VGER:

Variable Geometry Energized Rotor for Marine Propulsion

Final Report

Prepared for

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NOTICE

ABSTRACT

In the 1920's Anton Flettner, a German engineer and inventor, successfully demonstrated the use of rotor-sails to propel ocean vessels. Rotor-sails employ the Magnus (Kutta-Joukowski) effect, wherein a rotating cylinder in an air stream generates a force perpendicular to the air stream. Flettner's innovation took the form of vertical cylinders, spun by electric motors and mounted where masts might otherwise be installed if the ship were rigged with conventional sails. Reportedly the rotor-sails outperformed conventional sails but could not at that time compete with the economics of fossil-fuel engine propulsion. However, a variety of modern technologies, including new materials and more efficient electric motors, could successfully resurrect the rotor-sail concept. Potential enhancements include "energizing" the rotor (i.e., using photovoltaic materials to help meet electric power needs to spin the rotor) and "variable geometry" (i.e., variable geometry that enables a rotor to transform into a stationary vertical axis wind turbine power station when the ship is in port).

ACKNOWLEDGMENTS

Many people and organizations contributed to the work described in this report. First and foremost, TransTech would like to thank NYSERDA for partially sponsoring our work. Good science takes time. The body of knowledge presented herein could not have been created without NYSERDA's material support, expert technical review and patience.

Special thanks belong to Michael Klein-Urena who has been ably present during every phase of this project. Mike, as a summer intern, somehow managed to keep TransTech going when my wife died suddenly in 2008. Without that help, the work on VGER might have ended with that tragedy.

Like all experimental models, the one built for this project will be a work-in-progress for some time to come. Steve Wright and Ethan Wiseman of Thomas Electric Control provided invaluable assistance installing the model's first suite of electronics.

Colin Hamilton, a student at MS 447 in Brooklyn, New York (The Math and Science Exploratory School) executed design changes / improvements with alacrity and ability.

Finally, all of the work report herein is dedicated to my late wife. She was a beautiful, kind Buddhist who grasped intuitively the potential for rotor propulsion to make a better world. My wife was the first to encourage me to pursue improvement of Anton Flettner's noble invention, and it is in her honor that our experimental model is named *Gailforce 1.*

Contents

Introduction

In the 1920s German engineer and inventor Anton Flettner successfully demonstrated use of rotor-sails to propel ocean-going vessels. Rotor-sails employ the Magnus effect, wherein a rotating cylinder in an air stream generates a lift force perpendicular to the direction of the air stream. Assuming the wind is from the left and viewing the cylinder in plan view, Figure 1-LHS (left hand side) illustrates how the spinning rotor accelerates the wind on one side while retarding it on the opposite side. In essence, the spinning rotor does work on the wind, transforming kinetic energy (KE) in the wind into potential energy (PE) in the form of opposed pressure fields. Since KE = .5 *Mass*Velocity^2, the drop in pressure on the "accelerated air" side of the cylinder greatly exceeds the rise in pressure on the "retarded air" side of the cylinder. As the asymmetrical high and low pressure fields seek equilibrium, PE transforms into KE in the form of a thrust vector. Hence, while the cylinder is both "sucked" and "pushed" by negative and positive pressures respectively, the negative pressure usually dominates (Figure 1- center). This is not the only theory that explains the Magnus effect, but it is the most intuitive. Magnus correctly described the phenomenon and identified the variables, but he did not develop a theory to quantify the force. This came later in the form of the Kutta-Joukowski lift theorem.

As is well known in sailing circles, it is thrust, not lift, that propels a vessel and this is also the case for rotors. In addition to a lift force, a drag force is also produced by wind impinging on a rotor. Lift and drag are both vectors and their resultant is the thrust, also a vector, of course [Figure 1 – RHS (right hand side)]. On most points of rotor sailing the lift force greatly exceeds the drag force which is why the thrust vector in Figure 1 is only slightly canted from the perpendicular.

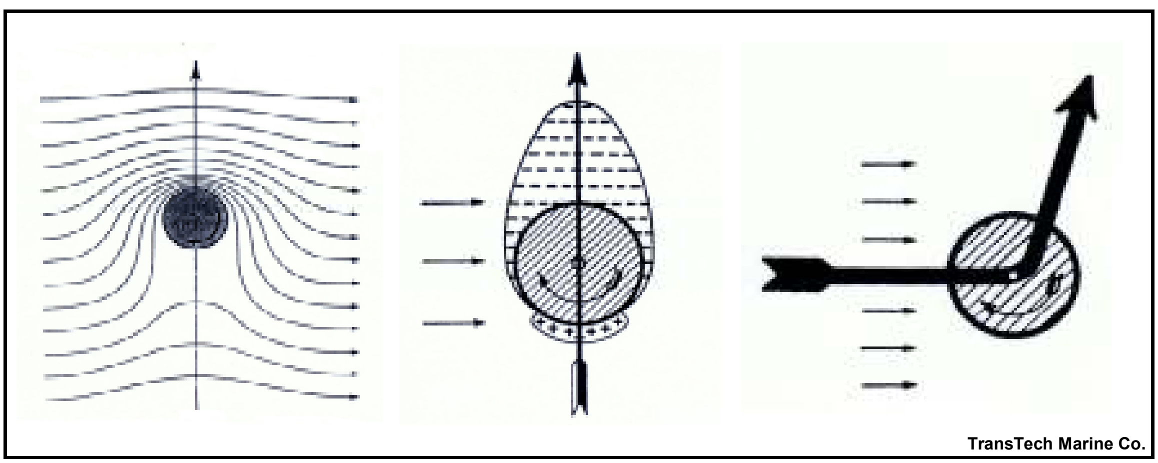


Figure 1

The First Rotor Ships

Flettner's rotors, as his invention came to be called, took the form of vertical cylinders spun by motors mounted where masts might otherwise be installed if the ship were rigged with conventional sails (Figure 2). The first rotor ship was converted topsail schooner *Buckau* (Figure 3 - LHS) which sailed from Danzig to New York via Scotland in 1928. After conversion, *Buckau* was re-named *Baden Baden.*

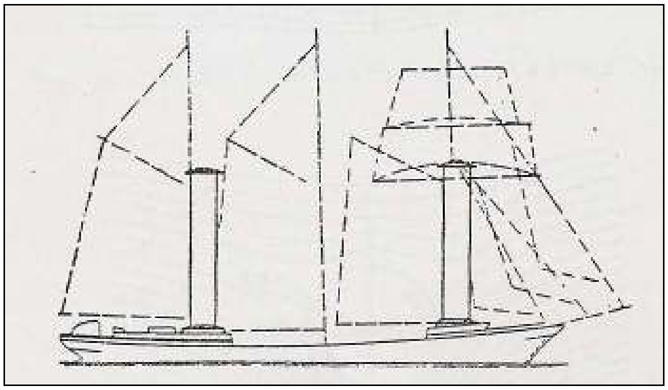
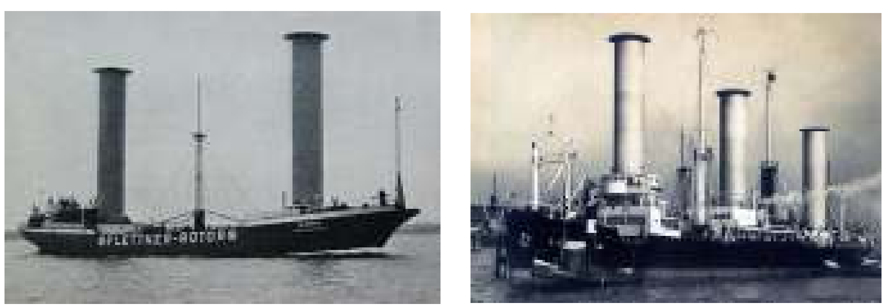


Figure 2

Success of *Baden Baden* in commercial service led to construction from the keel up of larger rotor ship *Barbara* (Figure 3 – RHS), which transported fruit from South America and the Mediterranean to Northern Europe. Both ships outperformed conventional commercial sailing vessels but could not forestall the change-over to steam and diesel propulsion that provided speedier voyages and more reliable schedules.



Rotorship *Baden Baden* Rotorship *Barbara*

Figure 3

A wealth of data was built up on rotor propulsion, not only by Flettner and the researchers at the Göttingen Aerodynamic Institute, but also by N.A.C.A (National Advisory Committee for Aeronautics) in the US. Among the findings were that the rotor need not be circular in cross section to produce lift (Figure 4) and the important contribution of end discs to production of lift (Figure 5).

