This manuscript is available at http://ieeexplore.ieee.org/ and may be cited as: Venezia, W. A., & Clark, A. M. (1994). Turbine under the Gulf Stream (TUGS): overview of an energy source potential. In P. Sabathé (Ed.), *Oceans 94 [held in conjunction with OSATES 94]. Oceans engineering for today's technology and tomorrow's preservation: proceedings, [13 - 16 September 1994, Brest - France]*. (pp. 443-448). Piscataway, NJ: IEEE. doi:10.1109/OCEANS.1994.364239

Turbine Under Gulf Stream (TUGS)
Overview Of An Energy Source Potential

William A. Venezia, Ph. D.
Naval Surface Wareface Center Carderock Division
8010 N Ocean Drive,
Dania, Florida 33004-3033

Andrew M. Clark
Harbor Branch Oceanographic Institution
5600 U.S. 1 North
Fort Pierce, Florida 34946

ABREGE **On vous présente les détails de la proposition pour une Turbine Au-dessous du Golf Stream (TAGS), qui a été soumise à l'Agence pour les Recherches des Projets Avancés (ARPA), associée au Projet du Reinvestissement Technologique (PRT). Le but de ce projet est de préparer le plan, de construire et de deployer le prototype nécessaire pour démontrer la capacité économique et technique de l'éléctricité provenant du Golf Stream. Le projet se base en partie sur les desseins de nouveaux générateurs et de nouveaux matériaux technologiques qui augmentent d'une facon significative la possibilité du succès. On vous présente aussi le premier dessein, les suppositions d'entretien et les suppositions économiques. Durant le projet, on mettra complètement à l'épreuve le dessein, les suppositions d'entretien et les suppositions économiques; on les evaluera et on les précisera. Afin d'atteindre du succès complet, le projet doit démontrer la technologie et produire les prototypes des turbines, qu'on pourrait produire en masse et vendre, avec le soutient d'entretien, à une grande variété de clients à travers du monde.**

ABSTRACT **Given are the details of a Turbine Under the Gulf Stream (TUGS) proposal submitted to the Advance Research Projects Agency (ARPA) under the Technology Reinvestment Project (TRP). The project is to design, build, and deploy the prototypes necessary to demonstrate the economic and technical feasibility of generating electric power from the Gulf Stream The project is based in part on new generator designs and emerging materials technologies that significantly enhance the likelihood of success. Presented is the initial design, economic, and maintenance assumptions. The design, economic and maintenance assumptions are to be thoroughly tested, evaluated and refined during the course of the project. To be fully successful, the project shall demonstrate the technology and produce prototype turbines which can be mass produced and sold with service support to a wide variety of customers worldwide.**

I. INTRODUCTION

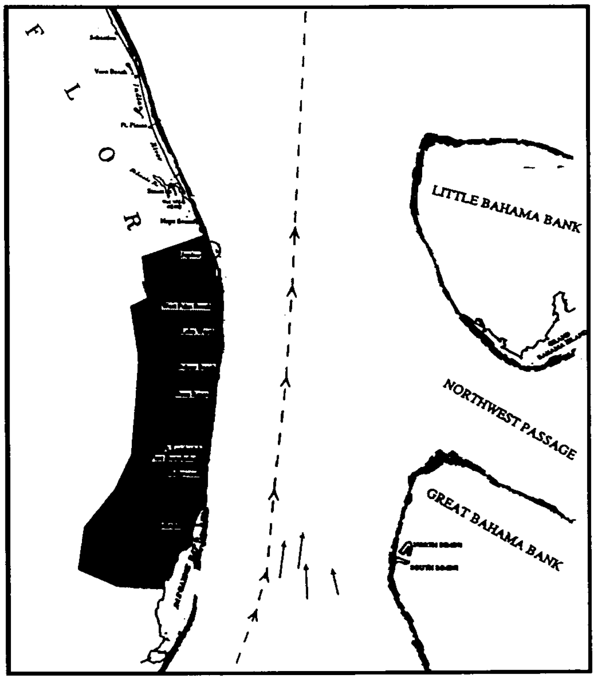
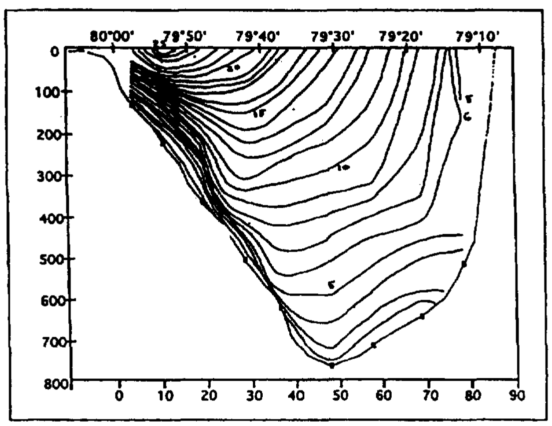


