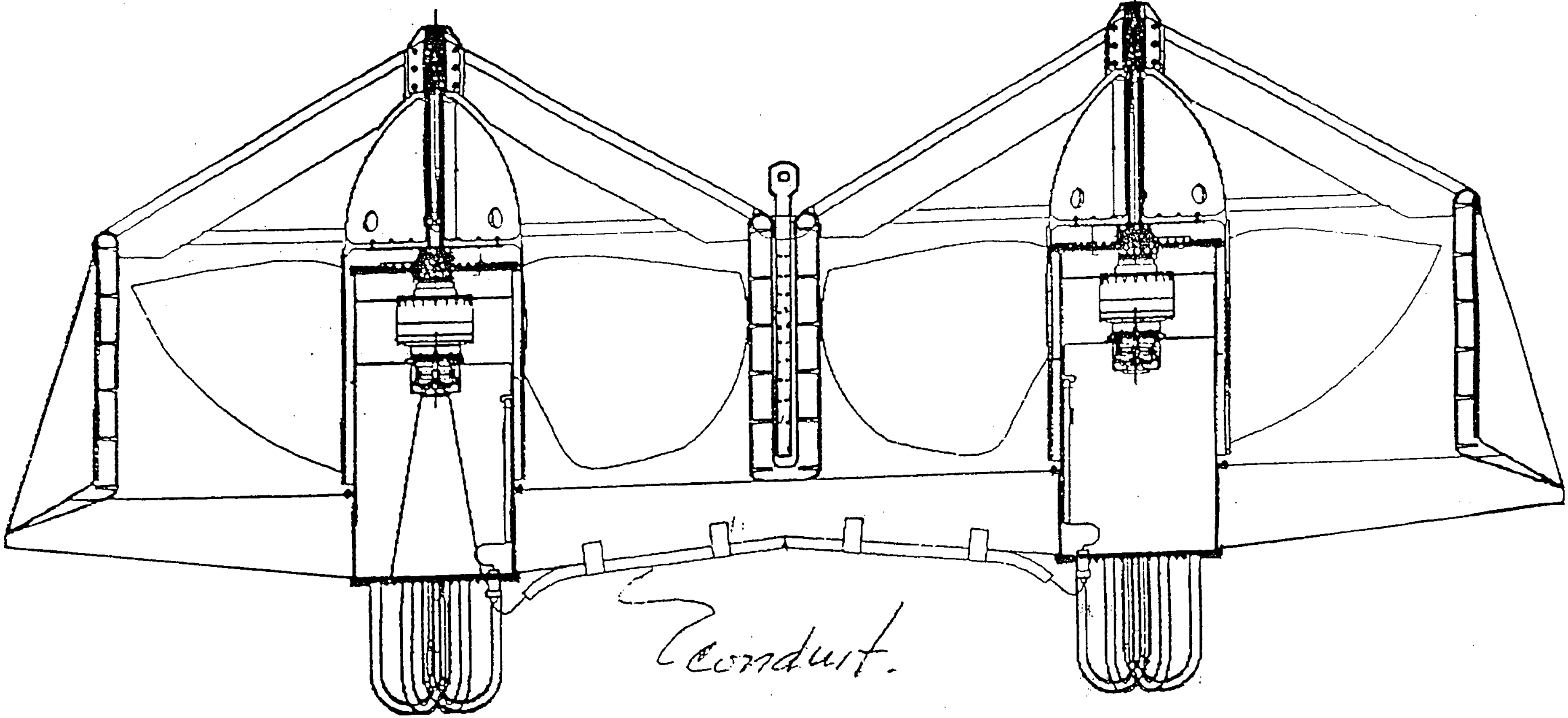


FIGURE 4

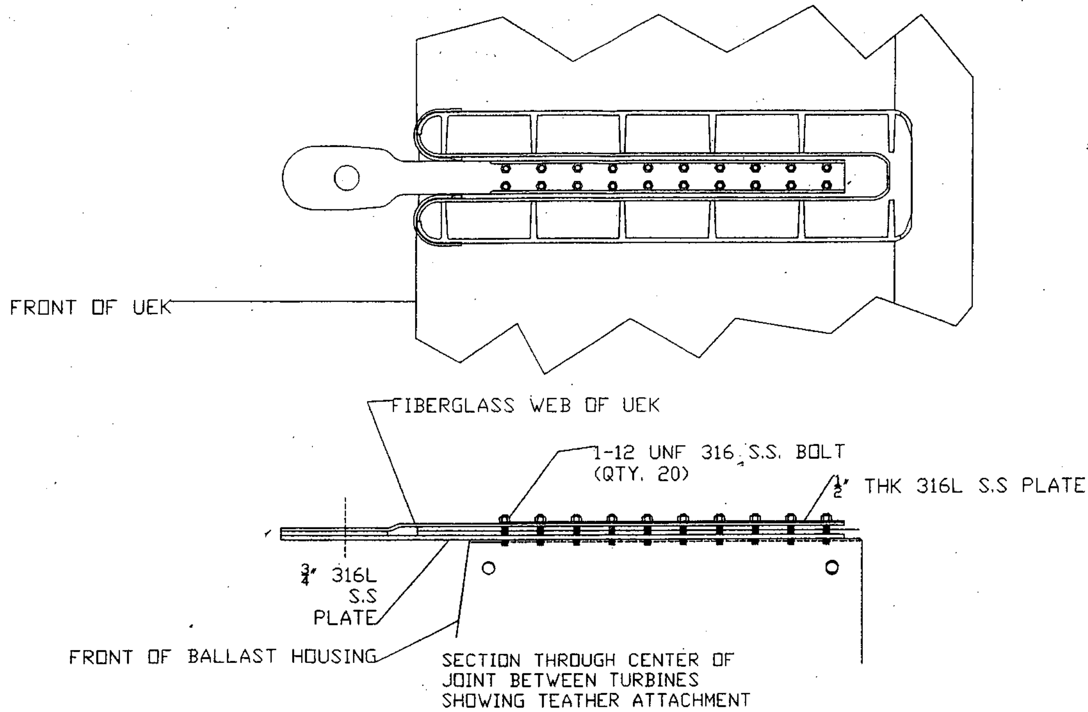
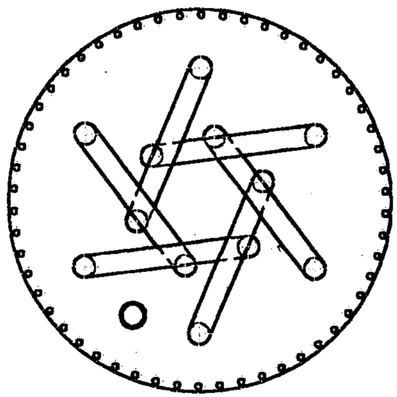
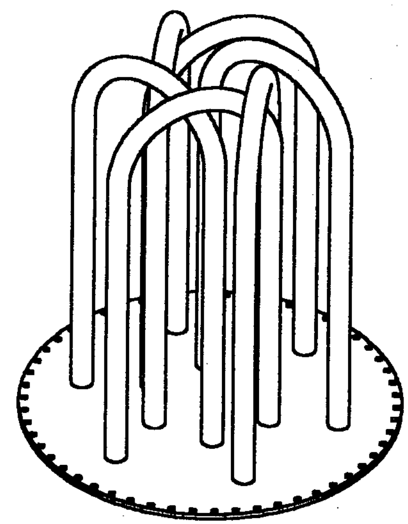
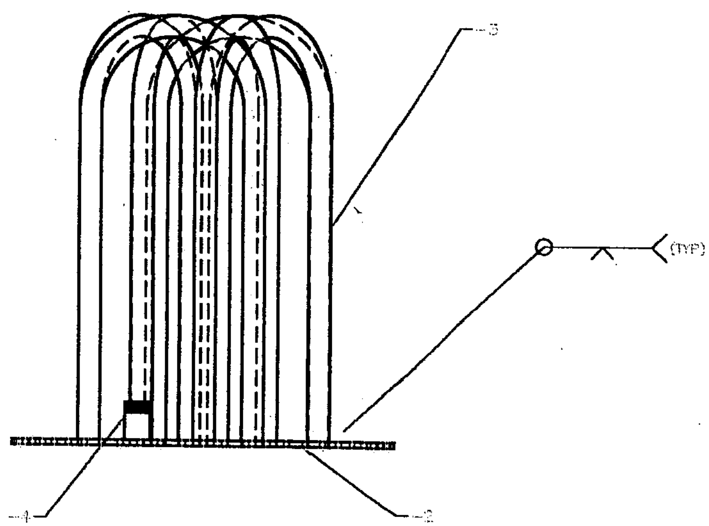

FRONT OF UEK
FIBERGLASS WEB OF UEK
1-12 UNF 316 S.S. BOLT
(QTY. 20)
½" THK 316L S.S PLATE
¾" 316L
S.S
PLATE
FRONT OF BALLAST HOUSING
SECTION THROUGH CENTER OF
JOINT BETWEEN TURBINES
SHOWING TEATHER ATTACHMENT

FIGURE 5







REV	DESCRIPTION	DATE	BY		
P1	INITIAL RELEASE	02/07/01	JHD		
P2	ADDED WELD SYMBLE	11/16/01	JHD		
P3	ADDED 3.000 PIPE NIPPLE	1/14/02	JHD		
P4	ADDED DASH 2	3/13/02	JHD		
P5	REDESIGNED WITH 8 TUBES	5/15/03	JHD		

QTY REQD -1		PART OR IDENT NUMBER	ITEM	DESCRIPTION	
1		COMMERCIAL	4	3" PIPE NIPPLE x 6.00 LG	
8		501110	3	TUBE, HEAT EXCHANGER	
1		501109	2	PLATE, HEAT EXCHANGER	
X		105107	1	ASSEMBLY, HEAT EXCHANGER	

JH DURHAM 02/07/01

DO NOT SCALE DRAWING

SEE PL

	105106	GEN CANISTER
	NEXT ASSY.	USED ON
	APPLICATION	

UEK

ASSEMBLY, HEAT EXCHANGER
22 FOOT UEK
(1-45)29

D 105107 P5

4.3 - Task 3 -- Electronic Subsystem Design

Conrad Pecile, Engineering Manager at Abacus, is responsible for the designs of the three electronic subsystems, one to be located onboard the UEK and two on shore. Unique to this project are the onboard Transmission Regulator, which rectifies the power from the two brushless alternators and converts the power to a regulated 5000 Vdc, and the Transmission Converter, which steps the transmission voltage down to 825 Vdc and delivers this voltage to the Turboverter, a standard design at Abacus, which extracts the maximum power from the system and delivers the power to the utility distribution system at 480 Vac 60 Hz three phase.

Breadboard testing of both the Transmission Regulator and the Transmission Converter have been completed. Critical to the tests were the semiconductor losses. The 6500 Vdc rating on the rectifiers and Insulated Gate Bipolar Transistors (IGBT) are recent developments whose slow speed of response were optimized with the switching frequency.

Transmission Regulator

The Schematic Diagram for the Breadboard Rectifier and Transmission Regulator is shown on drawing 45545, which appears on the following page. Half the system was tested at 2500 Vdc using standard controller cards for A5, A6, A1 and A2.

The output of one of the alternators was simulated at TB1 and rectified by rectifier CR13. Inductor L1, dual IGBT Q3 and capacitors C1-C4 form a standard boost regulator that steps the dc voltage to approximately 800 V. Dual IGBT's Q1 and Q2 form a square wave oscillator that is stepped up to 5000 Vac 1200 Hz square wave in transformer T1.

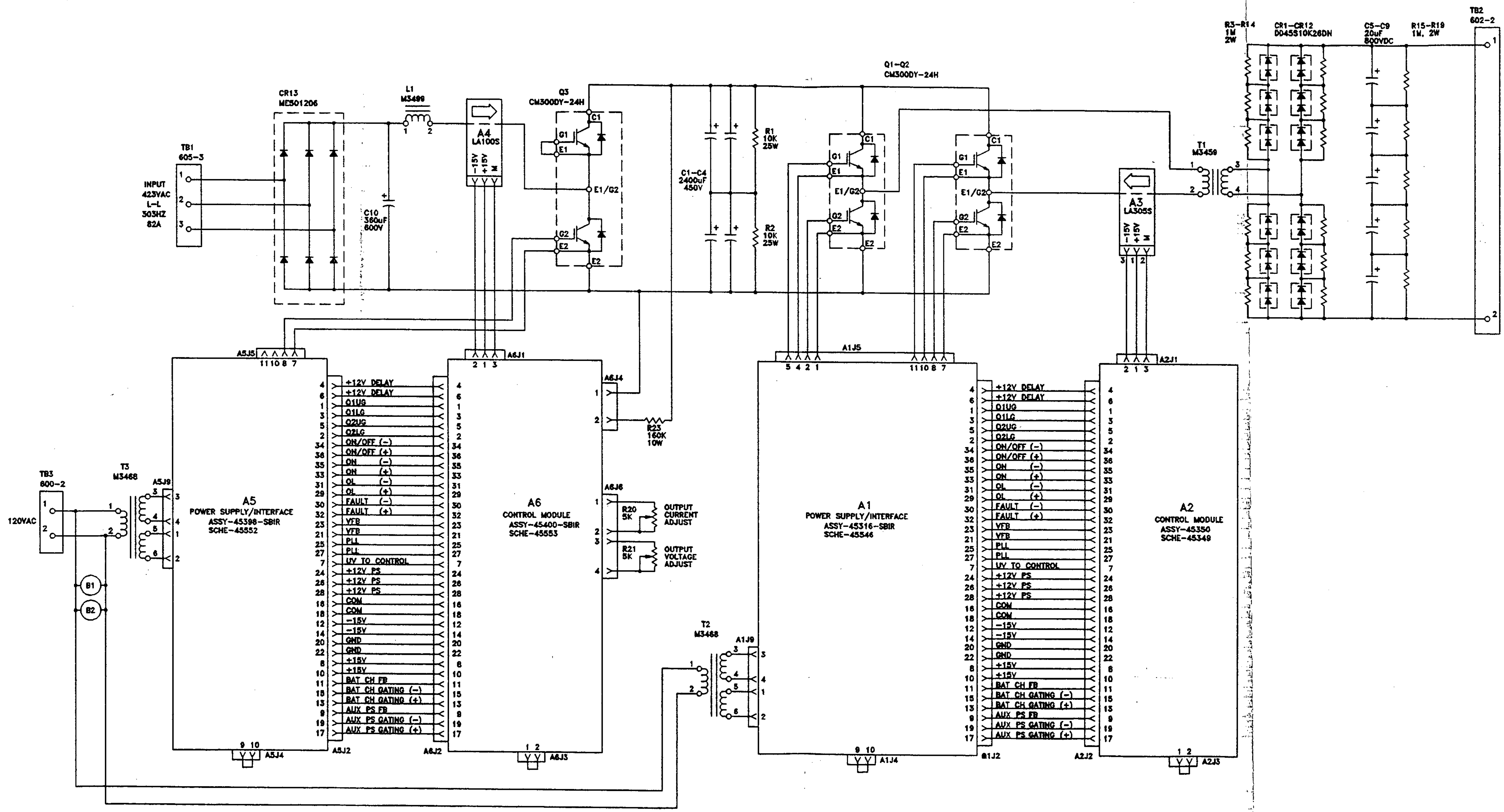
The transformer, which is designed and manufactured at Abacus, is the critical element in the Transmission Regulator design. The Honeywell glassmetal material has been chosen for the transformer core for optimum efficiency and minimum size.

The secondary of the transformer was rectified on the breadboard by several series connected rectifiers prior to the delivery of the selected high voltage rectifiers. The output is connected to the Transmission Converter through the cable as simulated for the correct resistance, inductance and capacitance.

The mechanical design of the Transmission Regulator will be completed early in the next reporting period so that it may be incorporated into the UEK design. Robert DeMilia, Mechanical Design Manager, is responsible for this critical design that takes advantage of the ocean water flow to cool the electronic assembly.

The Transmission Converter will operate at 800 Vdc for the Chesapeake Bay tests, and the boost circuit in the Transmission Converter will not be used. The revised schematic for the prototype Transmission Regulator is shown on drawing 45618, which also follows. The regulated voltage for the Chesapeake Bay Test is 800 Vdc. Each alternator three phase output is full wave rectified at CR1 through CR6 then applied to synchronized boost regulators at dual IGBT's Q1 and Q2. By applying the control signals to the IGBT's alternately at twice the switching frequency, the sizes of the filter inductors L1 And L2 and the filter capacitors C3 through C8 are one quarter the size they would be if the control signals were applied simultaneously.