Circular Cross-section Cylinder

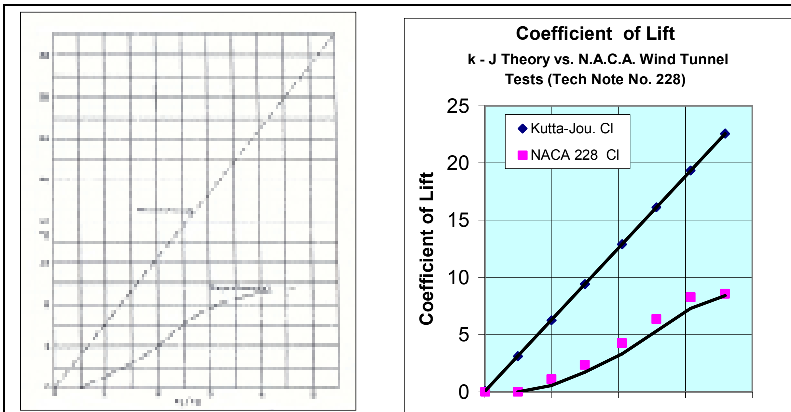
V_0 MPH	V_0 ft / sec	RPM	Lift Lb.	Drag Lb.	Cl	Cd	V_1/V_0	Power Watts
33.5	49.2	1800	1.48	1.66	0.54	0.614	0.72	27.2
22.3	32.8	1800	1.54	0.74	1.16	0.618	1.02	
11.2	16.4	1800	1.33	0.19	4.43	0.622	2.16	

Greek Cross Cross-section Cylinder

V_0 MPH	V_0 ft / sec	RPM	Lift Lb.	Drag Lb.	Cl	Cd	V_1/V_0	Power Watts
33.5	49.2	1800	2.66	2.38	0.98	0.879	0.72	62.4
22.3	32.8	1800	2.07	0.99	1.72	0.823	1.08	

Source: selected data N.A.C.A. No. 209

Figure 4



Coefficient of Lift vs. V_r / V_0 for Rotating Cylinder (N.A.C.A. Note 228)

Figure 5

N.A.C.A. Technical Note 367 is translation of a paper by Dr. Ludwig Prandtl in which he drew the diagram in Figure 6 to illustrate how rotors compare to conventional sails. The dotted line shows the *maximum attainable* performance of a conventionally rigged sailing ship on all points of sail. The cross-hatched area represents *best* performance on best point of sail (i.e., reaching); the un-cross-hatched area shows the same ship under *average* or more normal performance. Given the challenges of constantly trimming sails to attain maximum performance at a time when rigs were being cut down and crew size was being reduced, Prandtl concurred with Flettner's assertion that "push-button" rotor propulsion compared favorably to other sail technologies in most circumstances.

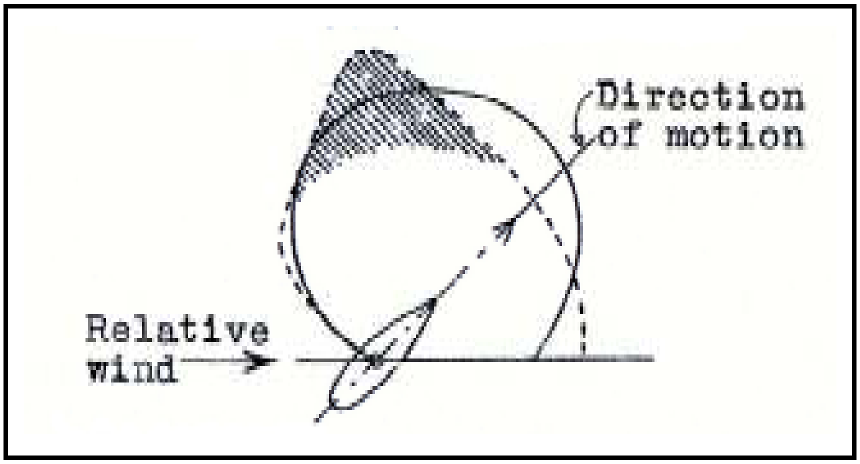


Figure 6

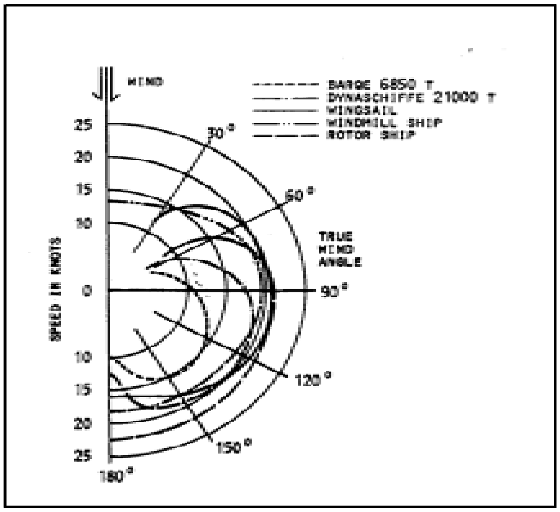
By the early 1930s a third rotor ship was on the drawing boards, larger and even more efficient than *Barbara*, but economic and political change in Germany led to termination of the rotor ship program before construction could begin. Flettner's effort to "save the sailing ship by mechanizing it" suffered from poor timing as WW II was followed by a period of cheap oil that stifled interest in wind-assisted prime movers for more than three decades.

A Second Look at Rotor Ships

The "oil shocks" of 1973 and 1979 saw the price of oil increase ten-fold which spawned renewed interest in rotor propulsion, among other wind-assist technologies, in the United States and Europe. Research conducted at SSPA[1] is particularly significant. Among other things, it quantified the favorable performance of rotors to other sail technologies (Figure 7) and revealed that rotors need not be smooth and that they need not be permanent structures (i.e., collapsible rotors are feasible and practical (Figure 8)) because …

> "*Sail canvas is as good a [rotor] surface as solid material … From an aerodynamic view, sail canvas may very well be used as a 'shell plating' for a Flettner-type sailing rotor*."

[1] Revival of the Flettner Rotor – Beneficial or Not for Merchant Vessels, Fishing Vessels, and Recreational Craft?" Ake Williams, Hans Liljenberg, Swedish Marine Research Center SSPA Goteborg, SNAME Transactions Vol. 91, pp 121-148.



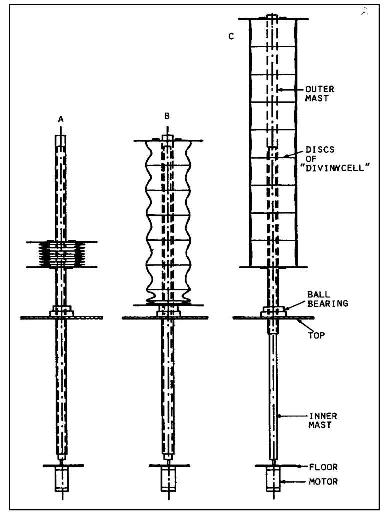


Figure 7

Figure 8

Other important findings of the 1980s concerning rotors will be discussed in greater detail later in this report. However, by the middle of that decade, oil had dropped back to $15 / bbl, shipping markets were severely depressed. The new wind-oriented technologies were no longer cost-effective. By the 1990s essentially all sail and wind-assist initiatives were suspended.

Rotor Propulsion Today

Today, the situation is quite different. $40 / bbl oil of the early 1980s now looks cheap and the maritime industry is under environmental pressures to reduce its contribution to air emissions and global warming. Some sobering facts:

- Roughly 90,000 commercial ships of all types world-wide consume about 280 million tons of fuel oil per annum, most of which is residual fuel oil (RFO), the heaviest, dirtiest, lowest grade and most toxic product of oil refining.

- Total installed power of the fleet is about 280,000 mega-watts (MW) which is slightly more than a quarter of the total installed generating capacity of the US (1,067,000 MW).

- The 280 millions tons of fuel consumed at sea produces almost a billion tons of air pollutants per annum, the great majority of which is CO_2, the major greenhouse gas, but other toxins are in abundance as well (Figure 9).

Pollutants in Ship Fuel		
Nitrogen Oxides	NOx	NO + O = NO_2, a compound of acid rain NO_2 + VOC + sunlight = smog
Sulfur Oxides	SOx	SO_2 + H_2O+ NO_2 (catalyst) = acid rain
Carbon Dioxide	CO_2	contributes to global warming
Volatile Organic Compounds	VOC	VOCs + sunlight + NO_2 = ozone
Particulate Matter	PM	soot, haze, cause of respiratory ailments

Figure 9

- Air emissions by ships do not, of course, remain at sea but rather, disperse over large regions (Figure 10).

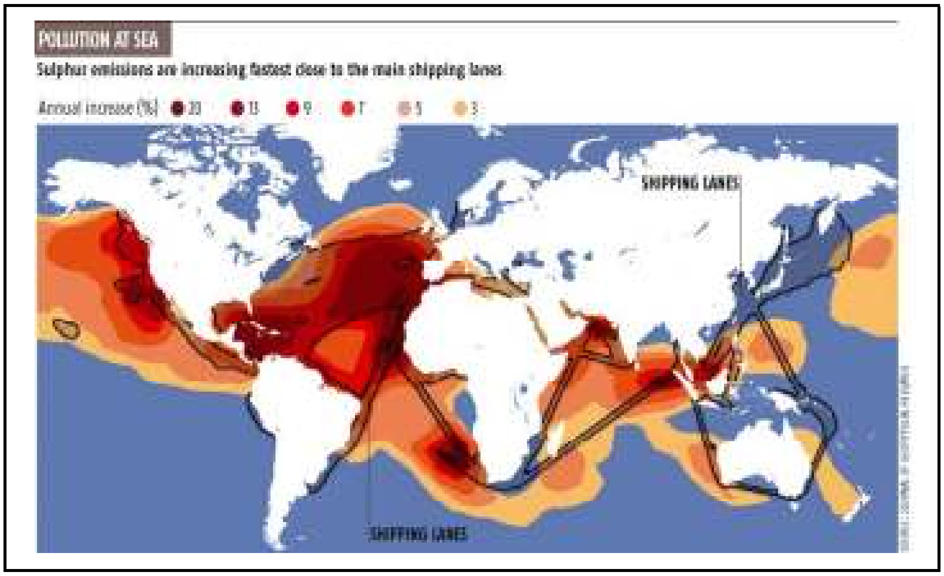


Figure 10

When environmental considerations are added to the fact that the bunker bill is now the largest operating expense for most of today's merchant ships (Figure 11), increased use of the wind has two persuasive advocates.