Fig. 1 Florida Current Segment of Gulf Stream

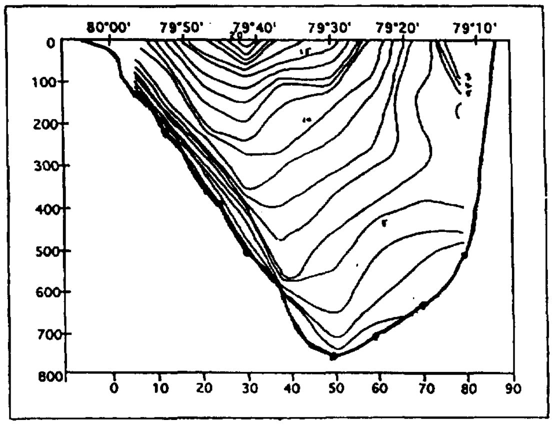
The Florida Current shown in Fig. 1 is a known source of renewable energy and has been considered before for practical use. Part of the Gulf Stream, this current has been extensively measured and studied since the sixties (Schmitz, 1966). In 1974 the McArthur Workshop on Energy from the Florida Current was conducted to explore extracting power from this source. Attending this conference were experts from all the relevant fields from power generation to oceanography (Stewart, 1974). There it was reported that an energy flux exists of about 25,000 MW in any single cross section. By harnessing just 4 percent of this flow, it would be possible to extract one to two thousand megawatts of power (von Arx, 1974). Fig. 2 shows a typical cross sectonal view of the velocity distribution and the variability of the position of the core. It is clear that the most lucrative energy resource lies is in a region about 30 km wide and 100 m beneath the surface (Lee, 1984).

In 1977, the Coriolis Program (Lissaman, 1980) conducted tests on a catenary turbine design by Mouton, Thompson, and Thompson of T.M. Engineering. This design, with a horizontal axis, featured flexible blades secured on peripheral rings which slid around a ducted hull

0-7803-2056-5



Typical Gulf Stream Velocity Distribution



Variability of Gulf Stream Core

Fig. 2 Two cross sections of the Florida Current one typical and one showing normal variability.

on plastic ring bearing pads. Power was transmitted mechanically from the moving rings to multiple generators mounted in the hull. A conical exit duct theoretically increased the water velocity over the blades. A 1-meter diameter model of this novel design was tested in a tank for blade vibration but was NOT tested for its power generation capability.

Only a portion of the energy available due to velocity in an unbounded flow field can be captured by any device with the maximum proportion described by the Betz coefficient of about 59 percent. The efficiency of various types of turbines has been compared in a graph Fig 3. using the ratio of blade tip speed to the fluid velocity as the defining parameter of the differing designs.