A REVISED. ADDED INPUT SECTION 9-17-01

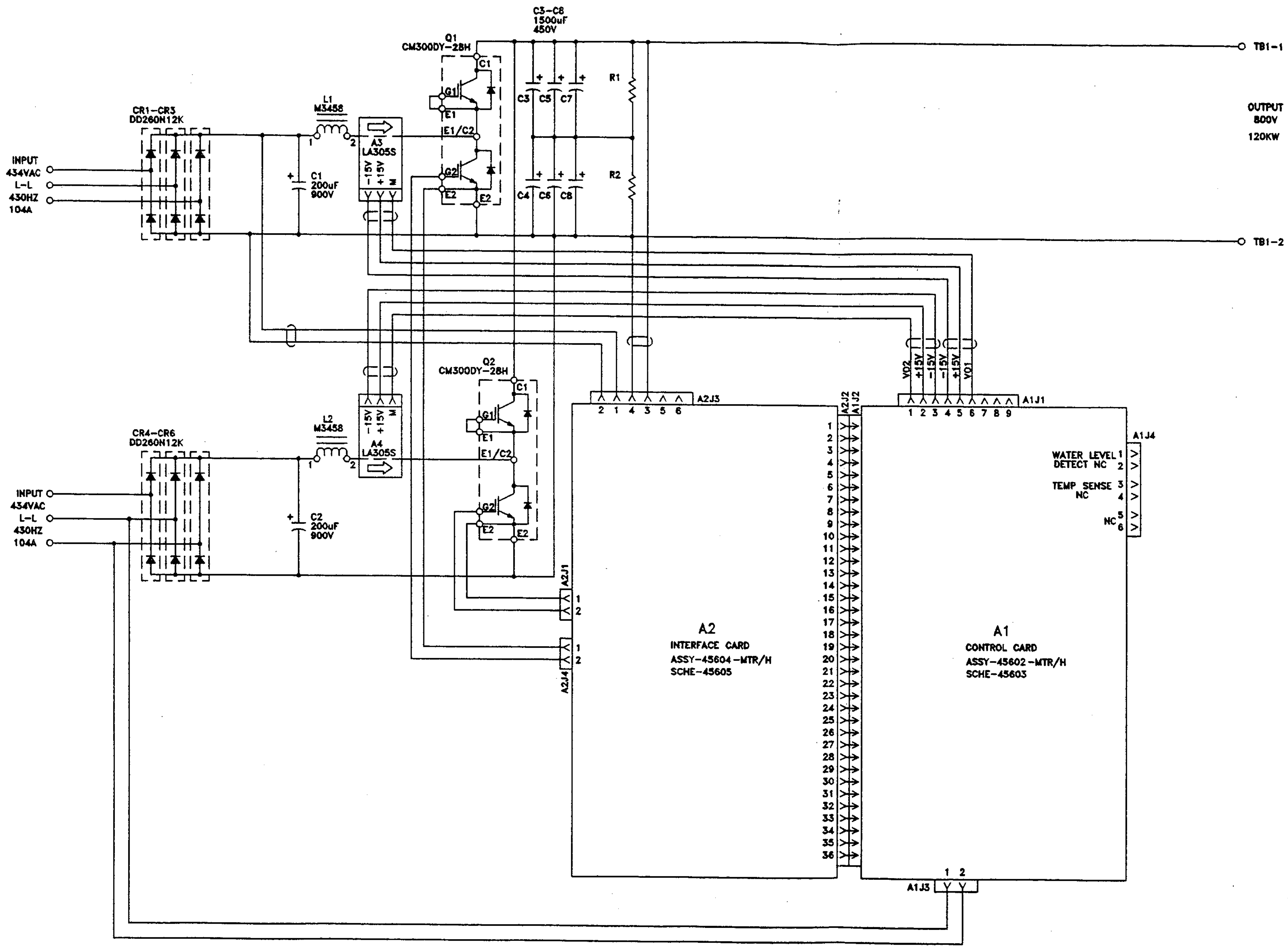


RD 8-27-01

SCHEMATIC DIAGRAM
BREADBOARD
RECTIFIER AND TRANSMISSION REGULATOR

45547 13813

45545



RD 2–26–02

SCHEMATIC DIAGRAM
TRANSMISSION REGULATOR
MODEL PDC800–1

45630 13814

45618

For the Chesapeake Bay test, the output of the Transmission Regulator is applied to the simulated cable. See below.

While the components for the dc/dc converter that steps up the voltage from 800 Vdc to 5000 Vdc are omitted from the prototype, their positions on the mechanical design are retained. Refer to the Assembly Drawing (On Board Unit) transmission Regulator Model PDC800-1, drawing 45630.

Transmission Converter

The Schematic Diagram for the Transmission Converter Breadboard is shown on drawing 45488. Prior to testing at 2500 Vdc, where the cost of component failure would be significant, the detailed performance of the circuit was evaluated between 500 and 800 Vdc input. Since no single semiconductor is available for operation at 5000 Vdc, it is necessary to assure that the selected circuit divides the voltage evenly between the IGBT's.

With reference to the drawing, capacitors C1-C3 form a voltage divider with capacitors C4-C6. IGBT's Q2 and Q3, rectifiers D3 and D4, inductor L1 and capacitor C7 form a buck converter. For this circuit arrangement, when the rectifiers D3 and D4 conduct, the voltage across Q2 and Q3 are each at half voltage as set at the collector of Q3 by rectifier D2.

During turn-on and turnoff transients, it is necessary to turn Q3 on before Q2 is turned on and turned off after Q2 is turned off. The lower capacitors C4-C6 are discharged more than the upper capacitors during the transitions from off to on and on to off. To keep the charges balanced, IGBT Q1 serves as a charger for the lower capacitors, and its reference is half the input voltage.

Significant among the breadboard test results was the proof of concept for the maximum power tracking subsystem. The turbine speed must be available to the Abacus Turboverter® so that the maximum power algorithm can determine the maximum power that can be inserted into the utility. The operating frequency of the alternators aboard the UEK is too high for transmission over the power cable, which is 17 km in length.

The technology applied is shown in Figure 6, Frequency Modulator Breadboard. The alternator frequency spans the range 432 Hz at maximum water velocity and no load to 102 Hz at the minimum useable water velocity at which 10% of rated power or 12 kW is generated. One phase of the three phase alternator is applied to an isolation transformer as shown in Figure 6.

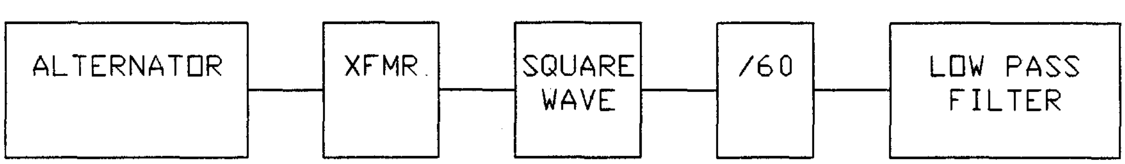
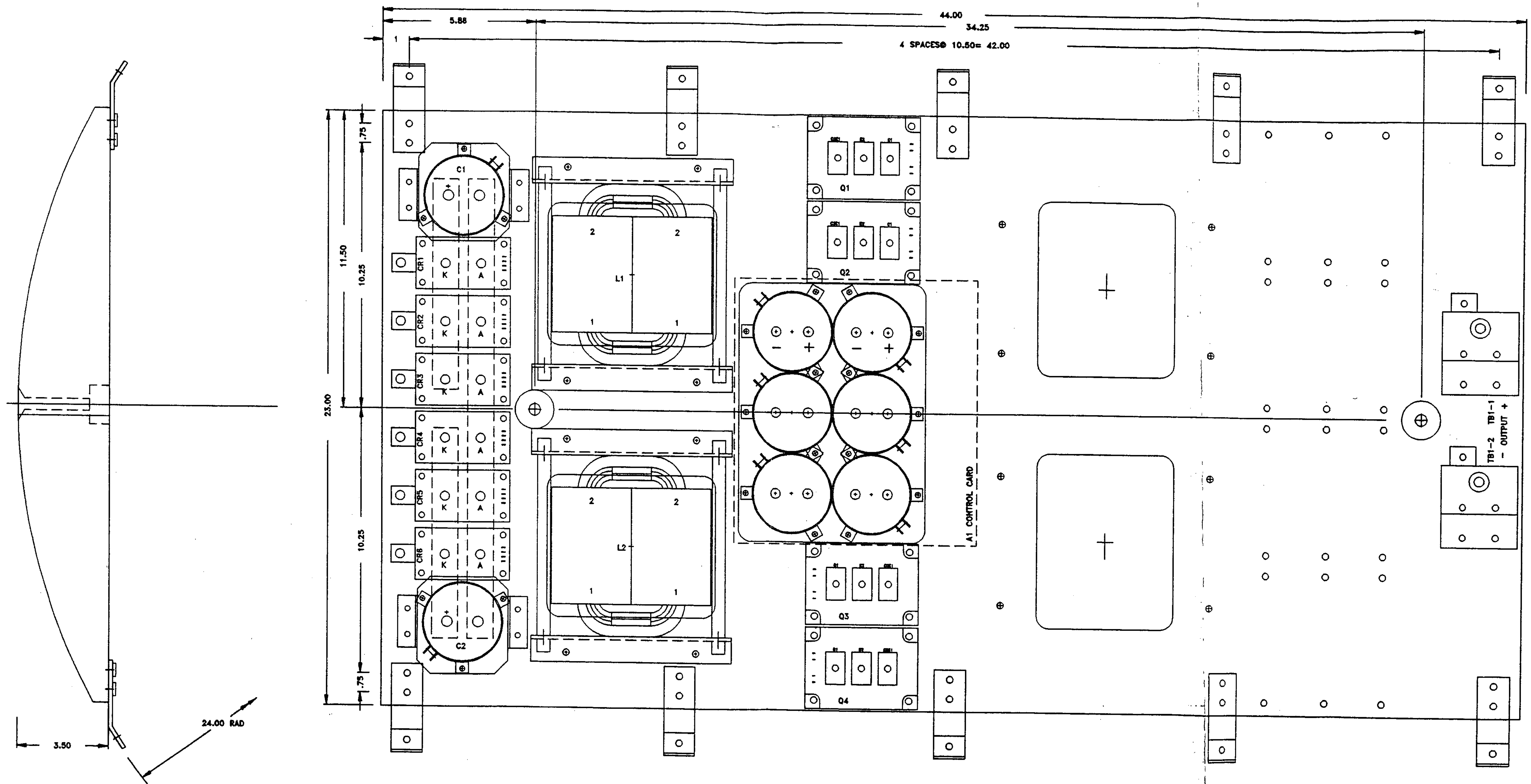


FIGURE 6 - FREQUENCY MODULATOR BREADBOARD



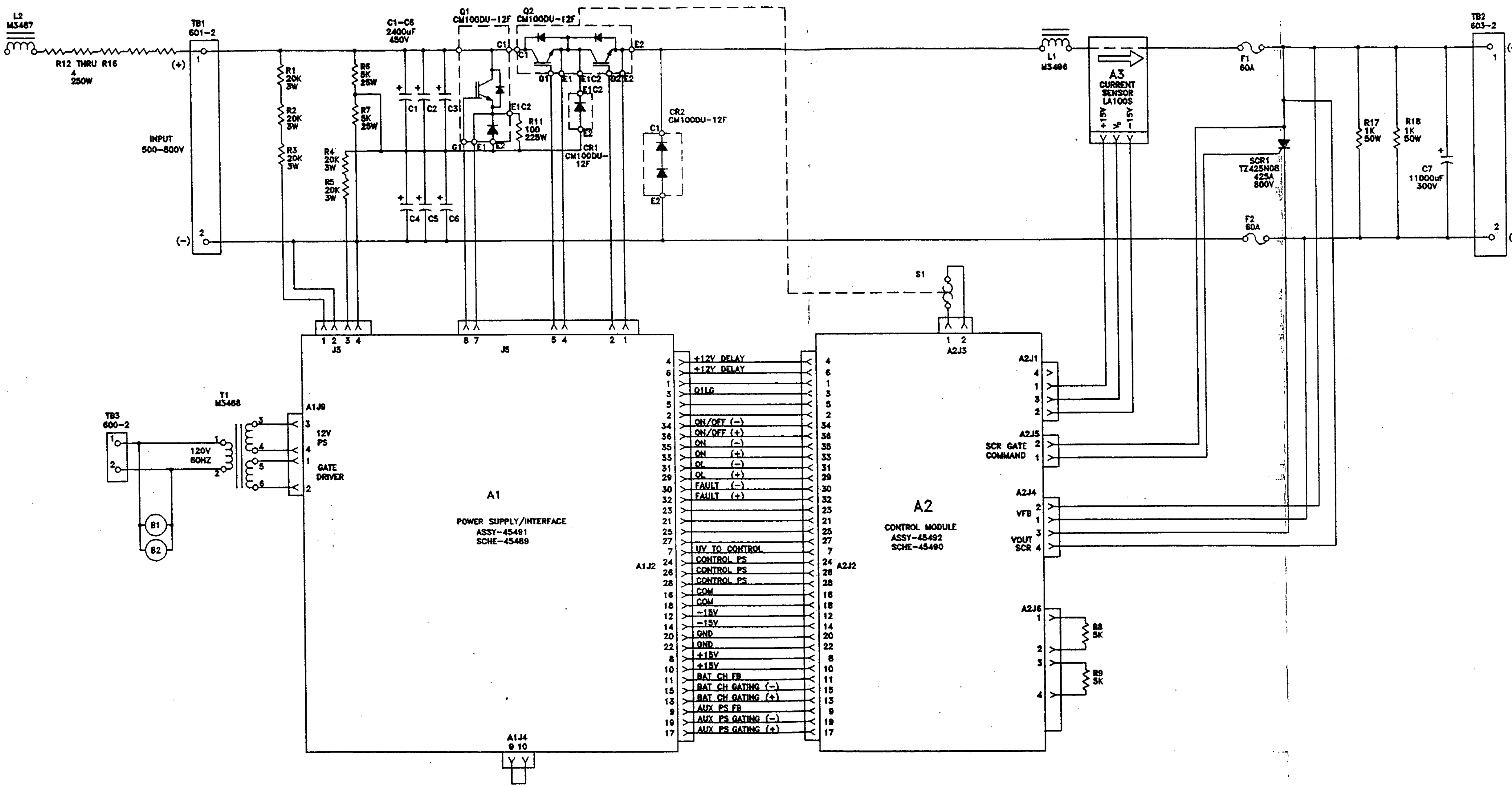
RD 4-9-02

ASSEMBLY DRAWING
(ON BOARD UNIT)
TRANSMISSION REGULATOR
MODEL PDC800-1

13813

1 1

45630



RD 4-2-01

SCHEMATIC DIAGRAM
TRANSMISSION CONVERTER
BREADBOARD

45575 13756

45488

The secondary of the transformer is converted to a square wave, and the frequency is divided by 60 in an Application Specific Integrated Circuit (ASIC). Output of the divider is applied to a two pole low pass filter, and this output is added to the reference signal for the 5000 Vdc Transmission Regulator.

This results in an amplitude modulation frequency on the power transmission to shore over the frequency range 1.7 Hz (proportional to 102 Hz to 7.2 Hz (proportional to 432 Hz). This frequency range was detected at the receiving end of the simulated cable impedance, as shown in Figure 7 at frequencies 2.2 Hz and 7.2 Hz.

4.4 - Task 4 - Manufacture Electronics

The Transmission Regulator, which is an integral part of the UEK, has been completed and fully tested with the Model 4109-4-800 Turboverter, the Inverter that converts the output from the hydroturbines to 480 Vac 60 Hz 3 phase 100 kW power suitable for testing in the Chesapeake Bay tests. Factory test results are reported below.