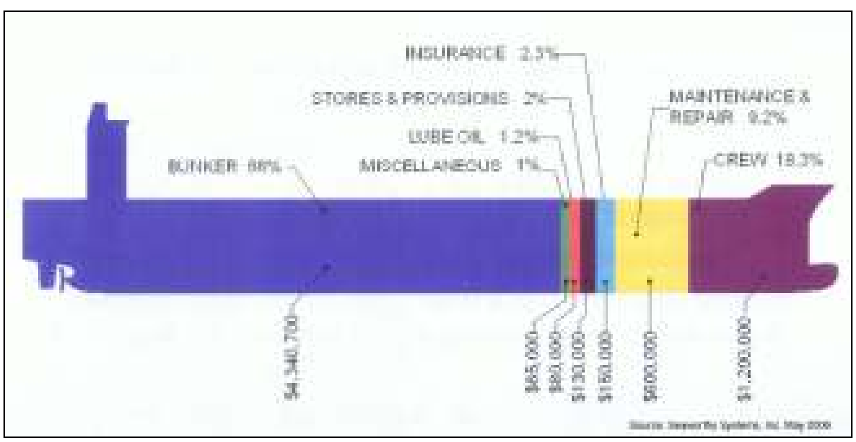


Figure 11

The contribution from wind to a ship's propulsion need is naturally dependent on the force of the wind and its direction relative to the ship's course. To enable direct comparison, TransTech examined the most popular sail technologies, namely, soft sail, rigid sail, wing-sail, and kite-sail (Figure 12) under the same conditions of 20 MPH wind slightly abaft the beam. The blue columns in Figure 13 show thrust per square foot of projected area, whereas the green columns in Figure 13 show the percentage of total required thrust that is substituted by each wind-based technology in the particular application. It is immediately apparent that thrust from rotors can greatly exceed other wind-based technologies.

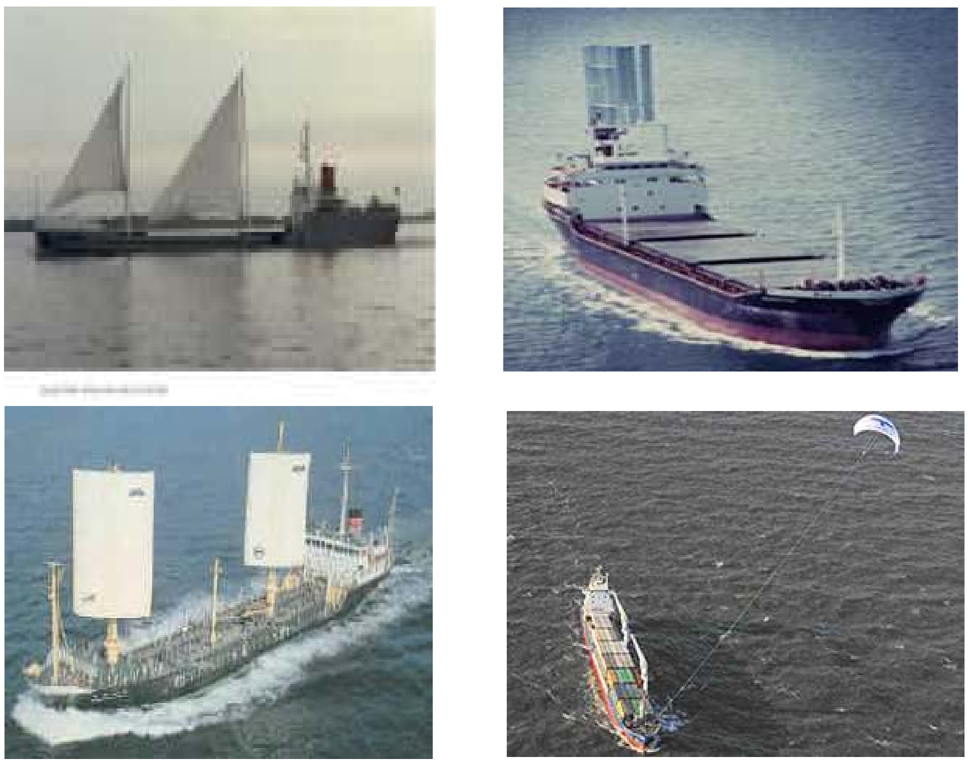


Figure 12

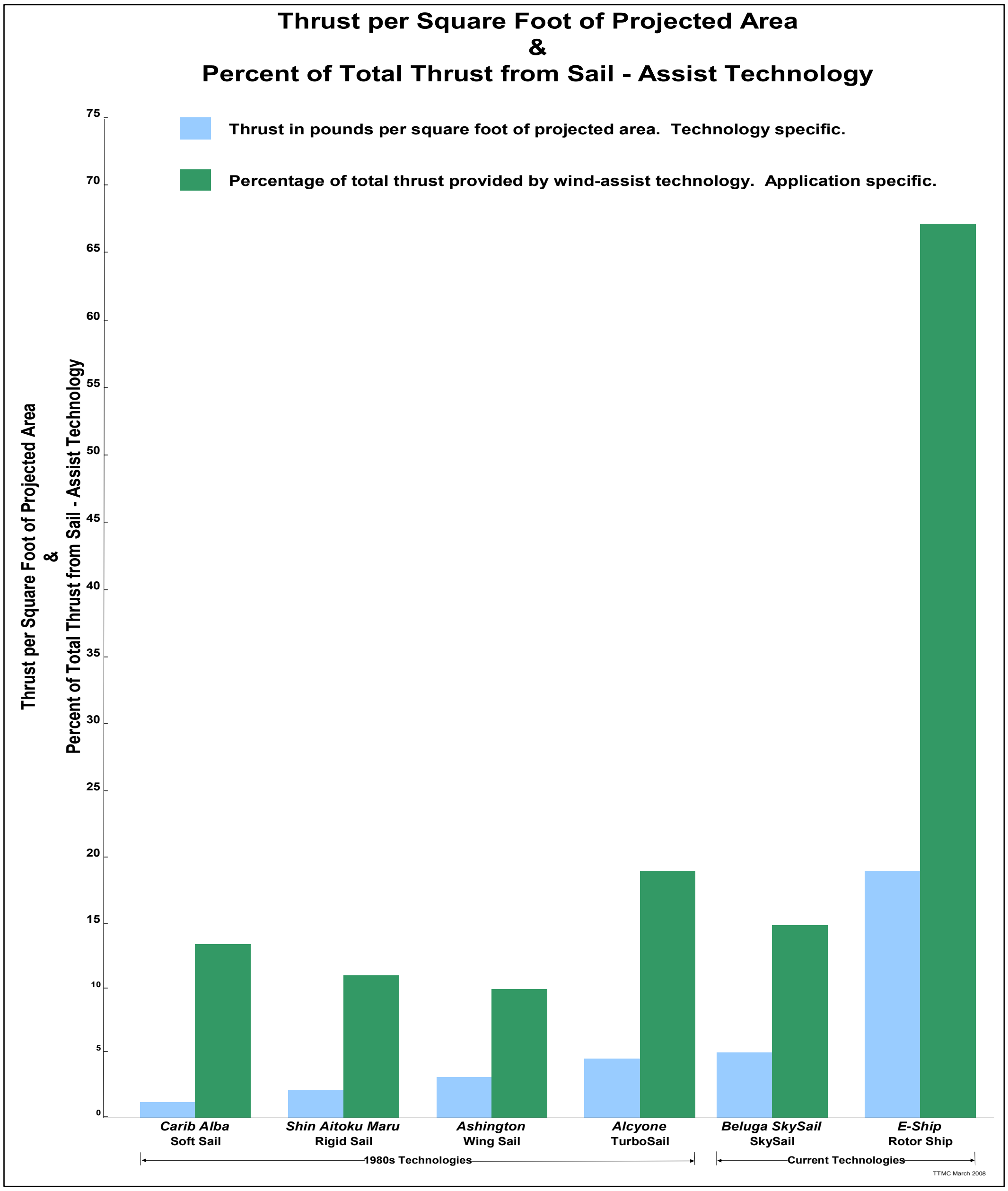


Figure 13

But there is no free lunch, rotors come with a cost the other technologies don't. Rotors are dynamic, not passive thrust producers. They must be spun and that requires power. So their advantage or contribution to marine propulsion must be assessed on a net energy use basis. The good news is the sizing and powering of rotors is not a guessing game. Before embarking on methods to improve Anton Flettner's invention, it was necessary for TransTech to master the sizing and powering of conventional rotors.