The Coriolis Program prepared a set of cost proportionality parameters to calculate the cost of producing any size catenary turbine based on its installation depth. That report concluded that a 170-meter turbine could be built to supply power at a rate of 5.3 cents per kWh at a depth of 420 meters and 4.7 cents per kWh at a depth of 755 meters. Total production costs ranged from $96 million to $110 million (Lissaman, 1980). In 1984, Nova Energy Limited conducted a test of a ducted Darrieus rotor in the Gulf Stream at a depth of fifty feet and a prevailing current of 3 knots. During this 4-hour test the 4-kW design generated 2 kW of electricity. A critique of this design was conducted by Tracor Marine with suggested improvements (Tracor, 1986). In the Nova Limited experiment, Tracor Marine calculated that a 1-MW unit (Darrieus rotor) could be built for just under $3000 per kW. That study predicted that the power from this unit could be supplied at a rate of 8.5 cents per kWh (Tracor, 1986). It should be noted wind turbines have been expensive to build, specifically $2000/kW in the early 1980's. But advances in technology reduced their cost by half by the end of that decade. These advances resulted in a reduction in the cost of wind energy from 25 - 30 cents/kWh to 7 - 9 cents/kWh. These calculations were based on an average annual wind speed of 16 miles per hour (Lamarre, 1992).

Past research indicates that energy can be generated from the Gulf Stream. The problems that existed in the past still exist. There are fluctuations in the current's axis due to winds and tides, and the current is not constant. Since the current is partially caused by the heating and cooling of seawater, the time of year has an effect on current speed. Above all, the ocean is a very difficult environment in which to work. Technology has improved over the past few years, as has our ability to work in the ocean. Therefore, the question is not whether or not a generator can be put in the ocean to generate electricity, but rather can it be done in an economically and environmentally sound way and still be commercially practical.

Much work in ocean current power generation has been a direct comparison with wind turbine technology. While this analogy may be valid in some respects, there are areas where great differences do exist Fig3. shows typical performance of wind turbines. Fig. 4 gives power flux extractible from the Florida Current.

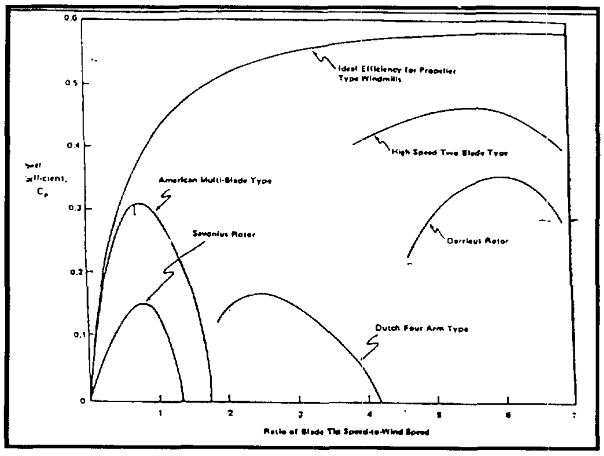


Fig. 3 Typical Performance of Wind Turbines

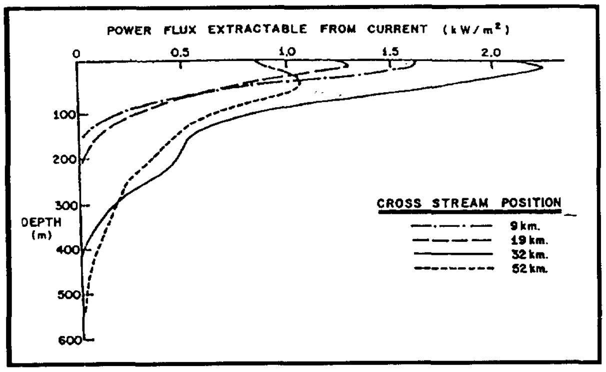


Fig. 4 Power Flux in Typical Florida Current Section

In all of the studies to date, only once has a small prototype been put into the Florida Current, and then for only four hours (Vega). This unit produced only half of its design capacity. A model of a different kind (Coriolis) was tank tested, but only for vibration. Electrically, it was not connected to a load. The two turbine design concepts were extrapolated to gigantic proportions in their effort to provide generating capacity per unit cost which would be deemed commercially significant.