Factory Test Results

Figure 8 shows a soft start sequence for the boost converter section of the transmission regulator. At the start of the wave form the dc input is approximately 160 Vdc. Once voltage climbs above the undervoltage threshold the boost section is commanded to turn on and the output voltage slowly climbs to the regulation point minimizing the inrush current to the capacitors

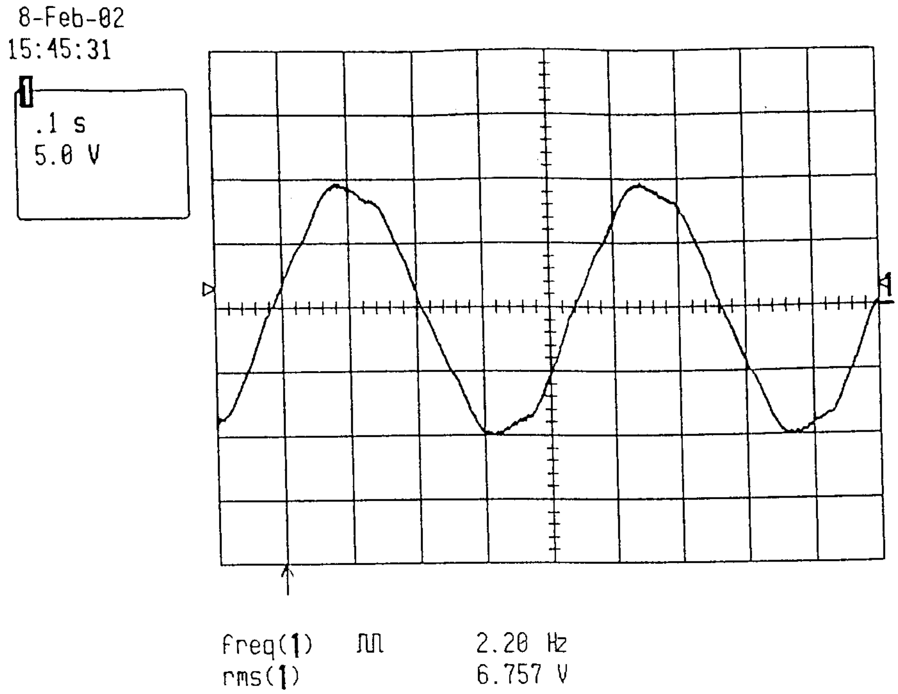
The output of the transmission regulator is regulated at 725 Vdc. Figure 9 shows the ripple at the output of the unit. The ripple voltage is approximately 3 Vpk-pk out of the 725 Vdc, which is approximately 0.5%.

Figure 10 and Figure 11 illustrate the modulation of the dc output voltage to communicate with the unit on shore. This signal is a scaled representation of the generator frequency. Once passed to the shore, the signal is extracted from the dc bus voltage and the inverter makes a decision based on the detected frequency.

Figure 12 shows the data that the controller processes to determine the amount of power that will be taken from the generators and transmitted into the utility line. The transmission regulator will divide down the generator frequency by 60 and modulate the regulated dc voltage with this frequency. This frequency is transmitted to shore where this frequency is detected and the inverter will output the corresponding power into the utility grid.

Fisher Electric Test Results

Fisher Electric supplied the alternators that convert the hydroturbine mechanical power to three phase variable frequency alternating current electric power. The specification, Drawing 13058 Rev A, appears in the following pages.



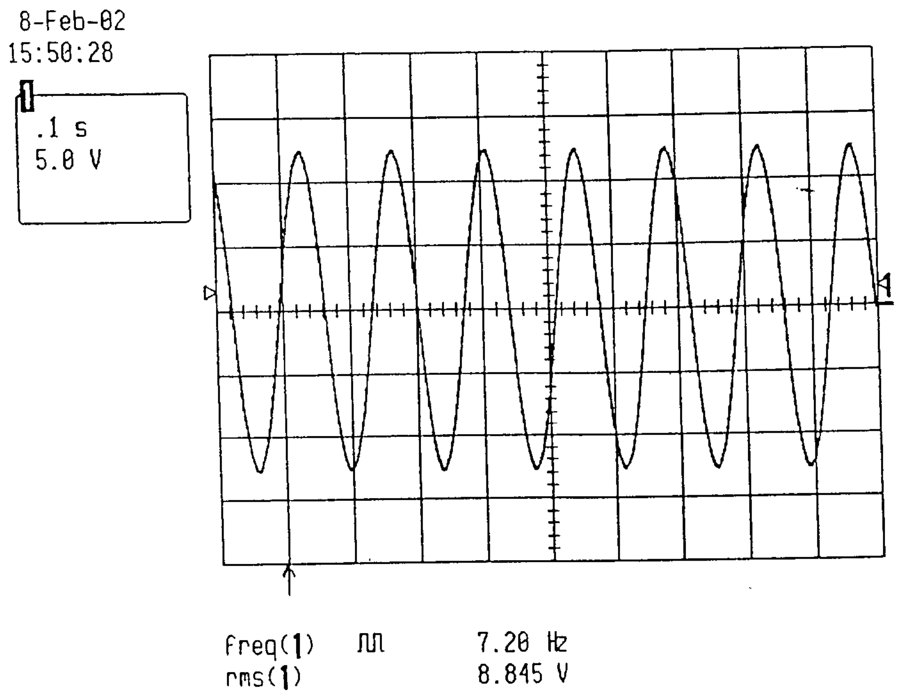


FIGURE 7
FREQUENCY DETECTION DATA

FIGURE 8

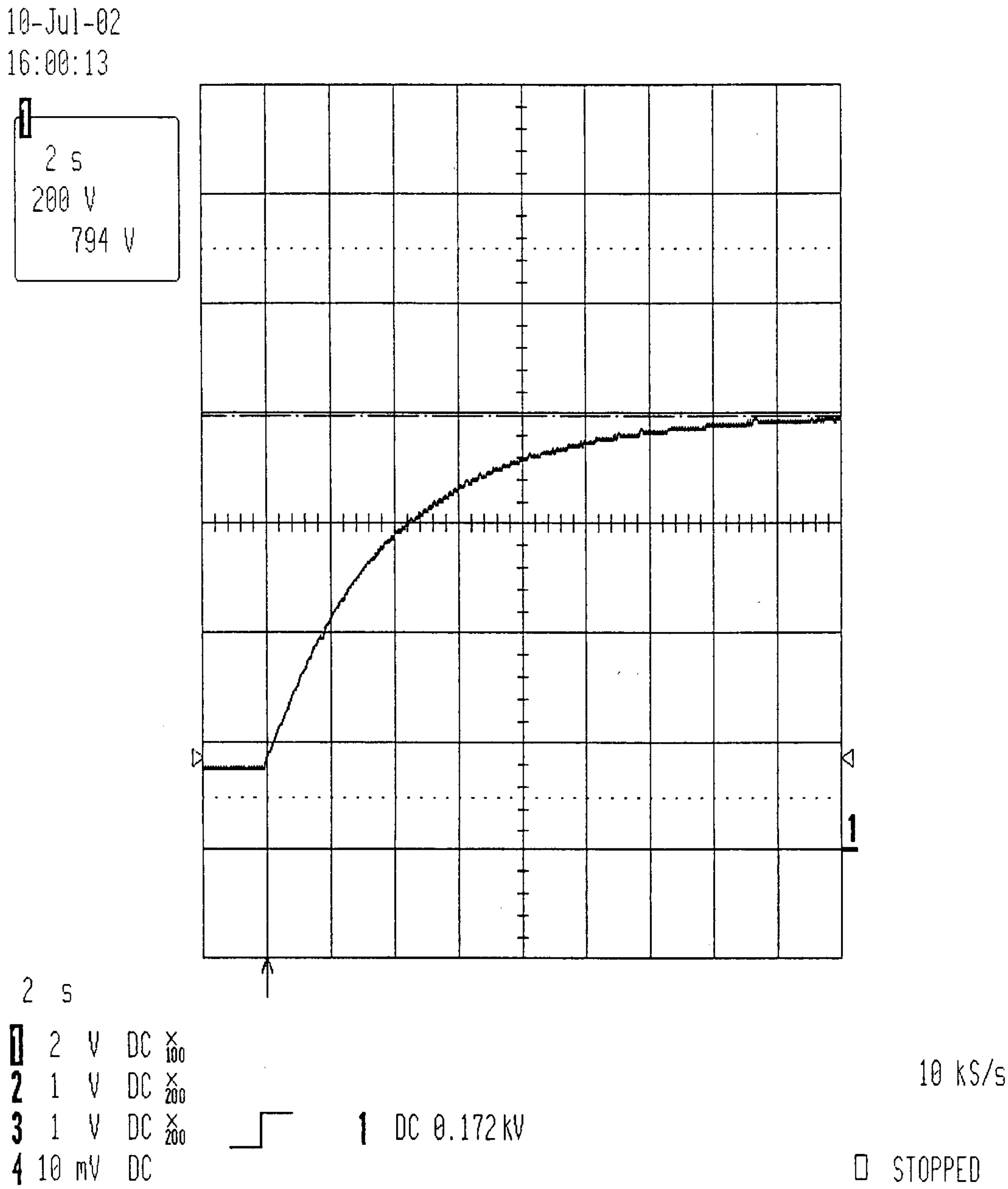

10-Jul-02
16:00:13
2 s
200 V
794 V
1
2 s
1 2 V DC x100
2 1 V DC x200
3 1 V DC x200
4 10 mV DC
1 DC 0.172 kV
10 kS/s
STOPPED

FIGURE 9

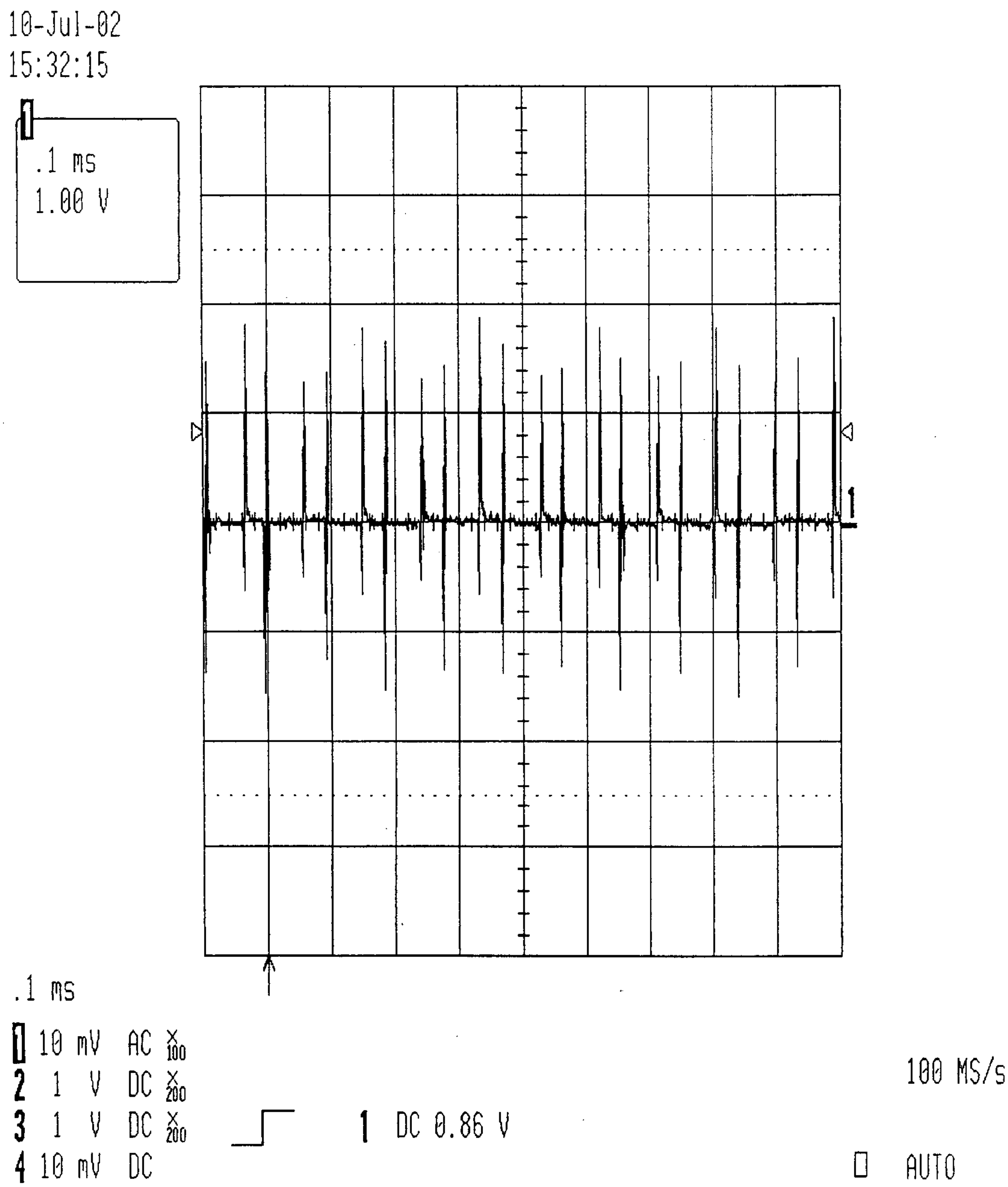

10-Jul-02
15:32:15
.1 ms
1.00 V
.1 ms
1 10 mV AC x100
2 1 V DC x200
3 1 V DC x200
4 10 mV DC
1 DC 0.86 V
100 MS/s
AUTO

FIGURE 10

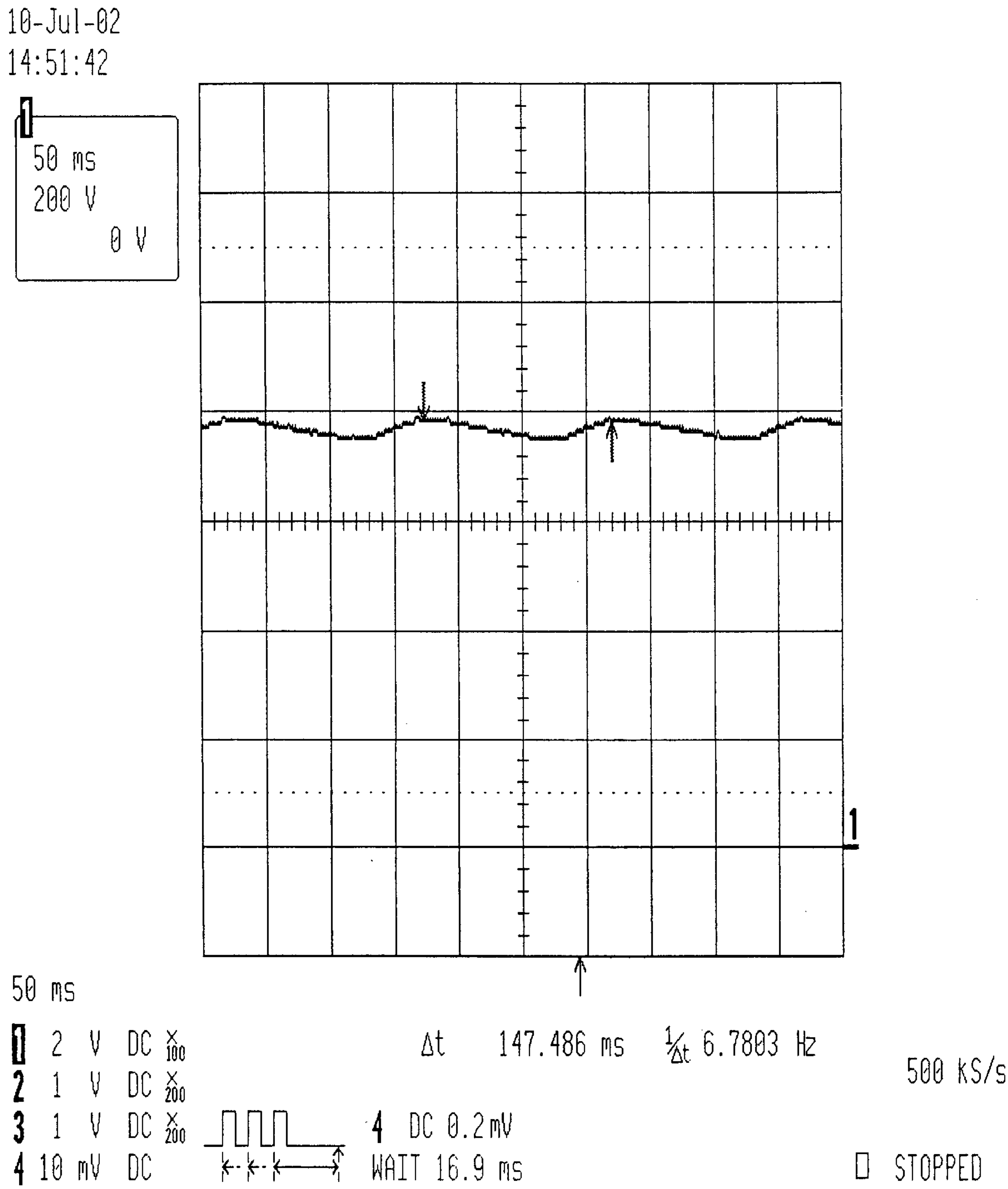
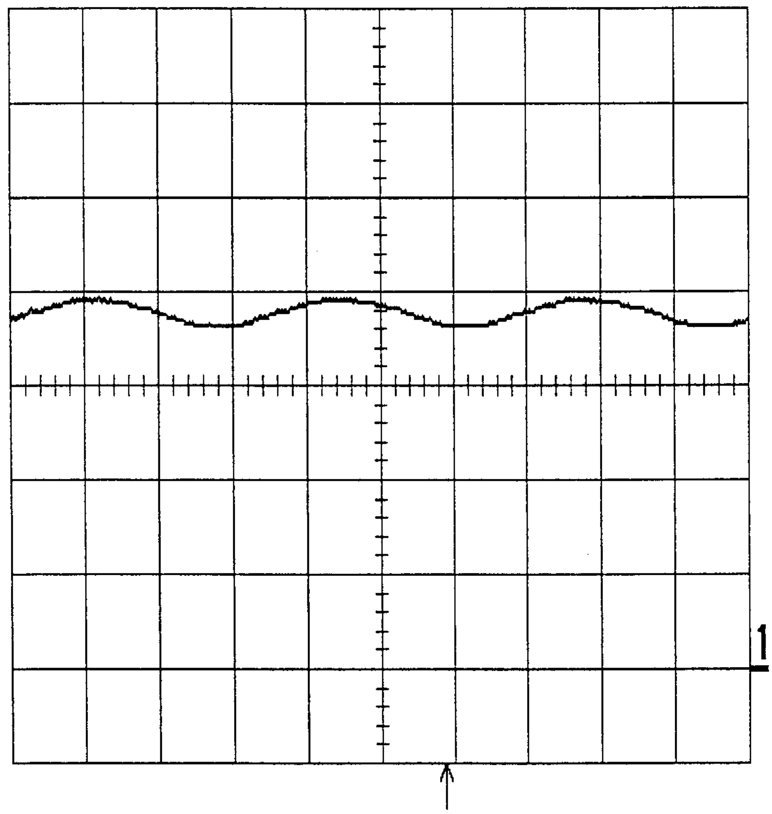