Sizing and Powering of Rotors

Number and Size of Rotors:

Flettner envisaged rotors as a way to mechanize the large sailing barques of his day, as well as potent auxiliary propulsion aboard steam and diesel powered ships. In the case of using rotors as prime movers, first and foremost, they must produce thrust equal to the EHP (effective horsepower or towrope horsepower) needed to propel a given ship at the design speed.

The number and size of rotors to be fitted aboard a given ship is driven by many of the same factors that determine the number and size of masts to be fitted aboard a conventional sailing vessel.

The difference between EHP and SHP (shaft horsepower) is significant because whereas the machinery of a rotor powered ship will also incur energy losses, these will be significantly less than the 40 to 50 percent of energy that is lost in spinning a marine screw propeller (even allowing for dragging a feathering propeller when under rotor power). Even the best marine screw propellers are relatively inefficient at converting torque to thrust. Hence, the amount of installed power in the prime mover (or main engine), referred to as SHP, is on the order of twice the amount of power actually needed to propel the ship, referred to as EHP, at its design speed.

The approximate thrust produced by the rotors of four rotor powered freight ships is presented in Figure 14, below. It is noted that thrust is *not* equivalent to lift; however, since the drag of a rotor in low speed (ultra-subsonic) wind is small compared to its lift, for the first turn around the rotor design spiral, the lift is taken as an acceptable first approximation of thrust. Drag, of course, must also be computed as the rotor design evolves

Total Lift Produced by Four Rotor Ships

	Total Number of Rotors	Rotor RPM	Design Wind Speed (MPH)	Velocity Ratio	Lift per Rotor (pounds)	Total Lift (pounds)
E-Ship	4	160 (1)	20 (1)	3.75 (1)	27768	111070
Stellan	2	190	16	4.03	11085	22171
Barbara	3	160	20	3.77	19061	57182
Buckau	2	120	14	2.82	4139	8277

Note: For *E-Ship* rotor RPM, design wind speed and velocity ratio are assumptions at the present time.

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Figure 14

Rotor Height, Diameter and RPM:

Inputs to the Kutta-Joukowski lift equation are the mass density of the fluid (rho, assumed constant for air), speed of the free air stream (V_o), rotor radius (r), and rotor revolutions per minute (RPM). The equation states that the lift produced is directly proportional to the air flow velocity, the density of the flow and the strength of the vortex G that is established by the rotor's rotation.

$$\text{Unit lift} = \text{rho} * V_0 * G$$

The vortex strength (G) equals the periphery speed of a point on the surface of the rotor (V_1) times the circumference of the rotor (2 * Pi * r). Hence,

$$G = V_1 * (2 * Pi * r)$$

where V_1 is equal to the circumference of the rotor times the rotor's RPM.

$$V_1 = 2 * pi * r * RPM$$

By substituting the equation for V_1 into the equation for G it can be seen that G is a function of the square of the radius of the rotor.

$$G = 4 * Pi\text{^}2 * RPM$$

Since V_0 is often given in (or converted to) ft. / s or m / s, RPM must be converted to revolutions per second (RPS) so that the units for V_1 are consistent. The equation for G is then

$$G = 4 * Pi\text{^}2 * RPM / 60$$

and the units for G are ft ^2 / s.

In the course of this investigation, it was discovered that a new rotor ship was under construction in Germany. Named *E-Ship,* this is the first true rotor ship to be built in eighty years. A picture of this ship and technical details are shown in Figure 15. The following discussion of the effects of variation of span (height), spin (RPM) and diameter on production of lift uses the rotors installed aboard *E-Ship* for the base case, at time of this investigation believed to be: span = 90 ft, RPM = 160, radius = 6.5. In 20 MPH wind, the lift produced by each rotor is 27777 lbs.

Enercon Ship Technical Details

LOA	426.4	Ft
Beam	73.8	Ft
DWT	10000	Tonnes
Service Speed	16.0	Knots
Rotors:		
Number	4	
Height	88.8	Ft
Diameter	13.1	Ft
RPM (est)	160	

Figure 15

Variation of Span (see Figure 16):

Rotor lift varies linearly with the rotor's span (or height or length, etc.).

The lift coefficient, which expresses the ratio of the lift force to the force produced by the dynamic pressure of the free wind (0.5 * rho * V_0^2) times the rotor's frontal are (diameter * span) is constant because lift and frontal area vary in proportion to rotor span.

The velocity ratio (V_1 / V_0) is therefore unaffected by rotor span.

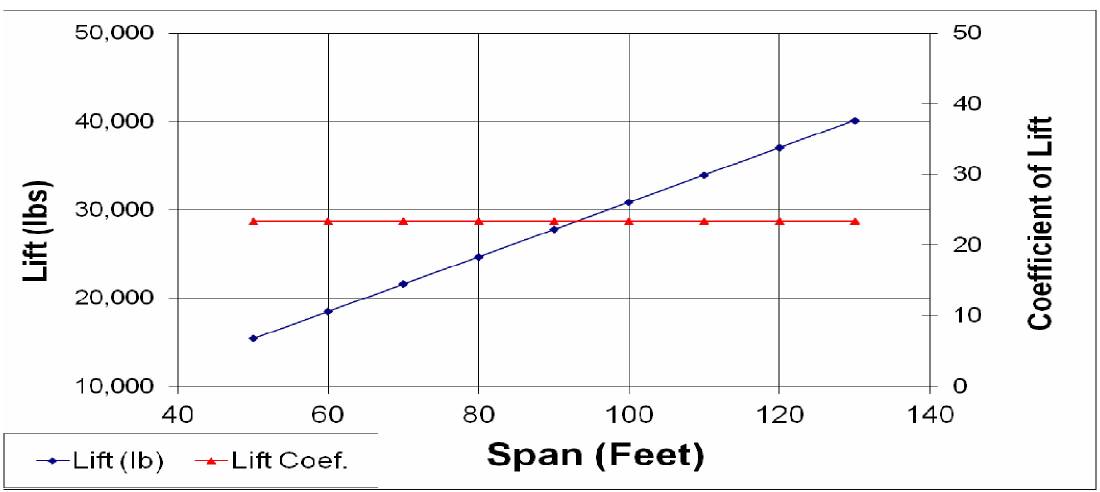

Figure 16

Variation of Spin (see Figure 17):

Rotor lift varies linearly with change in RPM. The lift coefficient also varies linearly with change in RPM because rotor lift changes with RPM whereas the frontal area is unaffected by changes in RPM.

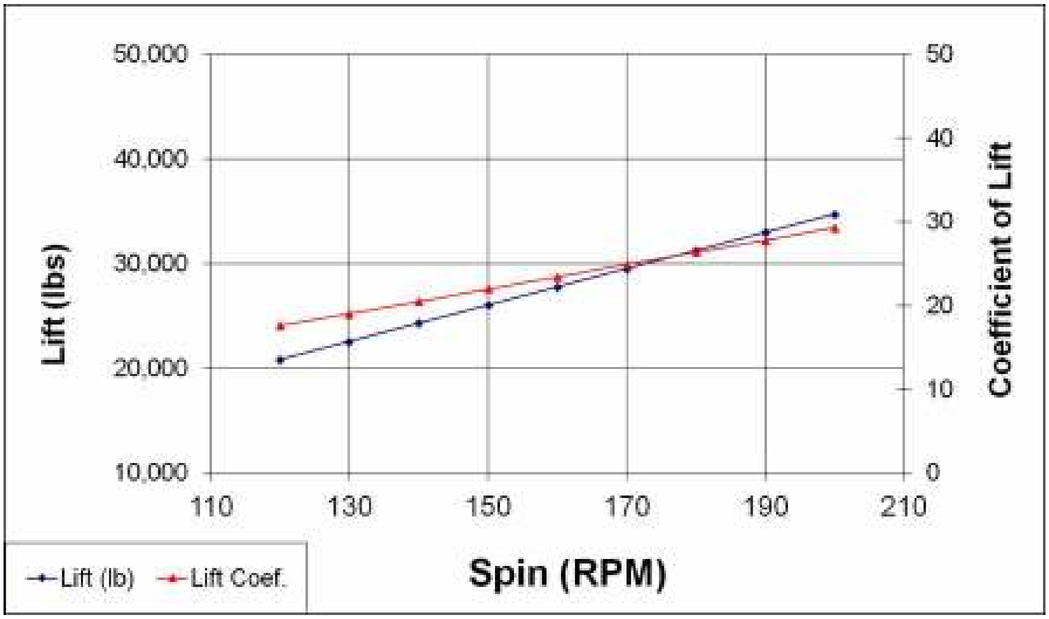

Figure 17

Variation of Radius (see Figure 18):

Rotor lift varies as the square of its radius. The lift coefficient varies linearly with change in radius because the rotor's frontal are varies linearly with change in radius or span, or both.