II. DESCRIPTION OF THE ALLIANCE

The alliance brings to bear the talents necessary to solve this complex problem and create a new product line in the power generation industry. A private sector contractor provides related defense technologies in turbine design and manufacturing. In our alliance, they represent the industrial and manufacturing side of the house. They will eventually build ocean turbines for sale at home and abroad. NSWC offers a practical location to test the prototype turbines and an interest in related technologies. The NSWC Fort Lauderdale facility is located at the closest approach to the Gulf Stream on the eastern seaboard. The facility possesses the necessary cables to shore and support facilities to make execution of a pilot project successful and economical. In addition the Carderock Division of NSWC possesses unique knowledge only available from within the government on propeller design, quieting, and electric generator design. HBOI is an internationally respected not-for-profit ocean engineering and marine studies facility. The Founding Fathers of HBOI realized the enormous potential if the energy in the Gulf Stream could be tapped. The work they started nearly 25 years ago is being carried forward by the current engineering leadership who is seeking to bring to practical fruition the visions of those who laid the foundation on which we build. FP&L represents the initial customer in our business alliance. The power generated during the test and evaluation portion of this project will be sold to FP&L. Eventually the turbines (tools) generated from this alliance will be manufactured and sold to FP&L or subsidiaries of FP&L.

All four of the alliance members are actively involved in publishing technology advances in appropriate journals and conference proceedings. TUGS will be a high visibility project to which all the members intend to devote considerable time in the reduction and analysis of data, and its publication, presentation and dissemination to the scientific community and public at large. FP&L has a strong corporate commitment to public outreach and education regarding energy conservation and production. FP&L built and operates a multimillion dollar public museum and education center, "Energy Encounters." Similarly, one of Harbor Branch's major operating divisions is Marine Education. The institution built and maintains its own multimillion dollar Seward Johnson Marine Education and Conference Center and funds as many as twenty simultaneous postdoctoral fellowships, graduate and undergraduate assistantships in the area of oceanographic and ocean engineering R&D. TUGS will undoubtedly serve as the basis of a number of graduate thesis topics.

III. INITIAL DESIGN

The advent of commercial scale wind power generation has proven the concept of an array of reasonably sized wind turbine generators replacing the traditional power plant. The concept works equally well for the generation of power from the Florida Current. As the current is stratified, with the maximum velocities at the surface, it is reasonable to place many reasonably sized units in arrays in the Florida Current, at the surface or just below keel depth of super tankers. Surface deployment always begs questions regarding navigational hazards and surface sea conditions, including the occasional hurricane. These questions are real, with sea keeping capability ranked high in the description of any seagoing vessel design. Possibly the unit generator could be located below the surface, sacrificing some velocity related generating capacity for the relative safety of depth. FP&L believes, as does the alliance, a submerged turbine field may be more reliable in hurricane direct hit than a conventional power plant or a nuclear plant.

In any subsurface concept, the unit generator must be capable of surfacing for maintenance purposes. Considering that routine maintenance and repairs are probably the most important component of "life expectancy," the unit generator and the mooring/power transmission design of the array must include provisions for disconnecting the unit generator and towing it to a shipyard facility within a reasonable distance from the array. Both channel depth and width en route to such a facility become major factors in the design and in the definition of "reasonable size." As this is *routine* maintenance, as each unit generator in the array must be routinely serviced (perhaps every few years), the procedure must not require "heroic effort." Therefore, the means for accomplishment must be reflected in the initial design.

The unit generator in a wind power array is mounted on a tower on solid ground. This is impractical in the Florida Current, as solid ground may be over 1000 feet below the maximum current. It is standard practice to moor buoys from the seafloor with an anchor, or several anchors. A subsurface buoy of proper hydrodynamic shape can be moored in a stable fashion with multiple anchors. Fig. 5 shows how such a system might be configured to form an array. A single cable could attach the unit generator to the subsurface buoy so that it can maintain a heading into minor current direction changes while the subsurface buoys maintain spacing between them.