10-Jul-02
14:51:42
1
50 ms
200 V
0 V
1
50 ms
1 2 V DC X 100
2 1 V DC X 200
3 1 V DC X 200
4 10 mV DC
Δt 147.486 ms 1/Δt 6.7803 Hz
500 kS/s
4 DC 0.2mV
WAIT 16.9 ms
STOPPED

FIGURE 11

10-Jul-02
14:33:33

1
.2 s
200 V



freq(1) 1.49 Hz
rms(1) 756.6 V
pkpk(1) 69 V

.2 s

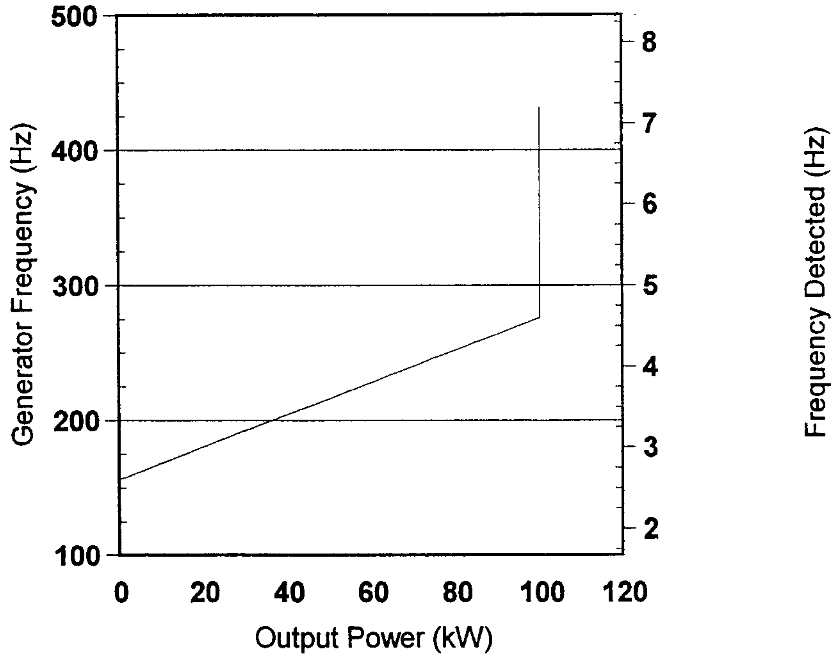
1 2 V DC x100
2 1 V DC x200
3 1 V DC x200 4 DC 0.2mV
4 10 mV DC WAIT 16.9 ms

100 kS/s

STOPPED

FIGURE 12

Generator Frequency/Detected Frequency vs Output Power



APPLICATION		REVISIONS			
NEXT ASSY	USED ON	LTR	DESCRIPTION	DATE	APPROVED
		A	Revise per Fisher Quote		

Three Phase Permanent Magnet Generator

Specification Control Drawing

This specification describes the generators (brushless alternators) for the dual hydroturbine UEK for the Ocean Current Power Generator. The project is sponsored by SBIR Grant DE-FG02-00ER82930 from the U.S. Department of Energy.

A 24 pole three phase permanent magnet generator is required for each of the turbines. Each turbine has a gear ratio of 94:1.

Power rating	60 kW
Maximum operating frequency	430 Hz no load at 4.14 knots water velocity, 2150 RPM
Open circuit voltage at 430 Hz	434 Vac rms L-L nominal
Minimum frequency at rated power	276 Hz
Power rating at 219 Hz	30 kW
Resistance per phase	0.024 Ω
Inductance per phase	250 microhenry
Units produced as matched pairs	
Coupling	Mate with Fairfield Model S50ATI planetary final drive; gear ratio 94:1. Drawing attached External spline 2.75"
Seal	A oil seal is necessary between the gearbox and the alternator in the adapter plate
Length (est)	17.50 (not including shaft)
Diameter (est)	16.00"
Weight (est)	235#

Notes: Efficiency is more critical than size or weight
For the open circuit voltage, fill the stator with a wire size that will produce a voltage between 240 and 293 Vac. The Abacus boost regulator will adapt.

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES TOLERANCES ON FRACTIONS ± 1/64 DECIMALS 3 PLC ± .015 2 PLC ± .03 ANGLES ± 1/2°	CONTRACT NO.	abacus controls inc. 80 READINGTON ROAD SOMERVILLE, N. J. 08876	
	DRAWN 1-11-02		
MATERIAL	CHECKED 1/11/02	Three Phase Permanent Magnet Generator	
	ENGINEER 1-11-02		
FINISH	APPROVAL	SIZE A 54241	13058
		SCALE	SHEET 1 of 1

BREWER ASSOCIATES N508995

Fisher Electric performed calibration tests in accordance with the specification at various rotating velocities measured in rpm as shown on the data graph, which appears in the following pages. Fisher used a three phase full wave bridge similar to the input circuit in the Abacus Transmission Regulator. The test results are in accordance with the specification.

Also shown in the following pages is the test result for the 12" fan which provides cooling for both the alternator and the gear speed increaser to which the alternator is attached.

4.5 - Task 5 - Finalize Cost Estimating

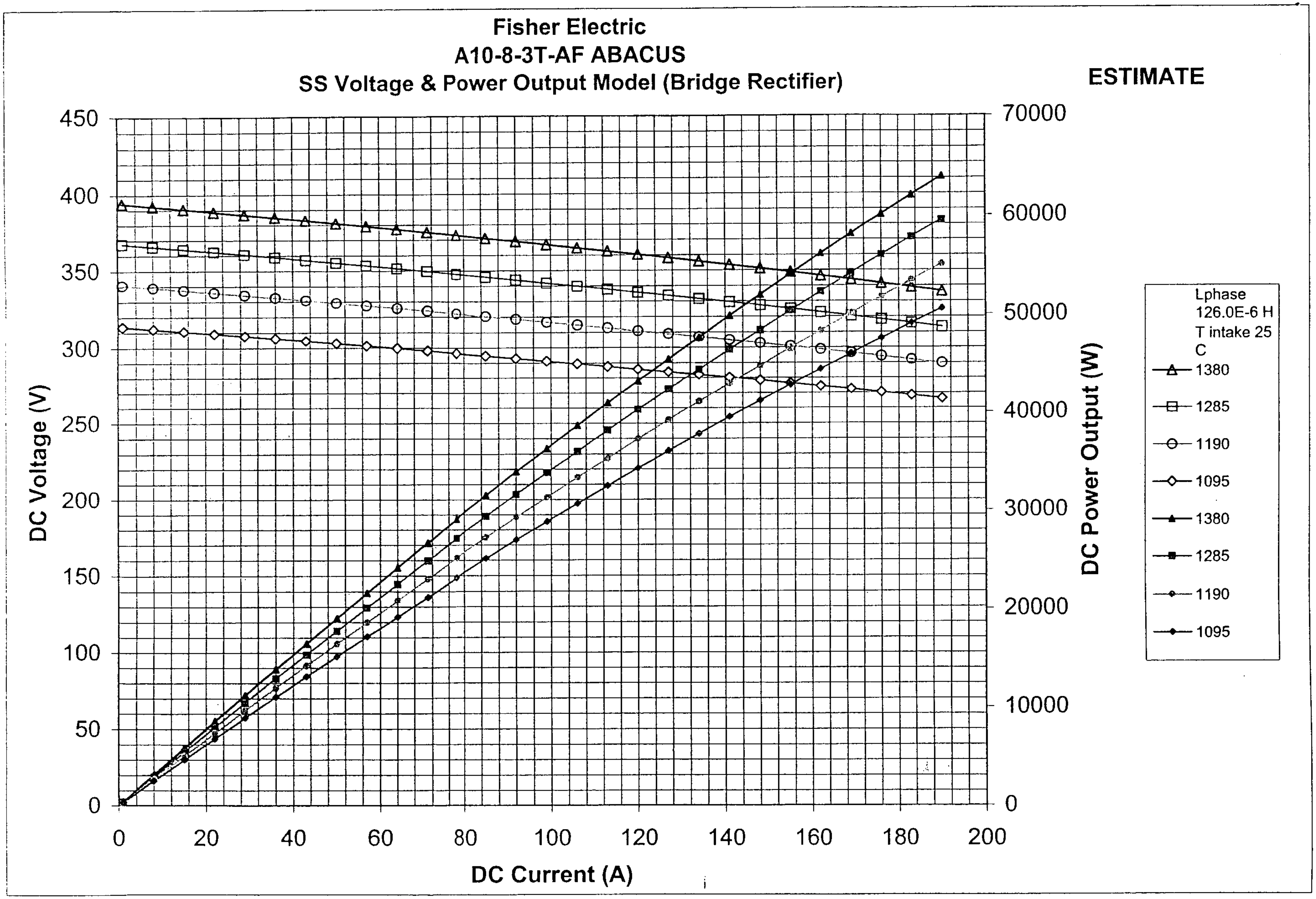
As discussed earlier in this report and discovered at the beginning of the Phase II program, the UEK requires a ballast force in the vertical direction to create the necessary vector force for the tether. With the limited budget for Phase II, Abacus took a "fix" engineering approach for Phase II and a redesign engineering approach for Phase III and future deployments. See **2. TECHNICAL FEASIBILITY and 3. ECONOMIC FEASIBILITY** above for details. The advantages of the Phase III design, the Ocean Power Generator (OPG), are most evident with a cost comparison to the Phase I design as modified.

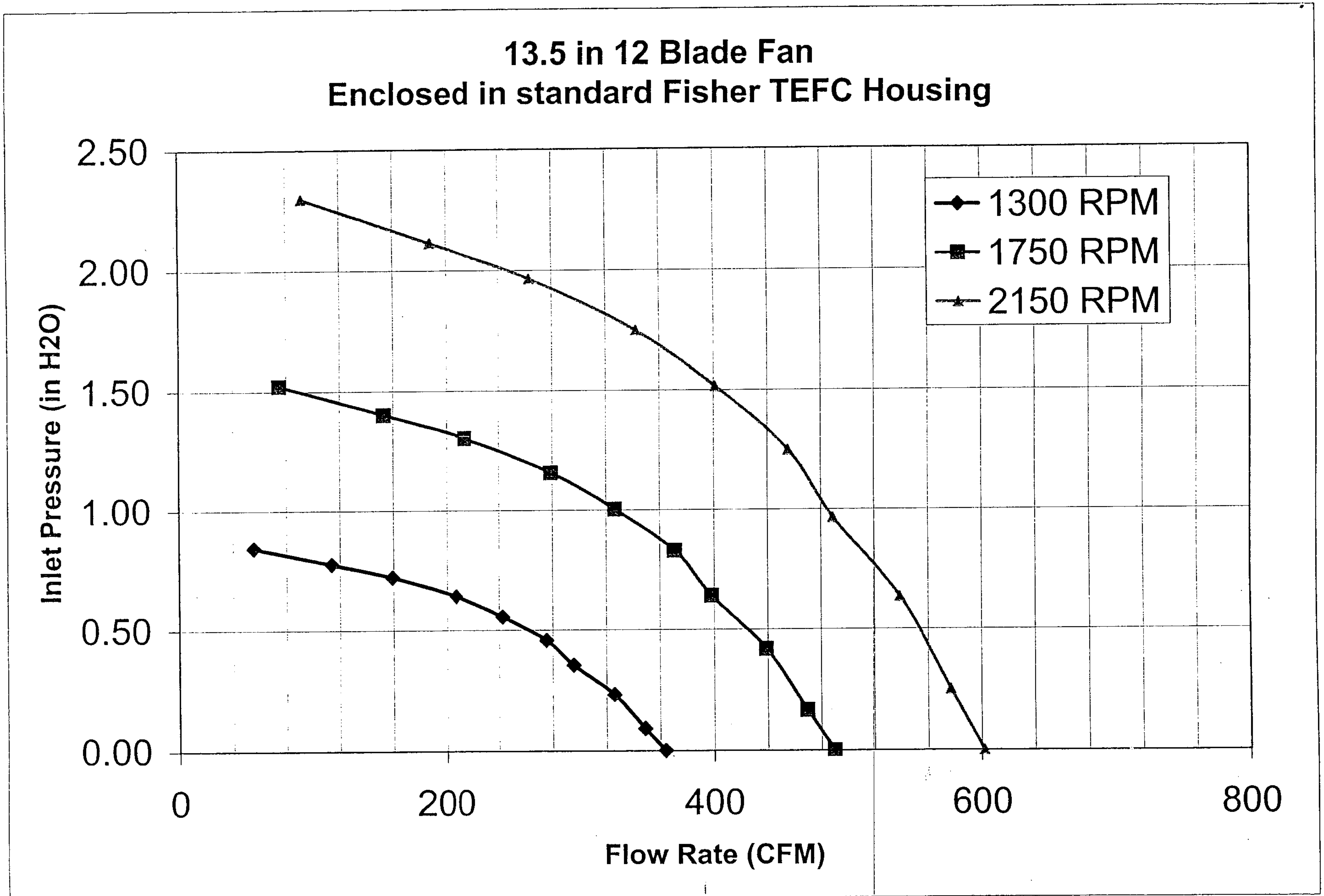
As shown on Drawing 45534 in 4.1 above, adding the ballast vessel adds the following cost items:

Item	First Unit	Five Units
1. Ballast vessel	$ 34,000.00	$ 150,000.00
2. Concrete mooring	18,600.00	55,000.00
3. Tether to mooring	4,800.00	24,000.00
4. Tether to UEK	1,600.00	8,000.00
5. Winch assembly and controls	6,000.00	20,000.00
6. Additions to installation costs	88,000.00	200,000.00
Additional Cost	$ 153,000.00	$ 457,000.00
Cost per Phase I Report	825,228.00	2,904,000.00
Cost with Ballast	$ 978,228.00	$3,361,000.00

The detailed results of the Cost Estimating Task are presented in matrix form on the LOTUS 123 spreadsheet OCEAN POWER GENERATOR COST ANALYSIS FOR 200 kW, 1 MW, 10 MW on the following pages. The costs apply to the Phase III design described in **2. TECHNICAL FEASIBILITY** in which the ballast tanks are an integral part of the power generator design. All of the costs except those whose "Supplier" column entry is TBD are supported by quotations based on Abacus Engineering requirements.

For the first 200 kW installation, the cost is $1,346,350 compared to twice the 100 kW cost above, $1,956,456, a cost reduction of $610,106. For a 1 MW installation the cost estimate is $5,432,100 compared to twice the 500 kW cost above, $6,722,000, a cost reduction of $1,289,900. It is easily recognized that the Phase III design is more economically attractive than the original design with a separate ballast vessel.