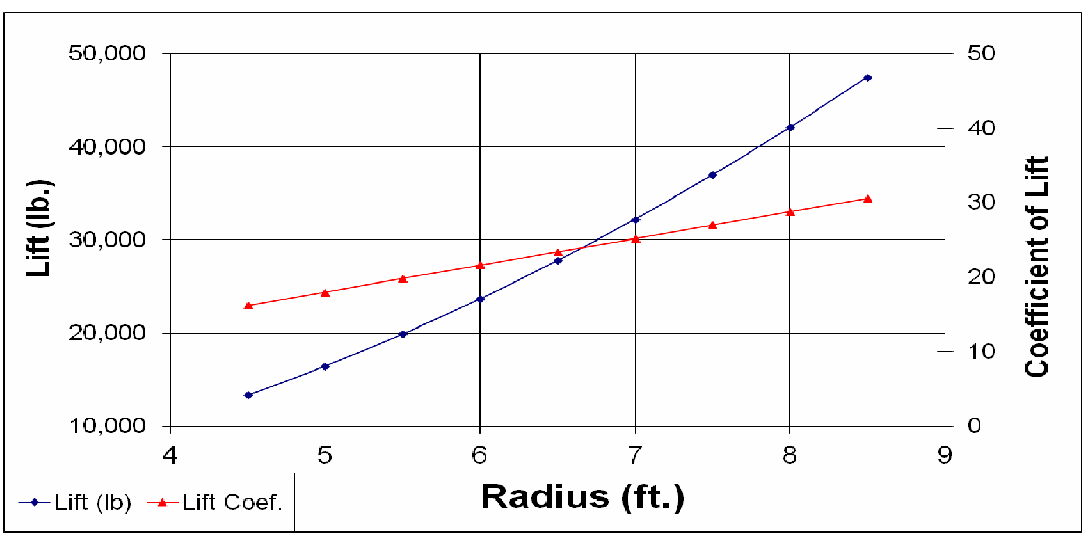

Figure 18

Simultaneous Variation of Span, Spin and Radius:

The effects of varying rotor span, spin and radius are multiplicative. Hence, within any range of principal characteristics an almost unlimited number of combinations are possible.

Practical design constraints will, however, shrink the feasible design space:

- Strength issues, ship stability considerations and air draft restrictions (bridge clearance) will limit rotor span (height).
- The upper bound on velocity ratio and the goal of minimizing power consumption to spin the rotors will limit RPM.
- The ship's beam, rotor foundation size and weight and cargo handling space requirements will limit rotor radius.

Powering of Rotors

Newton's equations of kinematic circular motion were used to compute the power required to spin a rotor of given mass and geometry at a given RPM. Computed power was compared to reported power in five rotor installations to confirm veracity of the computations (Figure 19).

Computed Rotor Power v.s. Actual Installed Rotor Power

	Total Number of Rotors (1)	Rotors Maxiumum RPM (1)	Reported Power per Rotor (KW) (1)	Assumed Seconds to Accelerate to Full RPM (2)	Margin for Friction + Electrical Losses (%) (2)	TTMC Computed Power per Rotor (KW)
Baden-Baden	2	120	**11**	60	50	**10.2**
Barbara	3	160	**31**	90	50	**31.5**
Yacht	1	300	**2**	10	50	**1.4**
Stellan	2	190	**25**	90	50	**26**
Snipa-R82	1	950	**0.67**	10	50	**0.42**

Notes:
1. Number of rotors. Maximum RPM and power per rotor are actual values.
2. Lacking actual data, time to accelerate to full RPM and margin for frictional and electrical losses are reasonable assumptions. It is assumed that a small vessel must be able to gets its rotor to full speed faster than a larger vessel that might be expected to remain on the same tack for several hours or days at a time.

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Figure 19

Sensitivity analysis was then undertaken of the effect of acceleration on rotor power, using best available information at the time for *E-Ship's* rotors. As can be seen in Figure 20, given that many ships remain on the same tack for days or weeks at a time in the course of a voyage, slow rotor acceleration should be tolerable, requiring proportionately and dramatically less power.

Rotor Power Consumption vs. Acceleration
(Rotor Span = 95.0', Diam. = 13.5', End Disk = 17.6')
Red = input , Blue = output

		Acceleration Time	
		30 sec.	30 min.
Rotor RPM		165	165
Rotor Weight tons)		30	30
Design Margin (percent)		100	100
Req'd Power per Rotor	(KW)	1086	18
	(HP)	1456	24
Power for 4 rotors	(KW)	4344	72
	(HP)	5824	96

Figure 20

Designing a Variable Geometry (VG) Rotor

When spun in an air stream, rotors produce thrust to propel (or assist propelling) the ship. When the ship is in port, propulsive thrust is not required. Rotors can then become an impediment to smooth cargo handling and subject to potential damage, if they are not folded out of the way. Research conducted in Sweden in the 1980s demonstrated that collapsible rotors made of canvass could be as efficient as Flettner's rigid, smooth metallic rotors.

TransTech's took the research further by investigating the possibility of using variable geometry to convert a rotor to a vertical axis wind turbine to extract energy from the free wind while the ship is in port. This wind energy could then be used to power the ship's house load, normally supplied by fossil-fuel generators, or it could be stored in batteries for future use, including the powering of an electric propulsion motor driving a screw propeller (such as for use at sea when the wind is not blowing).

Against the merits of a variable geometry rotor must be measured the cost, complexity and reliability. Figure 5 is an engineering drawing of a standard Flettner rotor. From the exterior, it looks simple to construct. In reality, the engineering required to build a light, strong and durable rotor within exacting tolerances is quite sophisticated. Any significant weight gain of the rotor due to added wind generator mechanicals or reduction of the rotor lift from higher aerodynamic drag would counter the gain from the wind generator.

Wind Turbine Development / Terminology:

Wind turbines have existed for several thousand years. For most of their history, they have converted the kinetic energy in the wind into rotary mechanical energy to mill grain, pump water or saw wood, etc. Over the past century, designs have been developed to further convert rotary mechanical energy into electrical energy by turning a generator to produce AC or DC electricity. AC generators power AC motors. Generators that produce DC can be connected to an inverter to produce AC, or they can power DC loads directly or charge batteries.

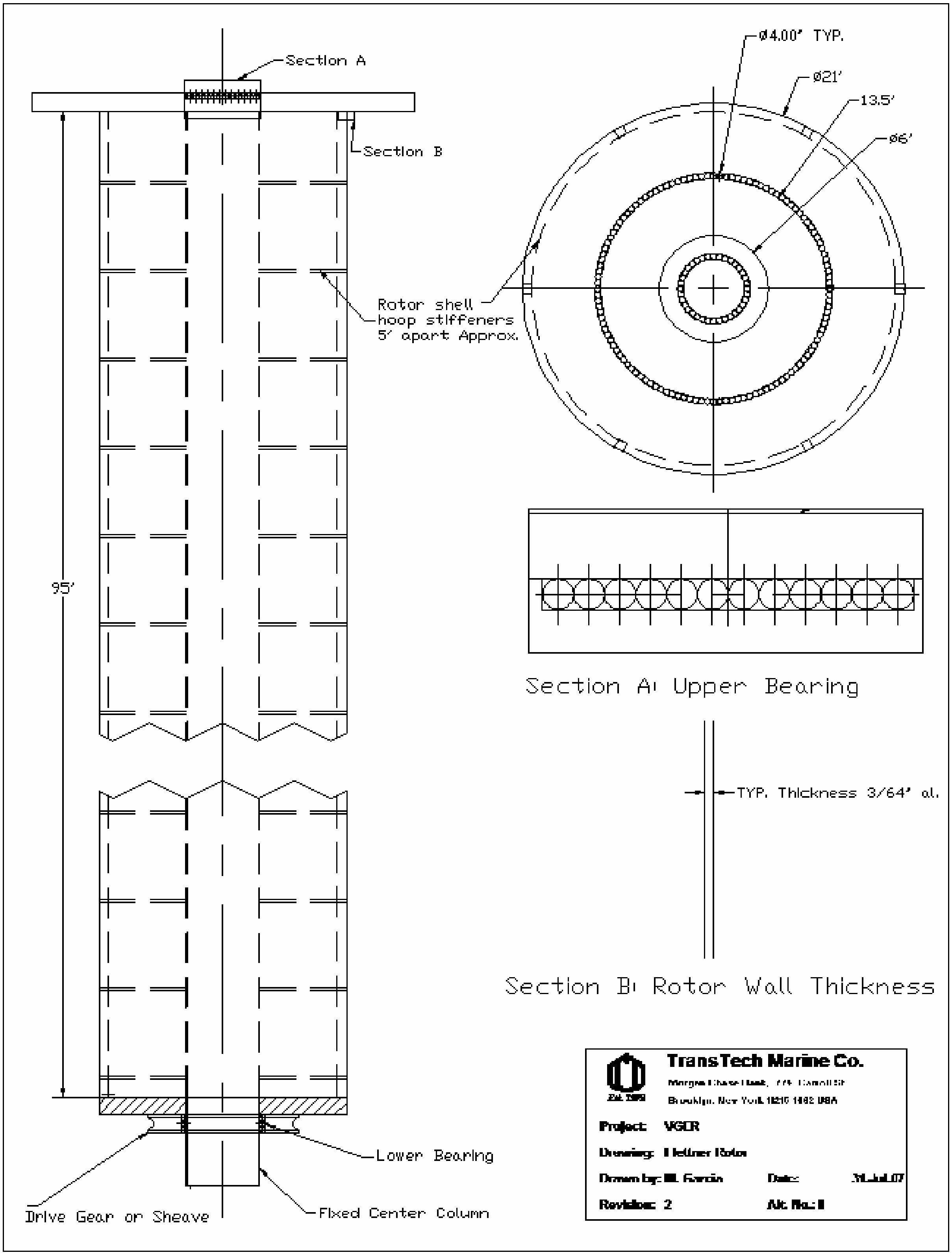

Section A
Section B
Ø4.00" TYP.
Ø21'
13.5'
Ø6'
Rotor shell
hoop stiffeners
5' apart Approx.
95'
Section A: Upper Bearing
TYP. Thickness 3/64" al.
Section B: Rotor Wall Thickness
Lower Bearing
Drive Gear or Sheave
Fixed Center Column
TransTech Marine Co.
Project:
Date:
Revision: 2

Figure 21

A rotor that converts to a wind turbine naturally fits into the class of machines called VAWTs (vertical axis wind turbine). In a VAWT the axis of rotation is across the path of the wind, as opposed to a HAWT (horizontal axis wind turbine) where the main shaft is parallel to the wind (facing either upwind or downwind).