In this concept, the main power transmission conductor to the shore is stretched between buoys on the bottom. Individual power lines from the generator-towed bodies would be spliced and permanently potted in the anchor. Conductors in the main transmission line could be proportionately (and therefore economically) sized between each anchor pair. The link at the end of the array, carrying power from only one generator, need not be as substantial as the final link to the shore which carries total power from the array.

IV GENERATOR DESIGN

HBOI has developed and tested an electric submarine propulsion unit (thruster) which is significantly more efficient than the current state-of-the-art unit. The basis of this unit is a multipole field or stator assembly built in a nozzle structure surrounding the propeller which is secured in a peripheral ring. A peripheral water-lubricated ball bearing system maintains the ring propeller in its proper relation to the stator, while transferring thrust loads to the stator structure. Torque is applied to the blade tip area where the work is done. The rotor magnets and stator windings are potted solid, and there are no electrical connections between them, only magnetic. This system employs a magnetic flux management technology There are no shafts or seals. Such a generator can easily use rectified multiphase AC output to provide low ripple DC for transmission to the shore with an efficiency of around 90 percent.

Conventional thrusters require an electric motor in a pressure-proof housing, a gear-reduction unit, and a reliable high pressure shaft seal to transmit the mechanical force to the propeller outside the housing. In a one-to-one performance test using identical propellers, the HBOI design achieved the same rpm with 25 percent less electrical power input than a conventional system. This same technology is immediately applicable to electrical power generation. Using the multiblade low tip speed to current speed rotor design, tremendous torque can be applied. This is facilitated by the slow-turning rotor generating electric power in the stator located around the outside of the turbine. The water-lubricated plastic ball bearings work very well in these low speed applications.

Yet another technique generating constant frequency AC power is from a variable speed rotor. This commercially available technology will also facilitate the proposed generator plan in that it does not require any connection to the rotor other than magnetic. Neither of these approaches, DC or AC, require any speed regulation of the rotor, thereby eliminating blade feathering devices or any intermediate variable speed power transmission system. Further, the entire generator, rotor, bearings, and stator can be constructed from plastics, eliminating electrolysis problems and simplifying maintenance and manufacturing.

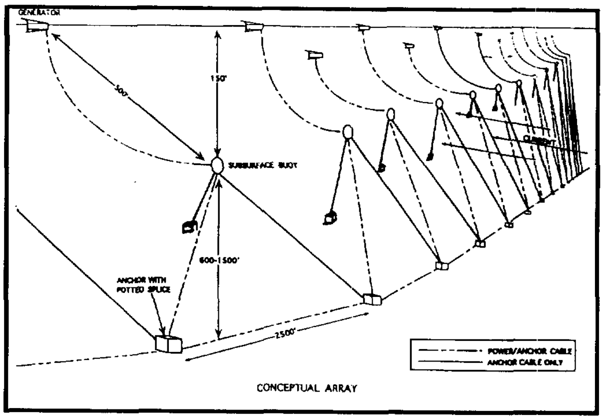


Fig. 5 Conceptual Array of Turbines

V. HULL DESIGN

A hydrodynamic hull shape can be built to maintain a depth with respect to the mooring buoy by changing the angle of attack with respect to the current, Fig 6. The underside of the hull becomes a partial turbine duct and the topside is a hydrofoil shape. The drag of the turbine, located aft, maintains the orientation into the current while on the surface as it pulls against the three-point mooring system. The "sail" contains the navigation lights and the protective electrical chamber. This is only one concept. The unique knowledge possessed by NSWC will be brought to bear on this hydrodynamic design problem. Recent advances in cable and buoy dynamics models and towed system design will be used to optimize the configuration for deployment. The generator, mounted on trunnions, can be rotated 90° to reduce vessel draft by the radius of the turbine. Electrical cabling to the stator passes through the trunnion to a passage in the hull leading to the electrical chamber