Fisher Electric
A10-8-3T-AF ABACUS
SS Voltage & Power Output Model (Bridge Rectifier)
ESTIMATE
DC Voltage (V)
DC Power Output (W)
DC Current (A)
0
50
100
150
200
250
300
350
400
450
0
10000
20000
30000
40000
50000
60000
70000
0
20
40
60
80
100
120
140
160
180
200
Lphase
126.0E-6 H
T intake 25
C
1380
1285
1190
1095
1380
1285
1190
1095


13.5 in 12 Blade Fan
Enclosed in standard Fisher TEFC Housing
Inlet Pressure (in H2O)
2.50
2.00
1.50
1.00
0.50
0.00
0
200
400
600
800
Flow Rate (CFM)
1300 RPM
1750 RPM
2150 RPM

June 14, 2002

OCEAN POWER GENERATOR
COST ANALYSIS
FOR 200 kW, 1 MW, 10 MW

Description	Supplier	Unit cost	Qty	200 kW	Unit Cost	Qty	1 MW	Unit Cost	Qty	10 MW
Hydroturbines	UEK	45,000	4	180,000	41,500	20	830,000	29,800	200	5,960,000
Final Assembly	Abacus & UEK	28,000	1	28,000	25,200	5	126,000	18,900	50	945,000
Ballast tank	Composites USA	34,075	2	68,150	32,710	10	327,100	28,030	100	2,803,000
Gear assembly	Fairfield	19,550	4	78,200	17,250	20	345,000	12,900	200	2,580,000
Alternator	Fisher Electric	18,000	4	72,000	13,000	20	260,000	10,000	200	2,000,000
Transmission Regulator	Abacus	55,000	1	55,000	37,000	5	185,000	21,600	50	1,080,000
Winch assembly	TBD	7,600	1	7,600	6,400	5	32,000	3,900	50	195,000
Anchor and chain	Park City Supply	5,000	1	5,000	4,000	5	20,000	2,900	50	145,000
Tether to anchor	Kulkoni Inc	48,000	1	48,000	43,200	5	216,000	38,000	50	1,900,000
Concrete mooring	TBD	22,000	1	22,000	20,500	5	102,500	18,800	50	940,000
Tether to mooring	Kulkoni Inc	16,000	1	16,000	14,400	5	72,000	12,700	50	635,000
Support items	Misc	5,000	1	5,000	4,500	5	22,500	3,000	50	150,000
Electric cable 15 kV	Oakonite	107,000	1	107,000	6,000	5	30,000	6,000	50	300,000
Electric cable 35 kV	Oakonite				205,000	1	205,000	140,000	10	1,400,000
Ocean central station	Abacus				246,000	1	246,000	124,000	10	1,240,000
Installation - OPG	T BD	18,000	1	18,000	6,000	5	30,000	3,000	50	150,000
Installation - cables 15 kV	TBD	200,000	1	200,000	1,200	5	6,000	1,100	50	55,000
Installation - cables 35 kV	TBD				450,000	1	450,000	110,000	10	1,100,000
Installation - central station	TBD				150,000	1	150,000	55,000	10	550,000
G&A + Profit	Abacus	28% above		326,000	28% above		1,310,000	23% above		5,550,000
Transmission Conv 200 kW	Abacus	44,800	1	44,800						
Tansmission Conv 1 MW	Abacus				178,000	1	178,000	151,000	10	1,510,000
Inverter 200 kW	Abacus	65,600	1	65,600						
Inverter 1 MW	Abacus				289,000	1	289,000	259,000	10	2,590,000
TOTAL				1,346,350			5,432,100			33,778,000
Cost per kW				6,732			5,432			3,378

5 - SITE LOCATION

Abacus and UEK decided to investigate locating the prototype Ocean Current Power Generator at the U.S. Navy South Florida Test Facility at Dania, Florida. Contact was made with Thomas Metz and William Venezia. To further evaluate the site and to identify the ideal distance east of shore to locate the UEK, Abacus placed two subcontracts. The first was to William Venezia, Ph.D. to provide site specific information on meteorology, oceanography, and facilities. His report is summarized in 5.2 below, and the full text may be obtained by requesting it from Deborah Dixon at Abacus Controls Inc.

To obtain the best oceanography data concerning water velocity in the Gulf Stream, Abacus had the good fortune of subcontracting with Thomas N. Lee, Ph.D., Research Professor of Meteorology and Physical Oceanography at the University of Miami and a renowned expert on the Gulf Stream. He has published several papers on the Gulf Stream, some of which are included in his references in his full report, which may be obtained by requesting it from Deborah Dixon at Abacus Controls Inc. Since his data spans two years[5], it is with confidence that Abacus selects the site of his choice: 17 km east of Dania, Florida, at a depth of 30 m where the expected range of water velocity is 129 cm/sec to 213 cm/sec.

5.1 - Report of Dr. Lee

Dr. Thomas Lee has written a report that evaluates and summarizes available current data from the Straits of Florida between Miami and Palm Beach to develop representative statistics of the current spatial and temporal variability that can be used in the development and deployment of an Ocean Power Generator by Abacus Controls Inc. The design criteria requires current speeds of 170 to 180 cm/s for generating approximately 60 kW per hydroturbine. The unit continues to provide electricity at 140 cm/s current speeds, but requires 50 cm/s to power its onboard instruments. It will be deployed on a 900 m mooring anchored to the bottom. Particular emphasis in this report is paid to the statistical behavior of currents with mean speeds in the 170 to 180 cm/s range that are reasonably close to shore off Dania Beach, Florida in the region of the US Navy South Florida Testing Facility.

A considerable background of information exists on the Loop Current in the eastern Gulf of Mexico and on the Florida Current, particularly in the northern part of the Straits. This report is concerned primarily with flow properties of the northern Straits. Bottom topography in the northern Straits of Florida is relatively simple consisting a steep walled channel with a maximum depth of about 800 m near the center of the channel. The only topographic feature is a 200 to 400 m deep terrace (Miami Terrace) that forms just south of Miami and extends north to about Hillsboro inlet. North of Hillsboro the bottom slopes rather smoothly offshore from the shelf break to the center of the channel.

The Florida Current is an intense, vertically sheared flow in approximate downstream geostrophic balance with the horizontal pressure gradients. The axial current is sheared both vertically and horizontally. The mean current axis is located about 80 km offshore of Key West, 28 km offshore of Miami, 30 km offshore of Dania and 29 km offshore of Palm Beach.

The data used in his report come primarily from previous studies of Florida Current variability using direct current measurements with shipboard vertical profiling devices. The current data from the Miami section were obtained from profiling current meters lowered at 3 hour intervals from 4 vessels anchored across the Straits over a 17 day period from June 3 to 19, 1971. In addition, current profiles derived from a free-falling "dropsonde" technique (Richardson and Schmitz, 1965, Brooks, 1979) at 12 to 15 stations across the Straits of Miami over a 9.5 year period from May 1965 to November 1974 are used to increase spatial and temporal data coverage at this section.

At the Palm Beach section, current variability is determined using PEGASUS profile data taken as part of the STACS (Subtropical Atlantic Climate Studies) Program. The PEGASUS technique is a free-dropped, acoustically tracked profiler of horizontal ocean current and temperature. These data were collected over a 2-year period on 16 cruises with 9 stations across the Florida Current. These data have high vertical and horizontal resolution and the cruises were made frequent enough to resolve the energetic 2-day to 2-week period motions of the Florida Current.

Since downstream flow in the Florida Current and its statistical properties tends to follow iso baths in the northern Straits of Florida, one can estimate the statistical properties of the flow off Dania near the 290 m iso bath by interpolating from stations at similar depths at Palm Beach, Bal Harbor and Miami. Here, we use the estimated flow statistics for the 290 m iso bath at 30 m depth off Palm Beach given above and the statistics given in Table 7 for a location 18.5 km offshore of Bal Harbor Beach with a total water depth close to 290m. This interpolation for the 290 m iso bath 17 km offshore Dania Beach at a depth of 30 m gives a mean downstream flow of 171 cm/s with a standard deviation of ± 42 cm/s giving an expected range over a 2-week period of 129 to 213 cm/s. The mean cross-stream current is estimated at 7.4 cm/s with a standard deviation of ± 17.5 cm/s giving an expected range of -10 to 25 cm/s. The mean current speed is estimated at 171 cm/s with a mean current direction of 360° ± 11°. The minimum currents estimated for this location are 22 cm/s downstream flow and -22 cm/s cross-stream. This would result in a minimum current vector with a magnitude of 31 cm/s toward a direction of 315°.

Under normal operating conditions, the currents 17 km off Dania Beach at a depth of 30 m are expected to be toward the north with direction deviations of ± 11° and changes in current speeds ranging from 129 to 21 cm/s over any 2-week period due to the passage of Florida Current meanders and small scale frontal eddies. However, on occasion, possibly as often as 3 or 4 times per year, larger frontal eddies can move northward through the region causing a large offshore shift of the Florida Current axis and greatly reduced currents at this position. Under these conditions, current speeds could be reduced to 30 cm/s or less and current direction could be onshore or even reverse to the south. These events could last one or two days and during this time, the Ocean Current Power Generator will maintain its depth and be prepared to resume generating electricity when normal current flow returns.

5.2 - Report of Dr. Venezia

Dr. Venezia's report provides valuable information needed to plan and install the Ocean Current Power Generator in the Gulf Stream. Excerpts from his report follow. Dr. Venezia's interest in extracting power from the Gulf Stream was proclaimed in his article, "Turbine Under Gulf Stream: Potential Energy Source." [2]

Dr. Venezia presents climatological and oceanographic data as a compendium of information relating to the segment of the Straights of Florida east of Fort Lauderdale, Florida. Given are a general description of the location, overview of the climate and an overview of the ocean conditions characteristic of the area. Included is information on the bathymetry east of Fort Lauderdale. The area of consideration is an active Navy test range operated by the Naval Surface Warfare Center South Florida Testing Facility. Addressed in this report are the activities of the Navy range as they relate to working in the ocean environment under consideration.

Having a subtropical climate, southern Florida is under the domination of the northeast trade winds. The modifying influence of the Atlantic Ocean on the Florida Peninsula is responsible for relatively mild and moderately humid winters while summers tend to be long periods of warm humid weather. Abundant showers normally fall between May and September. A small daily temperature range is typical of the marine influence on climate here, as is the fact that the annual rainfall on the beach is on the order of 10 inches less than 10 miles inland. In wintertime, freezing weather and frost conditions seldom extend below central Florida. Intensification and westward spreading of the Bermuda High between May and September precludes penetration into the region by continental frontal systems and brings typical subtropical weather accompanied with light breezes to Fort Lauderdale.

During the winter months, only the most vigorous polar outbreaks are normally able to penetrate as far south as Fort Lauderdale. Then, instability accompanied by fast moving winter cold fronts may trigger thunderstorms during which winds may exceed gale force (greater than or equal to 34 knots) and generate rough seas. Following is a typical summary of Local Climatological Data for the Fowey Rocks station in Miami, Fl.

The water characteristics east of Ft. Lauderdale are highly variable, and as improved observational techniques have been developed, the extent of this variability has become more acutely appreciated. East of Ft. Lauderdale is the Florida Current portion of the Gulf Stream system (a major well-studied western boundary current). The Gulf Stream system consists of a composite of (1) the Gulf of Mexico Loop Current, which is highly variable anticyclonic system occasionally detaches from the main flow; (2) the Florida Current, which is a relatively stable jet whose near-surface flow occasionally exceeds three meters per second, and (3) the Gulf Stream, which is mildly unstable off Georgia and which becomes strongly unstable after leaving the continental land mass at Cape Hatteras. Observations have shown that the mean flow of the Gulf Stream past Florida (Florida Current) is close to 30 Sv, but that fluctuations up to 15 Sv (50% of the mean) occur with periods of 30 to 60 days. These may be related to meteorological forcing upstream (between the Mid-Atlantic ridge and the Gulf of Mexico) or to other, more distinct factors responsible for short-term climate variations.

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UEK Drag Force Calculations and Project Review

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OVERVIEW

The purpose of this report is to provide an analysis of the dynamic forces expected to be imposed on the Underwater Electric Kite (UEK) during deployment offshore south Florida in the Florida Current, and provide a general review of the overall system design. The procedures, assumptions, and conditions used in determining these forces are discussed along with discussion on system stability and issues that may affect operations when deployed.

This report was developed under contract with Abacus Controls Inc., PO Number 37763.

BACKGROUND

The Underwater Electric Kite (UEK) is a device designed to extract energy from the flow of the Florida Current, and convert this energy into useable electric power. The design of the UEK requires the unit to remain in the highest water velocity region of the Florida Current in order to extract the maximum amount of energy. This requirement exposes the unit to large drag forces, as well as other dynamic forces resulting from the flow of water around and through the unit.

In order to properly design and model the UEK system, certain parameters must be determined. These include the predicted drag and lift forces on the unit, a reasonable approximation of the drag coefficient, and a range of conditions and forces to which the system may be exposed. With this basic information, the rest of the system (mooring cables, anchor systems, control systems) may be reviewed and analyzed prior to advanced design and installation.

The specific tasks are indicated in the following sections, along with the analysis and results of each task.

Task 1. Establish the principal forces acting on the UEK and determine approximate drag coefficient. Describe methods of calculation and coefficient determination.

The UEK is a fairly unique shape as far as submerged objects are concerned, and as such very little information on such shapes regarding hydrodynamic forces exists. The UEK may be analyzed using various assumptions and methods, however, with each providing an estimate of forces on the unit. A series of methods were used to determine an approximate drag coefficient for the UEK in the velocity fields expected at the deployment site.

CONDITIONS AT DEPLOYMENT SITE

The predicted conditions at the UEK deployment site are vital for the determination of forces on the unit. The proposed deployment site is about 10.5 miles offshore Dania Beach, Florida in approximately 950 ft of water. The actual UEK operating depth is approximately 100 ft deep, near the core of the Florida Current. The Florida Current is the portion of the Gulf Stream that connects the Loop Current in the eastern Gulf of Mexico to the Gulf Stream as it proceeds into the open Atlantic Ocean beyond Cape Hatteras, NC. The Florida Current flows through the Straits of Florida, a curving conduit that joins the Gulf of Mexico and Caribbean to the Atlantic Ocean. The Florida Current passes closet to shore between Miami and Palm Beach, with the closest approach occurring off Dania Beach, near the proposed deployment site. While direct current measurements in the core of the Florida Current off Dania Beach are not available, data from Miami and Palm Beach were used to estimate water velocities at the deployment site (Table 1).

Flow Condition	**Cm/sec**	**Ft/sec**	**Knots**
Average	171	5.61	3.32
Minimum	31	1.01	0.58
Low Range	129	4.22	2.50
High Range	213	6.98	4.13

Table 1
Estimated Water Velocities at UEK Deployment Site
30 m depth (100 ft)

It must be noted that these are predicted conditions, and the flow in the proposed deployment area has been known to reverse or essentially stall for a short period of time due to large frontal eddies. While not directly relevant to this analysis, these phenomena could have significant implications regarding the UEK mooring design.

In addition to water velocity, other required parameters include water temperature and salinity. The estimated water temperature at the deployment site is approximately 72° F (22°C) with salinity between 35 and 36 parts per thousand (ppt). These values provide two other required water properties, the density and kinematic viscosity, with values of 1.987 slugs/ft^3 and 1.0816 x 10^{-5} ft^2/s, respectively.

UEK CHARACTERISTICS

The UEK is essentially a large, oblong shape with its largest surface area exposed normal to the flow, thereby providing the largest area of drag (Figure 1). Within this area, two 20 ft diameter turbines are mounted to facilitate maximum flow exposure. The total projected area of the UEK normal to the flow is 730 square feet, with a total width of 40.16 ft and height of 22 ft. The UEK has a width to height width ratio normal to the flow of 1.825.

Each turbine consists of 7 blades, with a projected area of about 26.5 ft^2 per blade. The blades are twisted to maximize flow and thrust, yet may be approximated as a curved vane with a 54° incline above the horizontal. The turbines are free to rotate in the current, thereby generating electric power via connected generators. While free to move, the blades still provide some resistance to flow and therefore contribute to the overall UEK drag force.

The overall projection of the UEK to the flow is best approximated as a large flat plate, with the same projected area and width to height ratio. This flat plate method provides a starting point that provides the maximum resistance to flow, and therefore the theoretical maximum drag force. This method also neglects the reduction in overall drag afforded by the water passing through the turbine blades. Several tables and graphs are available for flow around a flat plate normal to flow, and these provide a drag coefficient based upon Reynolds number.