Regardless of technology, the following components are common to all wind turbines:

Aerofoil: Set of blades that convert dynamic wind pressure into torque to turn the main turbine shaft. The number of blades that make up an aerofoil and the total area they cover affect wind turbine performance. To avoid turbulence, blades must be sufficiently far apart so that one blade will not encounter the disturbed, weaker air flow caused by another blade.

Anemometer: Instrument that measures the wind speed.

Brake: Used to slow turbines. This may be to prevent damage in high winds or to reduce power efficiency as wind speed increases, maintaining constant power output.

Controller: Optimizes turbine performance and distributes generator output to power consumers or to feed storage batteries.

Gear box / Transmission: Converts the low RPMs of the main turbine shaft to higher RPMs required by most generators to function. Some DC-type wind turbines do not use transmissions. Elimination of the transmission reduces complexity and maintenance, but a larger generator would be required to deliver the same power output as an AC-type wind turbine.

Generator: Converts mechanical energy into AC or DC electricity. AC generators produce the correct voltage (usually 120 or 240 volts) and constant frequency (60 cycles), even when wind speed fluctuates. DC generators power DC machinery and charge batteries. Battery storage systems are usually configured at 12 to 120 volts. DC generators can also produce AC electricity with the use of an inverter.

High-speed shaft: Output shaft of the gearbox connecting to the generator.

Low-speed shaft: Input shaft of the gearbox connecting to the aerofoil.

Wind Turbine Theory:

The amount of power a wind turbine can produce is directly proportional to the density of the air, the area swept by the aerofoil, and the cube of the wind speed. Since the mass flow of air that travels through the swept area of a wind turbine varies linearly with the wind speed (and air density), and the kinetic energy of a given mass varies with the square of its velocity, the wind energy available to a wind turbine increases as the cube of the wind speed.

Pwind = 0.5 x rho x A x V^3

	English Units		SI Units		Notes:
P		HP		Watts	1 HP = 0.746 kW
rho	0.002377	slugs /ft^3	1.225	kg/m^3	density at sea level, 59 o
A		Ft^2		M^2	for VAWT, A = diam. x height for HAWT, A = pi x R^2
V		Ft/s		M/s	V^3 = ft^3/s^2/s or m^3/s^2/s

The above equation computes all of the power in a free flowing stream of wind. It is not possible to extract all of the power from the wind because some flow must be maintained through the turbine. Hence, a wind turbine extracts energy by slowing the wind down, but not stopping it. The theoretical maximum amount of energy in the wind that can be extracted by a wind turbine is 59% or 16/27, proven by German physicist Albert Betz (1885 - 1968).

In practice, the wind energy conversion efficiency of wind turbines is less than the Betz Limit, presently around 40 percent, on average. In addition to the Betz limit, bearings, the gear box, and generator cause further energy losses. Putting all of the factors into the power equation yields:

Pturbine = 0.5 x rho x A x Cp x V^3 x ηg x ηb

where:

Cp = Performance coefficient (never greater than 0.59, Betz Limit, usually between 0.35 and 0.45).

ηg = generator efficiency (can be as high as 0.95 to 0.98 for high efficiency generator).

η_b = combined bearings and gearing efficiency (typically between 0.96 and 0.98)

Using the turbine power formula it is possible to estimate the power output of a VGER configured as a wind turbine. The turbine powers shown in Figure 22 are for a single VGER rotor, with Cp = 0.40, η_g = 0.95 and η_b = 0.97. These are estimates at the present time, but are believed to be reasonable. The overwhelming importance of wind speed is immediately apparent; as it doubles, power output increases eightfold.

Turbine Power Output vs. Wind Speed
One VGER Rotor (95.0' x 13.5')

Wind Velocity			Turbine Power	
MPH	**m/s**	**ft/s**	**KW**	**HP**
0.0	0.0	0.0	0.0	0.0
5.0	2.2	7.3	0.3	0.4
10.0	4.5	14.7	2.4	3.2
15.0	6.7	22.0	8.2	10.9
20.0	8.9	29.3	19.5	25.8

Figure 22

As stated earlier in this report, the amount of power that a VGER can generate must be measured against the costs (dollar cost, engineering effort and effect, if any, on rotor performance) and contribution the wind turbines can make to the ship's total power requirements. The contribution of the wind turbines to the ship's power requirements can be assessed by making some reasonable assumptions:

1) For one rotor (to simplify calculations) assume that the power requirements of the lowest powered motor (18 kW, corresponding to rotor acceleration time of 30 minutes) are to be supplied solely by battery power for 24 hours. Implicit in this assumption is that the ship is at sea (thrust is needed), the wind is blowing (warranting use of the rotors), the sun is not shining (low PV available to power the rotors) and the gensets are not in use. The 24-hour time span is equivalent to 12 hours of overcast daylight plus 12 hours of darkness. Beyond this time, if the sun still is not shining, the gensets would be used.

Required energy to power the rotor for 24 hours =

18 kW x 24 hrs = 432 kWh = 432,000 Watt hrs

2) Assume the rotor drive motors are 120 V AC. Amperage draw =

18,000 Watts / 120 Volts = 150 Amps

3) Required battery capacity for 24 hours =

150 Amps x 24 hrs = 3600 Amp Hours

4) Assume the average wind speed when ship is in port = 10 MPH. At this wind speed the wind turbine puts out 2.4 kW (Figure 6) = 2,400 watts. At 120 V, amperage output =

2,400 Watts / 120 Volts = 20 Amps

5) Using the wind turbine as a battery charger, at 20 Amps output, the time required to put 3,600 Ah back into the batteries =

3,600 Amp Hours / 20 Amps = 180 hrs = 7.5 days

Variable Geometry Rotor – Final Design Approach:

There is a wide variety of ways to conceivably transform a Flettner propulsion rotor into a vertical axis wind turbine. The possibilities include rigid materials / mechanical transformation to flexible material / flexural transformation. In the end, TransTech concluded louvers or a Savonius design (Figure 23) would be simplest to fabricate.

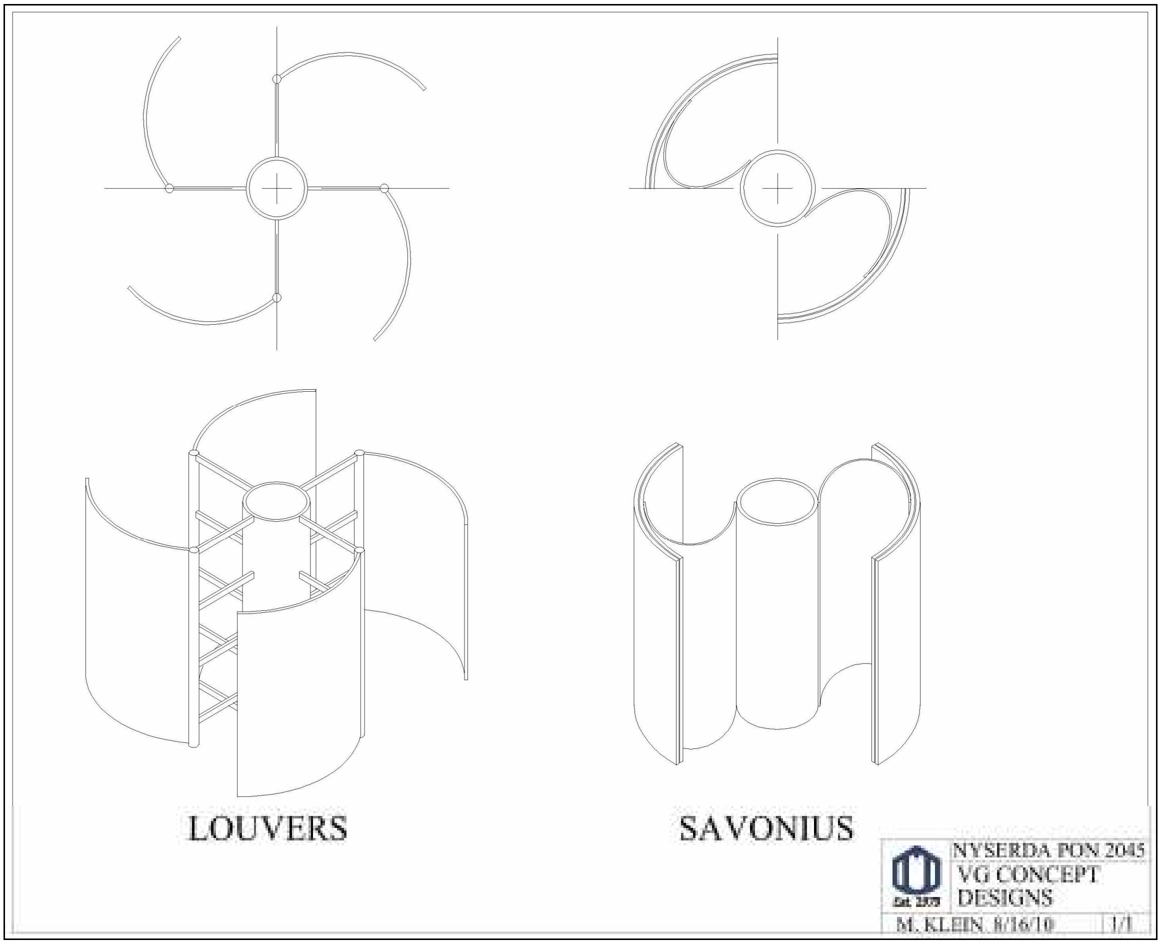
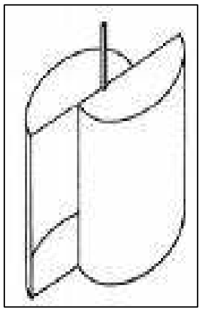