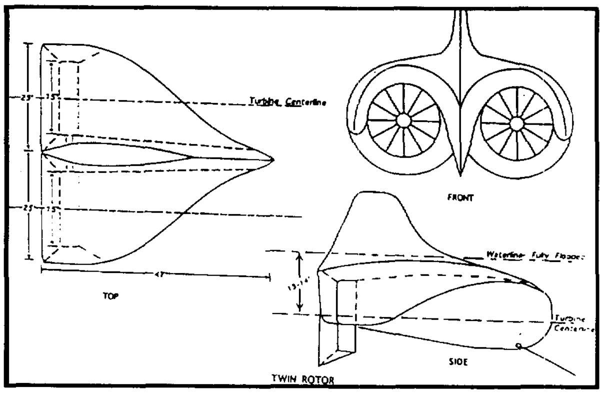


Fig 6. Hydrodynamic Hull Design

The hull will be constructed of high-strength plastic foam covered with fiber-reinforced plastic. Most of the interior would be comprised of ballast tanks. Fully flooded, the hull would float under the surface with only the "sail" protruding through the surface. The ballast tanks would be blown dry to reduce draft as much as possible.

Two legs of a triple mooring bridle are attached to the sides of the hull at a point less than half way back from the bow. The center main leg, carrying the transmission line, is attached forward on the centerline to a movable point. Moving this point forward or aft changes the angle of attack of the hull with respect to the current. The hull then changes depth until a new equilibrium is reached between the lifting force of the hull and the downward pull of the mooring cable. Underwater, the sail acts simply as a stabilizer. Should the hull accidentally go adrift, it will float at the surface with the lighted sail visible to any surface traffic. Considerable torque forces will be transmitted to the hull by the stator in the process of generating power. Consideration of this phenomena is evident by the twin-turbine design using two ring turbine generators side by side in the same hull, rotating in opposite directions. This eliminates any torque-induced attitude changes in a hydrodynamic hull while doubling its disk area. The power generation capacity is doubled without increasing the draft, the main constraint to shipyard access. Again, the U.S. Navy has valuable knowledge which could be brought to bear in the optimization process.

VI. TEST SITE AND TEST DESCRIPTION

Three 640 kW ring turbine generators and an instrumented prototype hull will be tested. The alliance shall install, test, and evaluate the three turbines. The test shall consist of placing two turbines in variable configurations under water in the ocean currents on the 600 ft. depth underwater tracking range. One turbine shall be fixed to a subsurface platform at a constant height above the bottom. The second two turbines shall be moored from the fixed platform in such a way its depth can be varied from surface to near bottom. The fourth turbine shall be used as a spare. The duration of the test and evaluation shall not be less than one year. The test and evaluation shall include as a minimum:

Following are the tasks to be completed.

- Installation of tower and two turbines
- Connection with two type 203 shore power cables
- Connection with fiber optic data and control shore cable
- Measurement of environmental data set
- Receipt and resale of turbine power to FP&L
- Exchange of one turbine with the spare, as needed, or at the half way point
- Recovery of the tower and two turbines