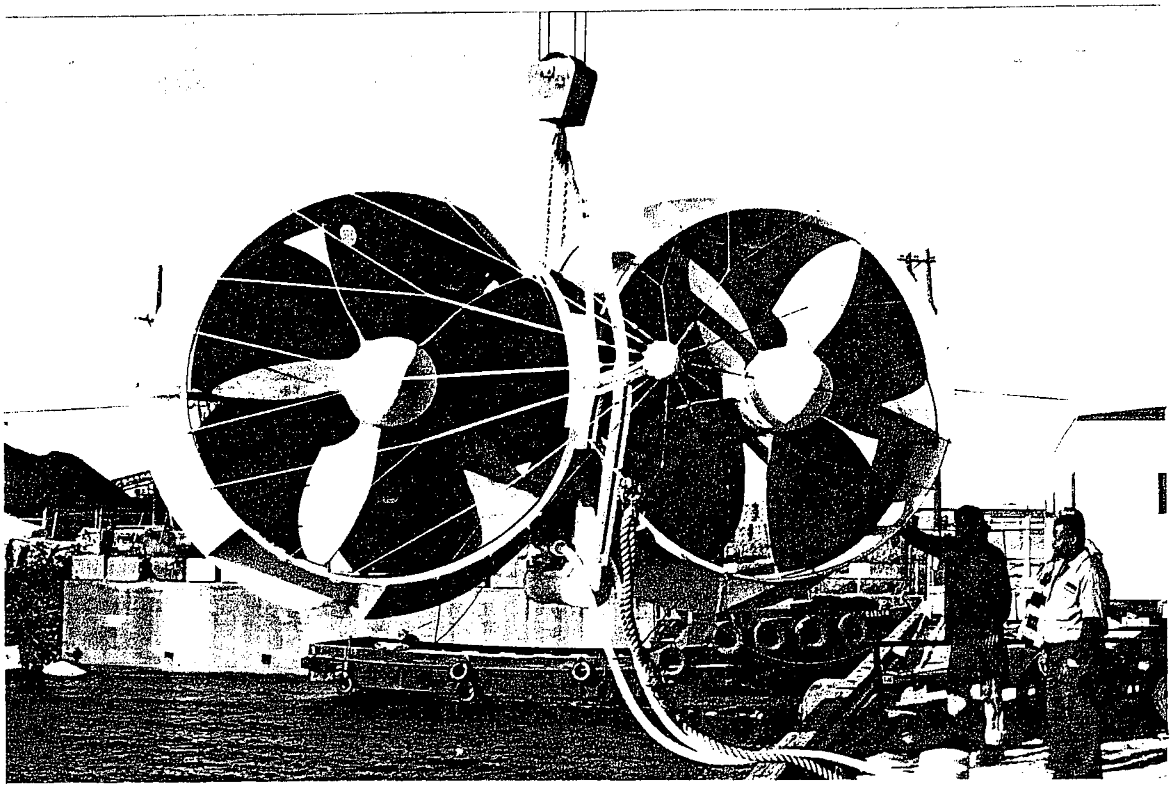


Figure 1
UEK (10 ft Diameter Blades, 5 Blades per Turbine Shown)

The Reynolds number expresses in nondimensional form a ratio between inertia forces and viscous forces on the fluid particles flowing around an object. The effects of Reynolds number of the flow about, and the resultant forces on, a body depend on the body shape. The shape for the UEK uses the flat plate analogy, taking the height as the characteristic dimension. The Reynolds number (Re) for a particular flow may be calculated by the equation

$$Re = V_0 d/\nu$$

where d is the characteristic dimension (height in this case), V_0 is the water velocity, and ν is the kinematic viscosity. One key use of the Reynolds number is to determine which type of flow an object experiences, whether it is laminar (smooth) or turbulent. Turbulent flow is often preferred in design since the layer adjacent to the body becomes infused with high-velocity, high-momentum fluid particles, which tend to disrupt pressure drag and reduce overall drag forces. This change is usually triggered at $Re > 10^5$. The range of Re for the UEK deployment from minimum to maximum water velocities is 2.05×10^6 to 1.42×10^7, with an average velocity Re of 1.14×10^7, indicating turbulent flow for all estimated water velocities.

FLAT PLATE METHOD

The UEK appears to the flow as a flat plate, yet unlike the flat plate flow passes through the turbines to the rear side of the unit. This is a fundamental difference in determining drag based on the flat plate analysis, because of the difference in pressure between the front and rear sides of the UEK and flat plate. In the case of a flat plate, the pressure distribution on the front side is positive relative to the pressure on the rear side, due to the differences in flow across the front surface and away from the rear surface (Figure 2).

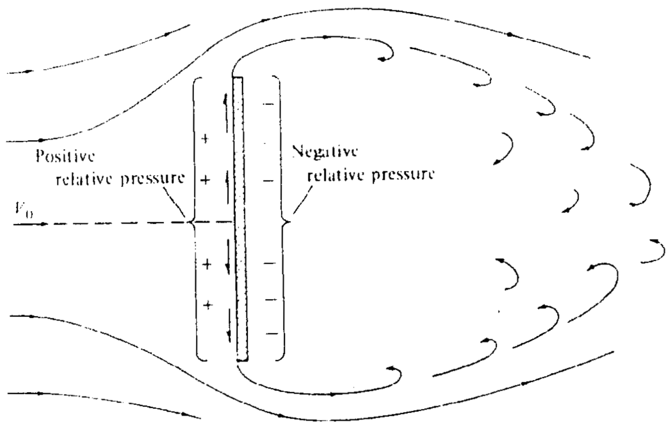


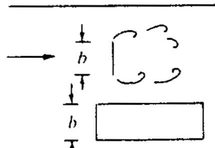
Figure 2
Flow Past a Flat Plate

This pressure difference is similar to that across the surface of an airfoil, where the difference in flow velocities creates lift on the foil. In the case of the flat plate, the pressure force only acts parallel to the flow, and therefore contributes totally to the drag of the plate.

A similar effect is experienced by the UEK, although due to the flow of water through the drag "surface" the pressure difference between the front and rear of the UEK is not as great as that of the plate, and therefore the drag force is not as large. The use of the flat plate method, however, is an effective way to estimate the theoretical maximum drag force the UEK may experience with no regards to the turbine blades and passage of water. The total drag of a plate normal to the flow, or the UEK in this case, is given by

$$F_D = 0.5\rho C_D V_0^2 A_p$$

where A_p is the projected area, V_0 is the water velocity, ρ is the water density, and C_D is the drag coefficient. This drag coefficient is dependent on the Reynolds number, and published values of C_D are available (Figure 3 and 4).



Type of Body	Length Ratio	Re	C_D
Rectangular plate	$l/b = 1$	$>10^4$	1.18
	$l/b = 5$	$>10^4$	1.20
	$l/b = 10$	$>10^4$	1.30
	$l/b = 20$	$>10^4$	1.50
	$l/b = \infty$	$>10^4$	1.98

Figure 3
Approximate Value of C_D for Rectangular Plate

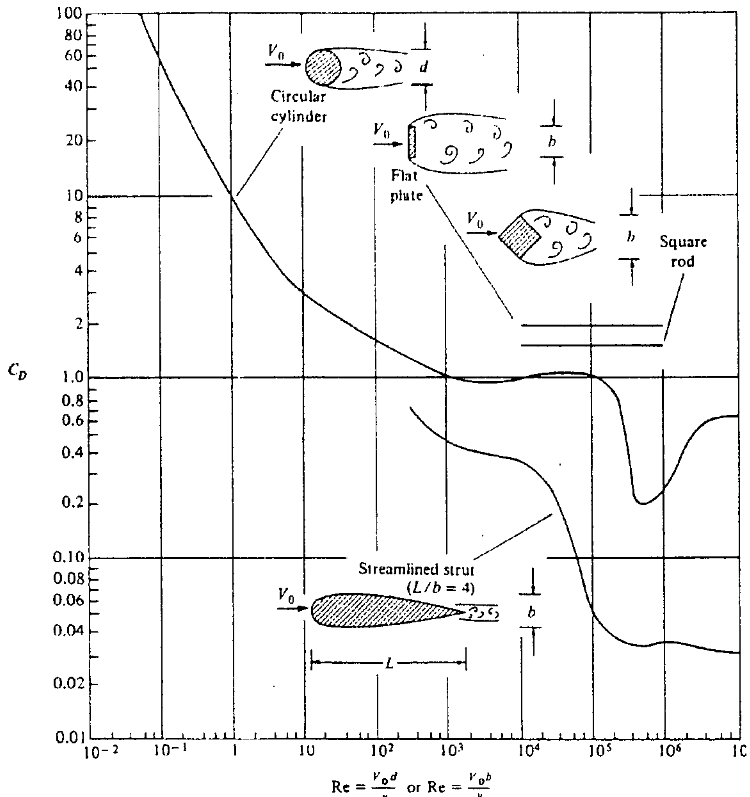


Figure 4
C_D versus Re for Various Bodies

The drag coefficient for a flat plate at RE > 10^4 and a length to height ratio of 1 is between 1.18 and 1.20; a value of 1.19 was used for this analysis.

Using the above equation and C_D = 1.19 the UEK drag force ranged from 880 lbs at the lowest velocity to 42,048 lbs at 6.98 ft/s. It must be noted, however, that a small change in drag coefficient C_D can lead to significant differences in estimated drag, in some cases several thousand pounds for the UEK. For the purpose of this flat plate "worst case" estimation, however, the choice of 1.19 is appropriate.

MOMENTUM METHOD

Another method of estimating the UEK drag forces is by looking at the forces on the blades themselves and then adding the drag from the rest of the unit. This blade analysis utilizes the conservation of momentum principle, which states that (from Newton's second law) the summation of all external forces on a system is equal to the rate of change of momentum of that system, $\sum F$ = d(momentum)/dt. In fluid mechanics, the basic form of the equation applies when there is a uniform velocity in the streams crossing the control surface, as long as the control surface delineates the body of interest. The momentum equation is commonly used in the determination of the force exerted on a piece of equipment, such as a nozzle or bend in a pipe, given a certain discharge and pressure. In the case of the UEK, an individual blade may be taken as the body of interest, and the volume of water passing over it as the mass in the control volume. The mass flow rate, m, is used in this method, and is defined as

$$m = \rho A_p V_0$$

where ρ is water density, A_p is the projected blade area (about 26.5 ft^2), and V_0 is the water velocity.

Two methods may be used, one which simply assumes the flow strikes the blade and water flows in both directions along the blade, and the second which conserves all of the fluid throughout the change in flow direction. Both methods will be used and the results compared. The contributing drag from the rest of the structure, approximately 346 ft^2, was determined using the flat plate method and C_D of 1.19, for a maximum non-momentum drag force of 19,759 lbs.

The first momentum method is similar to the projected area drag calculation method. The method assumes frictionless flow along the surface, the flow strikes a surface inclined at some angle θ, and the only force on the surface is normal to the surface (Figure 5).

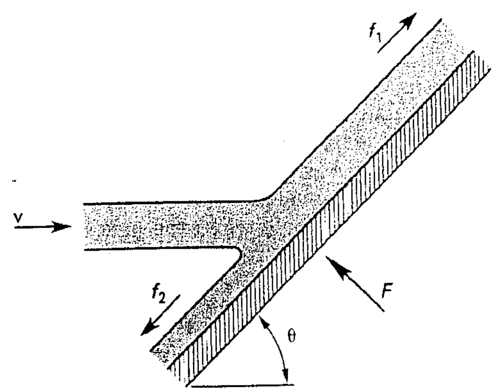


Figure 5
Flow Striking an Inclined Surface

The force perpendicular to the surface is found by

$$F = mV_0 \sin\theta$$

The force in the direction of flow, i.e. drag force, is given by

$$F_D = mV_0 \sin\theta / \sin\theta, \text{ or simply } FD = mV_0$$

which is also equal to

$$F_D = \rho A p V_0^2$$

which is the familiar drag force equation without the drag coefficient, C_D. By assuming frictionless flow, and accounting for the pressure drag by maintaining constant flow, the need for the drag coefficient is eliminated. This provides a method of determining drag while accounting for the blade effect, which was not possible in the flat plate method due to the pressure issues.

So, using the inclined surface method, the UEK drag forces in the direction of flow ranged from 53 lbs per blade at the minimum velocity to 2,565 lbs at 6.98 ft/s, with a drag force of 1,,657 lbs per blade at the average water velocity. Multiplying these blade drag values by 14 blades, the resulting UEK drag from blades range from 742 lbs to 35,910 lbs, with an average drag of 23,198 lbs. Adding the non-blade drag force, the maximum drag force is estimated at 55,669 lbs.

The second method assumes a fixed vane that effectively changes the direction of the entire flow, which results in two reactions. The x-direction reaction contributes to the drag, while the y-direction reaction is countered and cancelled by the reactions on the other blades (Figure 6).

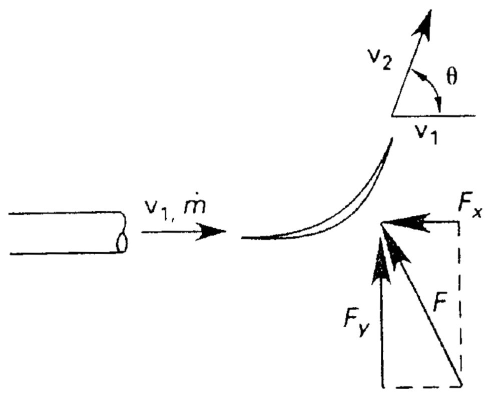


Figure 6
Flow Striking a Vane

Once again the mass flow rate, m, is used, and the assumption is made that the flow is constant. The UEK vane angle is approximated at $\theta = 54°$ above the horizontal. Since two components of the reaction force are used, the change in velocity for both directions is found by

$$\Delta V_x = V_2\cos\theta - V_1 \quad \text{and} \quad \Delta V_y = V_2\sin\theta$$

The reaction forces are then found from the mass flow rate and the change in velocity,

$$F_x = m\Delta V_x \quad \text{and} \quad F_y = m\Delta V_y$$

The F_x force contributes to the drag force, while the F_y force is exerted outwards from the hub of the turbine, along the blade at an angle of θ degrees. This is countered by the outward force from the other blades arranged around the hub, and is therefore cancelled. This method is more analytical in that it accounts for the entire flow and all of the forces associated with the redirection of the flow.

Using this method, the blade drag forces ranged from 22 lbs to 1,057 lbs per blade; with an average flow drag of 683 lbs per blade. Again multiplying by 14 blades, the total drag for this method ranges from 308 lbs to 14,798 lbs, with an average flow value of 9,562 lbs drag. Adding the non-blade drag force, the maximum drag force is estimated at 34,557 lbs.

Please note that in both momentum methods, the fluid rotation, or vorticity, was not considered. Due to the unique and complicated nature of the water flow though this turbine, and the lack of either methods or empirical data dealing with such a configuration, the rotational effects were assumed negligible. The turbine symmetry, however, will most likely result in cancellation of vorticity effects in a fashion similar to the opposing y-forces indicated in the vane method.

CONCLUSIONS AND RECOMMENDATIONS

The various methods used to determine the approximate drag forces on the UEK during deployment resulted in different values, ranging from about 35,000 to as much as 56,000 lbs in the maximum anticipated current field. While each method approaches the problem from a different perspective, they all indicate that the drag forces on the UEK will be substantial, and as such the entire system must be designed to carry the loads.

The largest calculated drag force resulted from the first momentum method, which used both momentum change and flat plate resistance for various parts of the turbine. This method resulted in a drag force of 55,669 lbs at a flow velocity of 6.98 ft/s, or 4.13 kts. This value, **55,669 lbs**, should be used, along with an appropriate safety factor, in all system designs.

The most basic approach, that of the flat plate method, predicted UEK drag force at 42,048 pounds for the highest flow. This force was determined using a drag coefficient of 1.19, based upon a Reynolds number of 2.05×10^6, indicating turbulent flow through the turbine. While the UEK is not exactly analogous to the flat plate, the flow behavior should at least resemble flat plate flow. The difference between this result and the maximum drag force is most likely due to differences in the flow characteristics through the turbine blades and the inability of the flat plate method to account for this flow.

The second momentum method, calculating momentum changes across a stationary vane, resulted in the lowest predicted drag force, 34,557 lbs. The reason for the lower value is likely due to the cancellation of the momentum y-component, which is deflected out at approximately 54 degrees radially, with the forces around the turbine essentially canceling each other. The only remaining drag forces are those parallel to the water flow, essentially the force multiplied by cosine of 54 degrees. Intuitively, this force seems quite low, given the size of the UEK and the relatively high water velocity passing through and around the unit. This value is not recommended for use in the design process, and should only be used for comparison with actual drag measurements obtained during field testing.

In regards to a drag coefficient for the UEK, given the range of predicted flow velocities at the deployment site, the best approximation is found using the drag force from the momentum method and the projected area of the flat plate method. The flow is turbulent at all predicated velocities, and in a turbulent flow domain, form drag is more significant than viscous drag. Using the momentum drag force in the basic drag force equation, $F_D = 0.5\rho C_D V_0^2 A_p$, an equivalent drag coefficient that would yield the same value is **1.58**. This coefficient value is based upon form drag measurements and the value of the highest calculated drag force, and as such should be used in all modeling and simulation efforts. Since most cable modeling programs use basic drag equations as part of their algorithms, this coefficient is most appropriate, and should yield the most conservative values. It must be stressed that in the design of at-sea systems, conservatism is not only prudent, but also oftentimes essential for success.

Task 2. Review overall design and provide comments.