Figure 23

1. **Louvers:**

VAWT designs exist that use fixed louvers. A VGER could be designed with interlocking louvers that rotate about their longitudinal axis. This could be accomplished in the same way that Voith-Schneider rudder propellers change the blade pitch to maximize thrust and minimize drag in one rotation

2. Savonius Machine:



In its simplest form, a Savonius VAWT is two half-drums fixed to a central shaft in opposing directions. Each drum catches the wind and so turns the shaft, bringing the opposing drum into the flow of the wind.

TransTech successfully constructed a working prototype of a Savonius VAWT / rotor for this project. It has not, however, been installed aboard the rotor ship model. While the mechanicals of this rotor / VAWT appear to be satisfactory, the weight is significantly greater than a conventional rotor, putting it at a disadvantage. Efforts will continue to reduce weight of the prototype.

Powering a Rotor with the Sun (Energized Rotor)

The Case for Hybrid Marine Propulsion:

Diesel-electric (D-E) propulsion is one of many form of hybrid marine propulsion. D-E propulsion connects a diesel engine to a generator (genset) to power electric drive motors to turn the ship's propeller(s). Adding a battery bank to power the drive motors in tandem with or in lieu of the genset(s) defines a hybrid propulsion system. Two of the greatest advantages of hybrid marine propulsion are the ability to significantly reduce air pollution and propulsive redundancy. The main disadvantages include higher initial cost, greater weight and greater system complexity. As fuel prices continue to rise and restrictions on air pollution from ships become more stringent, hybrid marine propulsion systems will become more prevalent across many sectors of the shipping industry.

At the present level of research and design, Figure 24 presents a simplified schematic of how VGERs would feed power to and extract power from an onboard hybrid power system.

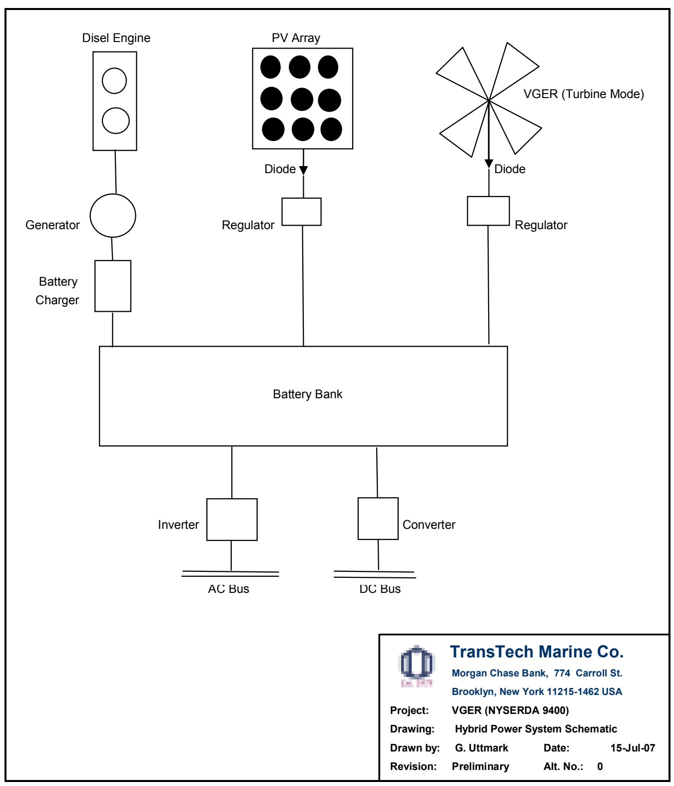


Figure 24

Photovoltaic (PV) Energized Rotor:

A PV energized rotor must expose sufficient surface area to the sun to convert enough solar energy to electricity to provide the power required to spin the rotor. From Figure 20 we know that at least 18 kW are needed to power one rotor (100 percent design margin in Figure 20 accounts for surge power to overcome inertial forces from full stop as well as other frictional and electrical losses). Two locations are possible for the PV arrays:

1) Coat the rotor and end disk with PV material:

   This was the original concept of VGER. It is appealing because a PV coated rotor with the drive motor contained inside the rotor makes a very tidy package. However, a number of problems were discovered with this approach:

   Available surface area: The total surface area of a VGER, as presently designed, is 4375 sq. ft., consisting of the rotor (4029 sq. ft.) and the end disk (346 sq. ft.). There will never be a time of day, however, when the sun strikes the entire area. At sunrise and sunset, sunlight will strike only the rotor main body, while at local noon, sunlight will strike only the end disk. Furthermore, sunlight will strike only the side of the rotor facing the sun, and only about 60º of the circumference will be sufficiently near normal to the sun to efficiently convert solar energy to electricity. These conditions are illustrated in Figure 25, which establish that covering the rotor itself with PV material will not produce sufficient power to spin it.

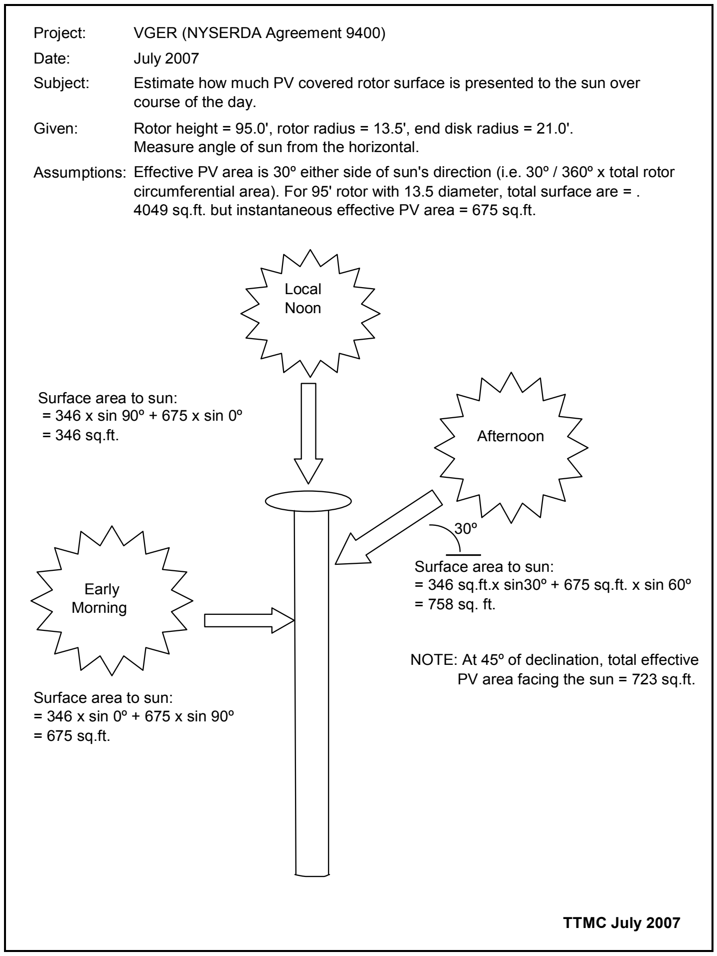


Figure 25

2) Coat the hatch covers with PV:

An alternative to covering the rotors with PV material is to cover the ship's hatch covers with PV cells. This strategy appears to have much to recommend it.

a) Hatch covers have large area with the entire surface receiving direct sunlight for most of the day.

b) Hatch covers are, by design, extremely strong and could easily support the new, high-efficiency PV "roofing" arrays (i.e. PV "tiles" from which roofs are built rather than PV arrays mounted in frames attached to roofs).

c) Moving PV material off the rotor eliminates the need to mount the drive motor inside the cylinder. The variety of drive motor options increases while the weight of the rotor decreases.

Figure 26 shows how the typical installation or PV arrays on a ship's hatch covers. Depending on the amount of solar energy available, it is believed that this arrangement will produce more than enough electricity to power the rotors.