An instrumented test facility will be deployed in 600 teet of water on the edge of the Florida Current at the NSWC test range off the coast of Ft. Lauderdale, Florida. Located at the closest approach of the Gulf Stream the test site has the distinct advantage of providing a varying current. Due to the constant meandering of the current axis there will always be some fluctuation in the current strength. The facility's superb environmental and physical characteristics offer a rare combination of technical, environmental, and logistic advantages including; open ocean environment and unrestricted water. The net effect of choosing a site exhibiting this current variability is a tremendous amount of data for the cost of a single deployment. The site has cabling available for communication with a shore station. The installation consists of a tower whose work platform is 80 feet off the bottom, 30-feet wide, and has end point booms 116 feet apart. This existing massive structure results in a tremendous cost savings and represents a very effective reuse of government funded hardware. The tower will be equipped with sheaves 116 feet apart with a multisheave-line hauler between them. An instrument system with backup battery power supply will control the line hauler and provide communication through a cable to the shore station. A steel cable will be affixed from a deep-water float through a sheave on the upstream end of the tower platform, through the line hauler, through the sheave on the downstream end, to a second deep water float. A generator hull is moored to this downstream float. The instrument system and battery will control and power the line hauler, regulating the depth of the generator mooring buoy. The battery will be charged by generated power and shore power. Instructions (towed body depth, etc.) will be sent from the shore station to the instrument station on the tower via a NSWC submarine fiber-optic cable, and information (battery condition, cable location and movement, etc.) will be sent back over the same fiber-optic link. Power will be transmitted to shore over two type 203 armored submarine cables. The tower will be connected to the shore-link cable and deployed with the two subsurface floats, steel mooring cable, and generator towed body instrument/power cable installed and in place. The towed body attachment end of the mooring/power cable will be payed out and attached to a surface float. The instrument system/shore link will be operated before and after the tower facility is submerged. The generator can be either towed or hauled to the site connected to the mooring/instrument cables, and deployed. Aboard the prototype hull, the parameters being measured include, but are not limited to: roll, pitch, yaw, heave, surge, sway, water flow ahead of the towed body, water flow ahead of the turbine, water flow behind the turbine, pressure differential across the turbine, strain on the mooring cable, depth of towed body, depth of buoy, heading, turbine rpm, and power generated. The hull will remain on the surface with a surface craft tender until all systems are checked out and working. Among the variables controlled by the instrument system will be generator loading, tow point (attitude) adjustment, etc. Towed body depth for subsurface tests can be controlled by both attitude adjustment and subsurface float depth adjustment at the tower. Free-field water flow velocity measurements will be made from an acoustic Doppler current profiler bottom mounted on the 600' range. Under these real operating conditions such parameters as turbine blade design, exit or augmentation cone value, hull design, mooring design, maintenance needs, and real power extraction capabilities will all be analyzed experimentally. The generators will be controlled and monitored from the shore station. No tender vessel will be necessary on station. The test tower that will be used for this project has previously been installed on the NSWC test site in a major joint operation conducted by HBOI and NSWC. NSWC's cables are available for complete monitoring of the underwater turbine system, and to allow communication with the monitoring devices, and of course, to transmit power back to shore.

FP&L will install equipment to condition, monitor and record the power being produced. The power itself will be sold to FP&L, and therefore, this particular pilot R&D program will actually be producing revenue during its term. The prototype model will produce enough electricity to provide power for long term experiments on the system. We will generate based on a conservative assumption (20 percent of design output) $50,000 in power sales during the one year deployment.

VI. REFERENCES

Lamarre, Leslie (1992): "A Growth Market in Wind Power". *EPRI Journal*; 17:8, December, 1992, pp. 4- 15.

Lee, Thomas, N. (1984): Letter to Dr. Lanny Yeske, Tracor Marine, dated September 11, 1984.

Lissaman, P. B. S. (1977a): Energy available from arrays of ocean turbine systems moored in the Florida Current. (AV R 7038, AeroVironment Inc., Pasadena California).

Lissaman, P. B. S. (1977b): Power extraction from a flow in a bounded circuit. Interim report. (AV R 7071, AeroVironment Inc., Pasadena California).

Lissaman, P. B. S., R. L. Radkey (1980): "Coriolis Program: Analysis of the Potential of Ducted Turbine Energy Systems". *Oceanology International 80*, pp. 18 - 26. Schmitz, W. J., and W. S. Richardson (1966): A preliminary report on operation straight jacket. Institute of Marine Science, Marine Laboratory, University of Miami. Data Report 66-1.

Stewart, H. B., Jr. (1974): Proceedings of the MacArthur Workshop on the Feasibility of Extracting Usable Energy from the Florida Current. Palm Beach Shores, Florida, February 27 - March 1.

Tracor Marine, Inc. (1986): "Engineering Feasibility Study of the Nova Energy Limited Proposed 1 MW and 2 MW Vega Ocean Turbine Systems", Report 86-707218-1, January 10, 1986.

Von Arx, W. S., H. B. Stewart, Jr. and J. R. Apel (1974): "The Florida current as a potential source of usable energy". Proceedings of the MacArthur Workshop on the Feasibility of Extracting Usable Energy from the Florida Current, H. B. Stewart,Ed.