The UEK device and its associated mooring and support systems pose a daunting engineering challenge, and involve a wide range of issues that must be considered. Any one issue could be sufficient to cause total system failure, or at least significant downtime and expensive repairs. Many of these issues have been identified, and the purpose of this task is to review the overall system from a global perspective, as opposed to a component-level viewpoint. Such global issues include types of models and simulations that should be conducted, mooring system design, issues related to system degradation, and actual deployment, maintenance, and recovery of the system at sea. This review is based upon past experiences in the field of ocean engineering and first-hand knowledge from actual projects at sea. Information on the existing system has been gleaned from drawing packages, project descriptions, SPIR progress reports, and numerous conversations with project personnel (George O'Sullivan, Bob DeMilia).

SUPPORT VESSEL

The most important issue regarding the actual deployment of the UEK is the choice of support vessel, and the assurance that the vessel can handle not only the UEK, but also the myriad of other equipment required for deployment, and the ability to operate in the core of the Florida Current. Similar large structures have been deployed in the waters off south Florida, some ending with success and others with abject failure. Causes have ranged from a lack of understanding regarding oceanographic and bottom conditions to blatant disregard for such factors in pursuit of the objective. The deployment site is subject to high currents, heavy seas, and uncommonly strong winds during most of the year, all driven by the presence of vast amounts of energy-rich, warm ocean water carried by the Florida Current. These factors can conspire to seriously impact at-sea operations.

The size of support equipment required to handle objects such as the UEK also require an adequate platform to operate safely. While the UEK will be submerged at or near the surface during transit to the site and during deployment, the system will experience considerable drag forces and probable shock loads while exposed to wave action, and will transmit these loads to the handling equipment. The use of undersized equipment or support vessel would pose significant risk to the UEK, deck personal, the vessel itself, and the project overall. An adequate weight handling system, ideally a crane, adequate deck space, dynamic positioning capability, and sufficient stability to work in the range of sea states is essential. An ROV is also required for connecting to the shore cable, and any required site preparation work. Again, the ROV must be capable of operating in large currents and dynamic conditions.

Other issues more specific to the UEK system include the types of computer models that should be run during design, the mooring system, and modifications to the UEK itself to improve performance. The UEK system is basically a subsurface mooring system consisting of an anchor system, mooring line, ballast vessel, and the UEK. While straightforward conceptually, the actual deployment of such a system is subject to a wide range of forces, including drag, lift, cable stress and strain, corrosion, biofouling, and mechanical fatigue. Each factor must be addressed to prevent total system failure. Of these factors only one, mechanical fatigue, will not be addressed in this report. Since this factor is primarily associated with the actual turbine generator system (blades, shafts, etc.), this analysis is left to the UEK designers. The other factors are ocean-dependent, and will be discussed.

MODELING AND SIMULATION

The deployed system configuration should be modeled and simulated prior to advanced design to determine approximate loads that may be imposed on the system. Experience has shown that since the advent of computer modeling, significant time and funds have been saved by the use of computer simulation prior to deployment. Factors such as cable drag and lift, strumming, and line tension become increasingly important with longer lengths and higher currents. Body drag is also important, as well as surface interactions. While the UEK is designed to reside at approximately 100 ft below the surface, during deployment, recovery, and large storm events, surface wave effects could occur. This periodic forcing could increase system loads beyond design limits if not considered during the design phase.

The recommended simulation program is SEADYN, a finite-element computer program that allows user-defined cable systems to be modeled dynamically. The output is organized into coordinates, velocities, and tensions for each element and node in the model. This program has proven very effective for numerous Navy and civilian projects, and has been verified through actual at-sea testing.

MOORING SYSTEM

The mooring system must be designed to resist all forces acting upon it, during normal conditions as well as extreme events. The proposed mooring configuration described in the October 25, 2001 Progress Report shows the UEK and ballast vessel moored in 902 ft (275 m) of water on a 2952 ft (900 m). The scope of this mooring design is 3.2 to one (line length to depth). Most mooring designs use a minimum of 5 to 1 scope for drag embedment type anchors. Shorter scopes are possible with other types of anchors (pile, deadweight, and direct-embedment), but associated costs increase significantly, especially in deep water. Bottom composition is also important to the effectiveness of the anchor, and must be determined prior to anchor type selection. The bottom type in the deployment area is typically a sand-silt mixture covering more consolidated materials. Drag embedment anchors have been used successfully in the area, and provided enough scope, would be an economical and functional solution if designed properly.

The mooring line must be capable of holding the ballast vessel, UEK and itself in the current, and also be capable of resisting corrosion, strumming, and biofouling. The mooring cable should be independent of the electrical cable, unless the electrical cable is specifically designed to function as a load-bearing cable. The cyclic forces experienced by the mooring cable would eventually fatigue the electrical cable conductors to failure, and could also damage any connectors or splices along the suspended length. Instead, the electrical cable should have its own strength member, capable of supporting the cable and preventing any extreme loads. This strengthened cable could then be married to the mooring cable from the surface to the seafloor, with sufficient slack to prevent force transmission between the two. This bundle of cables will change the drag characteristics of the mooring, however, and should be accounted for in the design.

The ballast vessel connection to both the mooring line and the electrical cable needs to be specified. The attachment connection should be capable of resisting torque and line twisting, as well as vertical and horizontal motions. As the flow varies and the ballast vessel depth is adjusted, the fleet angle, or angle the mooring line tends from the ballast vessel, will change, and this change must be compensated for. The UEK tether connection point must also be designed, so that the tether and electrical cable transition effectively to the UEK.

The ballast vessel adjustment system, which appears to consist of a submersible winch system, needs to be defined in much greater detail prior to any serious mooring system designs. The size, buoyancy, reserve buoyancy, power system, winch system, and anchoring system for the ballast vessel need to be specified. Unlike the anchor system for the mooring, the ballast vessel mooring will not have the benefit of scope or fleet angle, and must resist a force perpendicular to the seafloor. This precludes the use of a drag-embedment anchor, and necessitates the use of a pile, deadweight, or direct-embedment anchor. As mentioned earlier, these anchors require much more effort to properly install, and become increasingly difficult as the water depth increases.

The UEK attachment point is specified at the center of drag, although this has not been indicated on drawings to date. The center of drag, due to symmetry, is at the centerline of the unit both vertically and horizontally. A single attachment point, however, may pose problems regarding yaw in the flow. A better approach may be to use a single attachment point at the center, with two stabilizing guy wires running from the main line to the outside edges of the unit from a bridle-type arrangement. This will provide more stability and resistance to undesirable motions. It is also unclear whether the UEK structure can withstand the drag forces, which in cases may exceed 55,000 pounds. Perhaps an onshore pull test should be conducted to verify that the structure could withstand the loads prior to deployment. The applied load should not be the maximum drag force, but should instead include a suitable factor of safety, perhaps a factor of at least 2 times maximum expected load, and perhaps as much as 3 to 5 times.

MATERIALS AND DEGRADATION ISSUES

The materials required for the mooring and anchoring systems must be strong enough to hold the system, and must be capable of performing for long periods of time. While component weight is not as important for ocean-deployed systems, resistance to corrosion, biofouling, and degradation is very important. The use of steels, aluminum, composites, and synthetics are appropriate, although each has its own restrictions regarding use.

Stainless steel mooring lines and fasteners are a good choice for this application, yet attention must be given to the specific failure causes for stainless steels. Stainless steels are susceptible to pitting and stress corrosion in the absence of sufficient oxygen, and are therefore not suitable for conditions that would deprive them of oxygenated water. Biofouling, or the covering of objects with marine organisms, is one method of depriving stainless steel of oxygen. As the organisms grow on the surface, more and more of the surface is covered until the material is completed encapsulated. Another consequence of this growth is the added surface area and mass in terms of drag. A cable diameter may be increased several times over due to biofouling, with an associated increase in drag, which increases line tension and mooring system loading, potentially overloading the system.

Galvanic corrosion is another factor that could cause problems in the UEK design. Dissimilar metals in seawater tend to establish electric potentials between the metals, with one metal acting as the cathode and the other as the anode. Typically, the anode "sacrifices" itself to the benefit of the cathode, as in the use of zinc anodes to protect steel hull ships. This is notable in the use of two popular marine materials, aluminum and stainless steel. The aluminum acts as the anode, and protects the stainless steel through corrosion and reduction of itself "sacrificially." Mooring lines also tend to create additional corrosion potential due to the flow of water past their surfaces. While not well understood, accelerated corrosion has been observed due to this phenomenon, where insulated materials were still affected due to this dynamic effect. Typically, materials are chosen to minimize these effects, and with proper design, many of these problems can be avoided.

Biofouling is more difficult to eliminate, since the marine organisms do not limit themselves to only metal items, but tend to cling to every surface. The organisms arrive in planktonic form carried by the ocean current, and cling to objects that they encounter. While the high water velocities at the deployment site should reduce initial growth, experience has shown that organisms will still attach to an object in the high flows. Once attached, the organisms cling to the surface and begin to build carbonate structures that are secured to the surface by extremely strong organic adhesives. Some organisms even bore into the surface and physically "anchor" themselves. In addition to interference with moving parts, especially parts that are only operated occasionally such as during deployment or recovery, the organisms add surface area and mass to the structure, increasing drag forces and disrupting flow around and, in the case of the UEK, through the system. This would also happen to the ballast vessel, and could interfere with the depth-adjustment system. Growth could prevent the cables from moving on the drum or prevent the ratchet mechanism from functioning properly.

There are several ways to deal with biofouling, from the use of toxic coatings to periodic cleaning. Several types of antifouling paints and coatings are available, although due to their toxic nature not only to fouling organisms but all marine organisms, they are rapidly becoming prohibited for use. New formulations are being developed, incorporating repellents in the coating, but there is no clear solution to the problem at this time. Another paint-based method is self-fairing or self-leveling paint, which continually erodes their surface layers, thereby shedding any organisms that attempt to attach. This method is also environmentally unfavorable, however, because of the large amounts of materials that could be deposited into the marine environment. This method requires repainting on a more frequent basis than other paint-based methods.

Fiberglass gelcoats are also susceptible to biofouling, with the added problem of coating loss during removal activities. Small sections of gelcoat are lost when the organisms are removed, resulting in a portion of the fiberglass becoming exposed to seawater. Over time, fiberglass composites tend to absorb water, making them heavier and weaker than the original material. Since fiberglass is very difficult to inspect and measure in terms of water absorption, this becomes a larger problem than more conventional materials (steels, aluminum, etc.) The benefits of fiberglass, however, are the immunity to galvanic corrosion and relatively low weight, both in air and in water. Strength is also a benefit, and in some cases the strength of fiberglass is comparable to similar metal structures, with a fraction of the weight. Again, inspection is difficult, and replacement is often the only option if weakness or failure is encountered. Repairs are often not feasible due to degradation of surrounding materials, and the requirement of clean, sold material to insure a good bond.

The only practical method of preventing adverse biofouling effects is routine maintenance, which involves the mechanical removal of growth. In the case of the UEK, this is made more difficult due to the remote site location, logistics of working at the site, the depth of the unit, high currents, and difficulty in cleaning the complex turbine shape. Divers are typically used to clean vessels while in port, however the dangers involved in working offshore in high currents makes such a solution risky at best. The constant risk of becoming swept off the unit and carried away by the current is significant, and even the act of remaining on the UEK to perform useful work becomes almost impossible as currents approach 1.5 kts, much less the 4+ kts expected at the site. Bringing the UEK to the surface for cleaning is an option, but this again involves a support vessel, divers, and the dangers associated with high currents. The UEK must be shut down for the operations, with the associated loss in revenue during down time. The use of a purpose-built ROV system has been suggested, and may be the best solution for this unique application. In the mean time, biofouling must be considered a major factor in the total system design.

DEPLOYMENT, MAINTENANCE, AND RECOVERY

The actual deployment, maintenance, and recovery of the UEK are complex and difficult tasks, yet steps may be taken to streamline the operations. Several issues have been discussed earlier with regards to support vessel, mooring system, and routine maintenance requirements (biofouling). The following discussion relates to the process of putting the system in the water and recovering it for whatever reason, again from a global perspective. Actual details regarding step-by-step operations will not be discussed.

Prior to deployment, the installation site must be established and prepared for the UEK's arrival, ideally well in advance in order to compensate for any unexpected problems that may arise. Cables must be laid to the site, anchor systems and attachment pendants must be installed, and procedures must be tested for connecting the UEK to the underwater infrastructure. The cable end must be laid to the location, either from shore or an offshore junction site, and rigged with a recovery system and enough slack to permit recovery. The anchor system must be installed and set, so that the UEK will not drag the moor and shore cable when installed. The anchor and mooring line must be put in and connected to a temporary support buoy prior to UEK arrival. The ballast vessel anchor system must also be installed and set, and must be ready for reeling onto the depth-control system equipment. As mentioned earlier, this phase of the installation may be the most challenging, given the type of anchor system that may be required.

Once the items have been put in, the ballast vessel should be brought to the site first and installed. Its systems will require specially trained personnel, due to the hazards of working in an enclosed space at sea, in high currents, and with relatively unproven systems. The danger of premature flooding or sinking must be planned for and the personnel working on the vessel must be trained in dealing with such emergencies. The ROV will most likely be required to rig the vessel's lifting line(s) from the seafloor to the surface, and may be required in the event a line is lost or dropped prematurely. All of these contingencies must be described and detailed in the operations plan.

After the ballast vessel is in place, the UEK will be towed out to the site and attached to a tether from the ballast vessel. The electrical cabling, married to the mooring line, will also be connected to the generators. There must be a method of securing the turbine blades during deployment while personnel are working on the unit. Again, personnel will most likely be on the unit making connections and securing lines, and will be exposed to the same hazards as the ballast vessel installation. Once the UEK is secured and connected, the support vessel will stand off during system tests in case recovery is required. If all goes well, the shore will then command the system to descend to operating depth and begin operations.

Routine maintenance would involve biofouling cleaning, turbine lubricant changes, or other inherent maintenance items. Due to the high currents and unit depth, the best method of accessing the UEK will be to bring it to the surface. The ballast vessel and its depth-control system would accomplish this task. A support vessel would be required, but it should not need to be as large as the vessel used for installation. Instead a medium-sized dive boat could be used for servicing the UEK. Ideally the UEK would have access hatches and other devices to simplify planned maintenance tasks, to minimize time required on site and to reduce personnel exposure to the environmental conditions. Modular systems and quick-disconnect fittings for fluid changes and other maintenance would be extremely useful. Personnel restraint systems or attachment points would help reduce worker risk, and improve task efficiency. A strong mooring point for the support vessel would also facilitate better operations. Besides the mooring line attachment point, no other strong point presently exists on the UEK.

UEK recovery would entail disconnecting the unit from the ballast vessel, and either replacing the UEK with a surrogate buoy to hold the tether and electrical cable, or remove the tether and electrical cable from the system along with the unit. In the event the ballast vessel required removal, both the vessel and the UEK would be removed, and a buoy installed in their place to hold the mooring line and electrical cable. A surrogate buoy of sufficient size and design for the high current environment would be required, and should be available on site in the event of an immediate recovery. Storage for such a buoy would also have to be arranged in the vicinity. A large support ship, similar in size to the deployment vessel, would be required, along with an ROV in the event the mooring or cables were lost. The UEK would be removed in the reverse order it was installed; with the support vessel removing the unit from the mooring system and towing the unit back to port. Again, personnel would be involved, so due care would be required in regards to contingency and operational planning.

CONCLUSIONS AND RECOMMENDATIONS

The UEK installation is a complex and formidable task, and it involves a significantly amount of design and engineering in addition to that of the UEK itself to be successful. The deployment site remoteness, oceanographic conditions, and shear size of the equipment and associated loads on the system provide a great challenge. Even the smallest creatures in the sea pose a potential problem, yet with careful and thoughtful designs and planning it will be a success. There are many issues to consider, and may different ways to address them, yet in the end the "one best way" will end in a successful installation. A computer model is recommended, which will provide a large portion of the information needed for the mooring design. More details are needed on the ballast vessel depth control system, as well as the vessel's dimensions, construction, and physical characteristics. The UEK is scheduled for testing in late 2002, and the information gained will greatly assist in the final system design. The issues of corrosion and biofouling must be dealt with, but other aspects of the design must be completed first. This is a very interesting project, and should prove to be very educational and gratifying to all who participate.

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UEK Follow-on System Analysis

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OVERVIEW

The purpose of this report is to provide follow-on analysis of the various forced expected to be imposed on the Underwater Electric Kite (UEK) during deployment offshore south Florida in the Florida Current, and provide recommendations on methods of mooring and stabilization. The procedures, assumptions, and conditions used in this analysis are based upon information provided by Abacus Controls, as well as calculations made during this investigation.

This report was developed under contract with Abacus Controls, Inc., PO Number 37763.

BACKGROUND

The Underwater Electric Kite (UEK) is a device designed to extract energy from the flow of water through its turbine, and convert this energy into useable electric power. The test deployment location for the UEK is the Florida Current, offshore south Florida. The design of the UEK requires the unit to remain in the highest water velocity region of the Florida Current in order to extract the maximum amount of energy. This requirement exposes the unit to large drag forces, as well as other dynamic forces resulting fro the flow of water around and through the unit.

These forces, as well as a general overview of issues relative to UEK deployment and operation, were discussed in a previous report. Based upon that report and other design work pursuant to actual UEK construction, additional analysis and discussion was requested by Abacus Controls.

The specific tasks are indicated in the following section, along with analysis and results of each task.

Task 1. Review attachment point design, drawings, and strength calculations based upon maximum design loads from previous analysis.

The UEK is a fairly unique shape as far as submerged objects are concerned, and as such very little information regarding hydrodynamic forces exists. The UEK has been analyzed using various assumptions and methods, and a worst-case drag load was determined. At a water velocity of 4 knots (6.98 ft/s), the maximum drag force on the UEK was calculated at approximately 100,000 pounds. This maximum load was used for all new calculations in this report. Loads used in the calculations provided as supporting information should be available from the source engineer, JTD Incorporated.

The UEK attachment point is composed of two Type 316 stainless steel (SS) plates held together with 20 1-12 UNF SS bolts, and is located at the joint between the turbine housings. The joint is comprised of two 0.75" thick fiberglass sections made of S500 glass (35% glass with vinyl ester resin). The actual fiberglass lay-up is slightly thicker than the material specifications, with a layer thickness of 0.078" vice 0.016" in the specification. This results in a lower laminate strength, since there is approximately 5 times less glass in the laminate to carry the load ($0.016/0.078 \approx 1/5$). A conservative value of 10 ksi tensile strength plus a safety factor was used in the provided load calculations. Load calculations were also made for this report, as explained below.

The attachment point could experience several types of failure, and each method was investigated. The attachment could fail by bolt shearing, where the bolts fail due to the shear forces imposed by the attachment bracket. The fiberglass material at the joint and between the SS plates could fail in tension, essentially tearing out from between the plates and around the bolts, and finally the stainless steel plates themselves could fail in tension, particularly at the point of smallest cross-section.

The attachment design, which uses two SS plates and 20 one-inch SS bolts, effectively shares the drag load (100 kips) between the bolts, all which are in double shear. The load is also distributed across 10 fiberglass cross-sections with regards to fiberglass loading. The load in the SS plate is shared by the top and bottom plates, which while of different thickness, are assumed to be one plate at the critical point of smallest cross-section.

The force on each bolt is then

$$F_{bolt} = F_{drag} / 20 = 100 \text{ kips} / 20 = 5 \text{ kips}$$

The stress area of each 1-12 UNF SS bolt is 0.663 in^2, so the stress in each bolt is

$$\sigma_{bolt} = F_{bolt} / A_{stress} = 7.5 \text{ ksi}$$

The bolts are in double shear, however, so the shear stress on each bolt is only half, or 3.75 ksi. The shear strength of the bolt is found from its yield strength, 35 ksi, resulting in an allowable shear stress of 10.6 ksi. The safety factor for each bolt is

$$SF = \sigma_{allowable} / \sigma_{bolt} = 10.6 / 3.75 = 2.8$$

This value is slightly less than the factor of 4 provided, yet still indicates the adequacy of the attachment bracket bolts under these maximum conditions.

The cross-sectional area of the fiberglass at the joint, taking the section width at 5.5" (same as stainless plate) is

$$A_{fiber} = (5.5" \times 1.5") - 2(\pi / 4 \text{ in}^2) = 5.25 \text{ in}^2$$

The stress at the fiberglass section is then

$$\sigma_{fiber} = (100 \text{ kips} / 10 \text{ sections}) / A_{fiber} = 2 \text{ ksi per section}$$

Since the as-built fiberglass laminate contains only 1/5 of the specified glass, the strength is only 1/5 of the specified strength, which is 128 ksi. This results in an as-built tensile strength of 25.6 ksi. Since the laminate strength decreases as the load is applied at an angle away from the warp direction, the strength was further reduced to 12.8 ksi, and 10 ksi was the strength used for calculations, as provided.

Using the stress and tensile strength of the fiberglass, the safety factor is

$$SF = \sigma_{tensile} / \sigma_{fiber} = 10 \text{ ksi} / 2 \text{ ksi} = 5$$

which is quite satisfactory for this application, and very conservative.

Finally, the stainless steel plate of the bracket itself has a minimum cross-sectional area when assembled of 6.875 in^2, and a tensile load of 100 kips. The tensile yield strength of the plate is given as 35 ksi. The stress and safety factor for the attachment plates is

$$\sigma_{plates} = 100 \text{ kips} / 6.875 \text{ in}^2 = 14.54 \text{ ksi}$$

$$SF = 35 \text{ ksi} / 14.54 \text{ ksi} = 2.4$$

Which is almost half of the provided safety factor of 4.5. Perhaps a difference in maximum load is used is the reason for the discrepancy.

The conclusion is that the attachment point design seems adequate to restrain the UEK at the maximum expected water velocity, 4 knots (6.98 ft/s) at a drag force of 100,000 pounds. The initial water tests should be monitored closely, however, in the event the drag forces exceed these design values.

Task 2. Describe relationship between difference in turbine performance with drag and degree of yaw with respect to current direction.

The UEK is composed of two counter-rotating turbines that generate electricity as they are rotated by water passing over them. Ideally, the power from each turbine is the same, and the loads and power output is balanced. In the event that one turbine does not perform as well as the other, however, the resulting difference in rotation could induce a change in orientation with the water direction, possibly causing the UEK to yaw and behave unpredictably.

The UEK drag calculations were based upon a variety of analytical methods, each with assumptions based upon water flow across, through, and around the turbines. Each resulted in a range of drag forces, yet they all assumed both turbines would perform identically. The new question is what would happen if one turbine either slowed or stopped relative to the other in a high current.

The most effective way to determine what this would do to the system's stability is to use a combination of the energy method and the forces from the momentum method. Based upon previous discussions and the earlier drag report, the energy extracted from the water results in a drag force in addition to the basic drag caused by a resistance to water flow. The UEK is estimated to produce 120 kilowatts (KW), or 60 KW per turbine. The unit generates 180 horsepower (HP) based upon various efficiencies, with a corresponding output of 90 HP per turbine. This may be converted into a drag force by multiplying by 550 ft-lbs/sec per horsepower and dividing by the water velocity, so each turbine at this power generation level would experience

$$F_{drag} = (90 \text{ HP} \times 550) / 6.98 \text{ ft/s} \approx 7{,}100 \text{ lbs of drag}$$

So, if one turbine stopped or began to turn freely, as in the case of a damaged gearbox, a net moment would be imposed on the UEK of

$$M_{UEK} = F_{drag} \times 10 \text{ ft (distance from center of turbine to attachment point)} = 71{,}000 \text{ ft-lbs}$$

This is in addition to the steady-state drag of the momentum method, approximately 100,000 pounds at the maximum water velocity. The relationship may be stated as a differential, such that

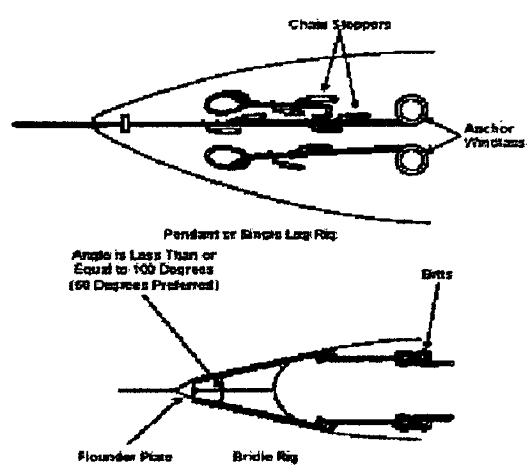
$$M_{UEK} = [(\Delta HP \times 550) / V_{max}] \times 10 \text{ ft}$$

This relationship indicates that only the difference in horsepower will cause an inequality in the drag force and induced moment about the center attachment point, with the maximum at ΔHP equal to the maximum per turbine output.

Another way to estimate this moment is to assume that one turbine is totally open, allowing the water to pass through with no interference, and have the other turbine completely closed. This would result in larger moments, but is less reasonable based upon the UEK geometry. The extracted power method seems to be the best basic approximation at this point, considering the lack of quantitative drag measurements. Once sea trials have been conducted, this relationship can be refined.

Task 3. Explain and provide information regarding method of mooring line attachment, to include both single pendent and bridle configurations.

Task 2 leads into this task, which discusses the various methods of attaching the UEK to its mooring line. Two basic approaches are available; a single pendent attachment and a bridle arrangement (Figure 1).



The single pendent rig is the simplest and most straightforward and is generally used for open ocean towing of ships with fine bows, sonar domes, bulbous bows or when the tow is most stable in this configuration. The advantage of the pendent rig is its ease of connection. There is little, if any, likelihood of the pendent fouling on the structure of the UEK. If the tow is not stable in this configuration, however, the single pendent rig is not capable of stabilizing the tow. The tow tends to rotate about the single attachment point, and under extreme conditions, erratic motions could lead to mooring failure.

The bridle rig is characterized by a two-legged bridle instead of a single pendent. According to the Navy Towing Manual, the length of each bridle leg should be approximately equal to the beam of the towed vessel, or about 60 degrees at each vertex. The fitting at the apex of the bridle is usually a flounder plate with the two bridle legs connected at its base and the apex usually connected to the tow hawser, or mooring line in this case. The bridle rig, by definition, uses two off-centerline fairleads. As a consequence, if the tow does not track directly astern of the tow vessel or mooring line, there may be an off-center dynamic load. This load, while tending to be self-correcting, unbalances the loads on each bridle leg. Therefore, each bridle leg must be of full towline strength (Figure 2).

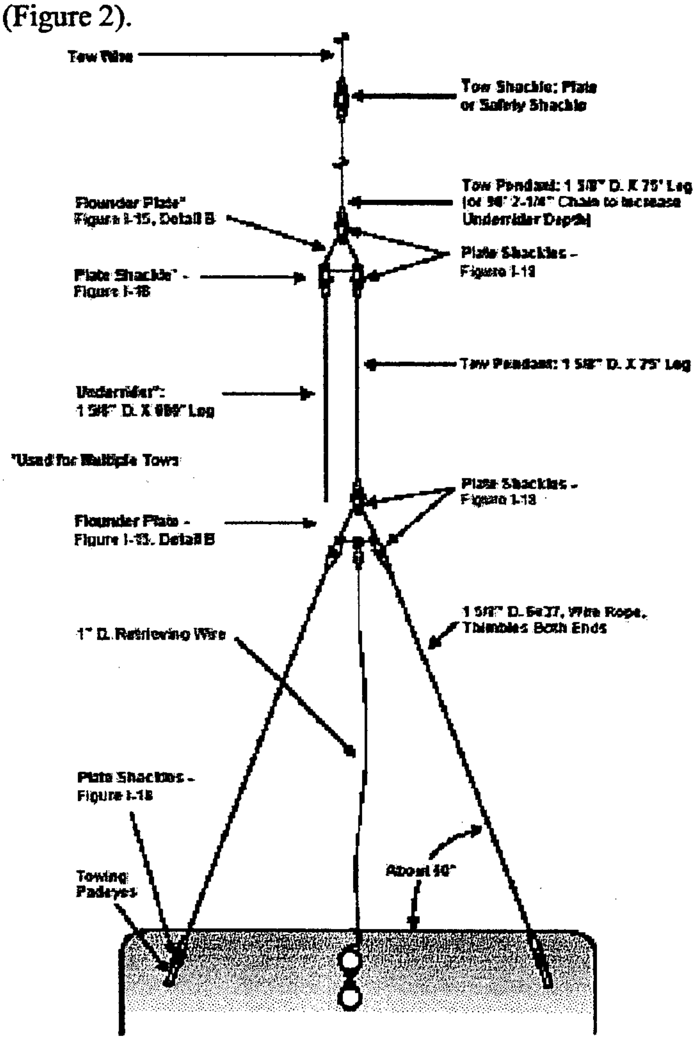


Figure 2 – Example of Wire Bridle with Wire Pendent

Another consequence of the bridle rig is the load imposed on the UEK. As shown in Figure 3, the bridle forces generate considerable compressive forces on the UEK, forces the UEK does not appear to be designed to withstand.

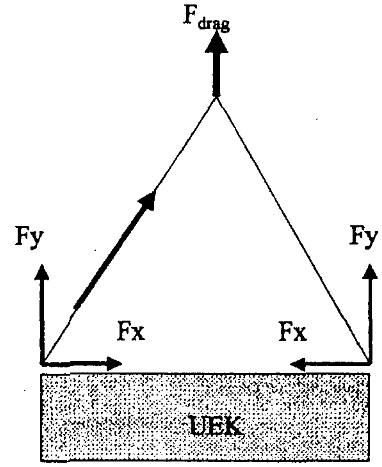


Figure 3 – Bridle Forces

The reactions on the UEK are found by determining the components of the bridle leg tension and bridle angle θ, which is related to the drag/mooring force by

$$T_{bridle} = F_{drag} / (2\sin\theta)$$

The F_y reaction is basically one-half F_{drag}, and the F_x reaction is $T\cos\theta$. Since there are two bridle legs, the compressive force on the UEK structure is $2T\cos\theta$, or $F_{drag}\cot\theta$. Using the 60° bridle angle suggested by the Navy Towing Manual and a 100,000 pound drag force, the compressive load on the UEK would be 57,700 pounds. This compression would most likely damage the UEK structure, or at least affect its performance.

The most feasible mooring arrangement appears to be a combination of the single pendent rig connected to the attachment bracket analyzed in **Task 1**, and a bridle arrangement to counteract the possible drag imbalance described in **Task 2**. In this configuration, the main mooring line would connect to the UEK at the attachment bracket, while two smaller bridle legs would attach to the UEK at the ends of the bearing supports. In the event of an imbalance, the bridle legs would act as springs, effectively countering the induced moment and retaining a perpendicular orientation to the flow.

In order to counter the imbalance-caused moment, the bridle legs must be sized such that they will not exceed their maximum strength while resisting the moment. When required, the bridle leg acts like a spring in that it stretches according to the deflection equation

$$\Delta = (T \times l) / (A \times E)$$

where Δ is elongation in inches, T is cable tension, *l* is cable length, A is cable cross-sectional area, and E is the cable modulus of elasticity. This equation may be arranged to determine the restoring force available for a known stretch, indicated by the magnitude of the cable tension T. For example, if the UEK were to experience a one degree twist from perpendicular, the force required to stretch the bridle cable the equivalent distance, 10 ft x $\sin(1°) \approx 0.17$ ft = 2.04", would be about 56,000 pounds for a 3/8" wire rope! Obviously the wire rope would fail long before it reached this value, but throughout the elongation up to failure it would continuously resist the moment. This shows the importance of understanding the predicted loads and the need to properly size all of the UEK mooring components.

Using the estimated maximum moment from **Task 2**, M_{UEK} = 71,000 ft-lbs, the size cable and deflection required to resist this moment is required, along with the compressive forces on the UEK structure, and the safety factor at the maximum cable tension. The actual F_y component of the bridle leg is simply equal to the difference in drag forces, or 7,100 pounds from **Task 2**. Assuming again the 60° bridle angle and attachment at the turbine center, the bridle tension would need to be

$$T_{bridle} = F_y / \sin(60°) \approx 8{,}200 \text{ pounds}$$

This would result in a deflection of 0.61" for 3/8" wire rope at a safety factor of 1.6 (13.1/8.2), and only 0.086" for 1" wire rope with a safety factor of about 11 (90/8.2).

This result indicates that for the projected moment on the UEK from a turbine failure or unbalanced load, a main mooring cable supplemented by two smaller bridle lines could ensure the stability and orientation of the UEK. Again, these values are all based upon a large number of assumptions, and until real test data is collected, these are only educated estimates of the UEK behavior.

CONCLUSIONS AND RECOMMENDATIONS

The results of this report indicate the UEK attachment bracket is sufficient supporting the drag forces on the system, and there are sufficient safety factors for each mode of potential failure. The drag imbalance section determined that while there is a definite imbalance and induced moment on the system, it is not very large, even at the maximum water velocity, yet is significant enough to warrant attention. The combination single pendent / bridle rig appears to be the best method of restraining the UEK, while also providing a method of self-correction during times of turbine imbalance. While all of these results indicate the system will perform in an actual deployment, only real in-water testing and analysis of the results can insure ultimate success. It can not be stressed enough how important actual test data is for such a unique system, and without that information all of the detailed deign work is only a best estimation of the actual behavior.

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