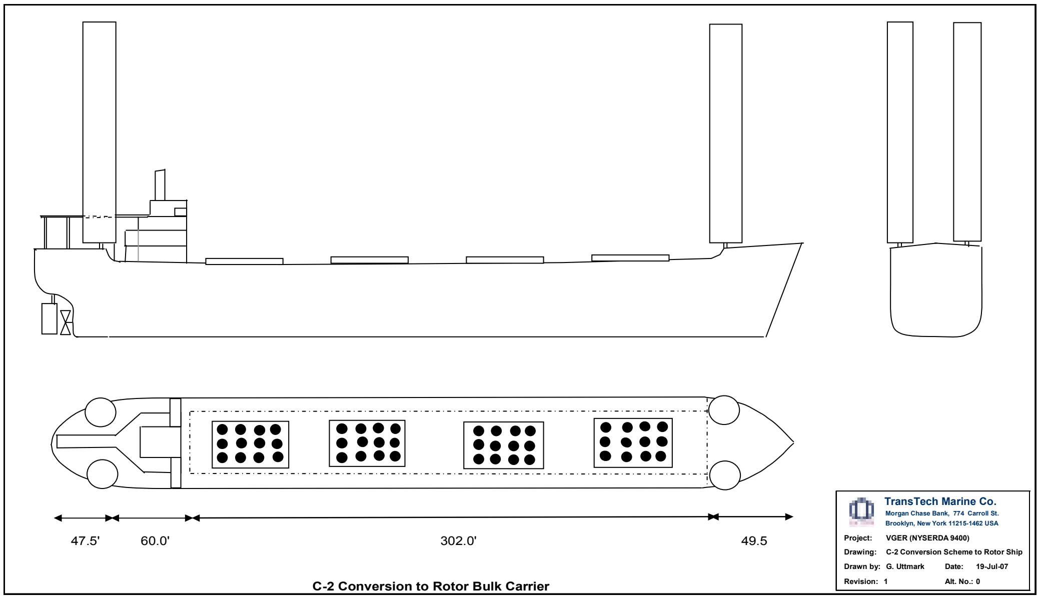


Figure 26

VGER Applications

It is well known that winds blow stronger and more reliably at sea (Figure 27). This has been the case since antiquity, but more recently, higher fuel costs and harmful emissions from ships have also entered the picture.

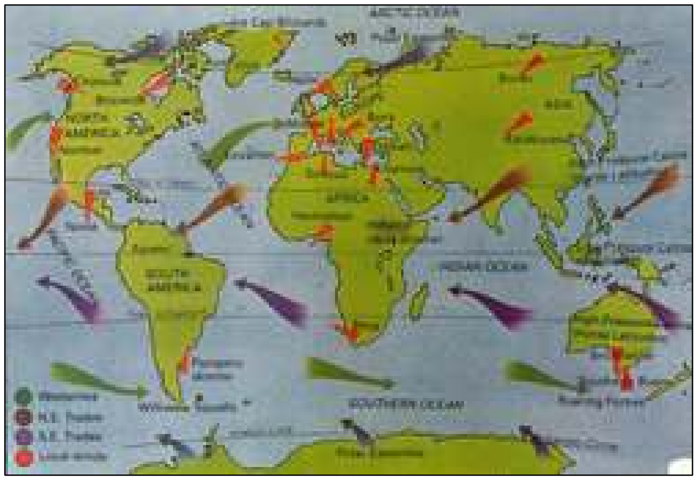


Figure 27

To provide a rough order of magnitude assessment of the benefits of rotor propulsion, TransTech studied how they would impact the annual fuel consumption, bunker bill and air emissions of a standard handysize bulk carrier. Figure 28 shows principal characteristics of the chosen ship, which in every way is a standard design representative of thousands of ships.

Case Study:
Rotors Aboard a Handysize Bulker

Principal Dimensions
Handymax Geared Dry Bulk Carrier

LOA	623.0	Feet
LBP	593.7	Feet
Beam	105.5	Feet
Draft	38.0	Feet
DWT	48,900	Long Tons
GRT	28,100	
Holds	5	
Cranes / lift	4/25	Short Tons
BHP	10,400	
Service Speed	14.5	knots
Fuel Rate	26.2	Tons per Day
Aux. Fuel Cons.	2	Tons per Day

Source: http://www.ihi.co.jp/ihimu/images/seihin/pl01_2.pdf

Figure 28

An interesting revelation produced by the case study was discovery that a handysize bulk carrier produces approximately half of its full-load displacement in air emissions every year that it operates (Figure 29, base case). Substituting one-third to two-thirds of mechanical propulsion with VGERs will reduce air emissions by between 10,000 and 20,000 tons per annum (IBID).

Case Study: Environmental Benefits

Annual Reduction of Air Emissions from Using VGERs
Case Study: One Slow-Speed Diesel Handymax Bulk Carrier

Annual Pollution Produced (tons)

	NOx	CO	CO_2	VOC	PM	SOx	Total
Base Case - no Fuel Reduction	846	72	31113	23	12	194	32261
One Third Fuel Reduction	564	48	20753	16	8	130	21518
Two Thirds Fuel Reduction	282	24	10361	8	4	65	10743

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Figure 29

The economic benefits of saving one-third to two-thirds of the fuel bill would range between USD 1.4 and USD 2.8 million per annum (Figure 30) at USD 475 / ton fuel cost. At a 10 percent discount rate, the present value of the savings would be on the order of between USD 13 million and USD 26 million.

Case Study: Economic Benefits

- At the current price of marine HFO bunkers of $475 / ton, rotors would produce significant annual savings for the owner of the Handymax bulk carrier:
- 1/3 Fuel Saved: Annual savings = 2,398 tons x 475 / ton = $1.39 M.
- 2/3 Fuel Saved: Annual savings = 5,876 tons x 475 / ton = $2.78 M

Figure 30

Conclusion

There are many sectors of the shipping industry where VGERs may contribute significantly to fuel savings and emissions reduction. In broad terms it is possible to anticipate that rotors will not find application aboard ships where there is insufficient deck space to mount them (Figure 31)

Figure 31

However, there are many ship types and sectors where VGERs can be mounted quite easily (Figure 32).

Figure 32

As long as the wind blows and trade in tangibles continues, VGERs offer a way to make a significant contribution to a cleaner and more profitable world merchant fleet. At the very least, Anton Flettner's noble invention may help fill an important propulsive gap as the maritime industry transits from the current almost complete dependence on fuel oil, to liquid and compressed natural gas, and ultimately to hydrogen.

- end -

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VGER:

Variable Geometry Energized Rotor for Marine Propulsion

Final Report - Appendix 1:
Rotor Ship Test Model

Introduction

Early in its investigations, TransTech concluded a working model would be useful in studying the design variables that comprise VGER. Three separate engineering systems initially, and a fourth by extension, would require correct integration for VGER to achieve commercial success. These comprised:

1. Hull System
2. Rotor Propulsion System
3. Rotor Powering System ("Energized Rotors")
4. Rotor Transformation System ("Variable Geometry")

This appendix records in photographs work done over a span of five years on items 1, 2, and 3 above. Since modern merchant ships spend far more time at sea than they do in port, the "energized rotor"-as-thrust-producer took precedence over the "variable geometry"-in-port-power-station component of the project. However, both dimensions of VGER have merit and work on "variable geometry" rotors as VAWTs (vertical axis wind turbines) is recorded separately in Appendix 2.

Hull System:

A model of the hull of a C-2 cargo ship was selected for testing a series of possible VGER designs. The C-2 design was chosen because:

1. At 10,000 deadweight tons it represented a significant size increase (at the time) over other applications of rotors to commercial ships and is the deadweight capacity of a typical motorized barge or small bulk carrier that might represent a realistic initial commercial application of VGER technology.

2. The C-2 was designed by the U.S. Maritime Commission and hundreds of them were built in the 1940s and 1950s. All design information and performance data on this ship design are in the public domain.

A scale of 1" = 9' was chosen for the model. This was a compromise; a larger 1" = 8' scale was deemed preferable. However, the initial contract with NYSERDA did not require or budget for a model and the larger size would have cost more. A smaller scale 1" = 10' model would have been easier to build and transport, however, there was concern that it might not be large enough to hold all the necessary electronics. The scale of 1" = 9' turned out to be a fortunate choice as it produced a model just large enough to fit the rotors, photovoltaic arrays and radio control equipment. The figure below compares the model to the ship.

Comparison of C-2 Ship and Model Design Parameters

Ship Particulars:		Model Particulars:
Linear Dimensions:		λ = 9'/1" (Scale Factor = 108)
LOA	459.25 ft.	51.03 in.
LWL	435.00 ft.	48.33 in.
Beam	63.00 ft.	7.00 in.
Depth to Main Deck	40.50 ft.	4.50 in.
Draft (Full Load)	25.75 ft	2.86 in.
Draft Avg. (Target)	18.00 ft.	2.00 in.
Displacement and Weights:		
Disp. Full Load (Vol.)	525000 ft^3 SW	0.406 ft^3 FW
Disp. Full Load (Wt.)	14600 LT	25.31 lbs.
Dwt. (Maximum)	10200 LT	17.68 lbs.
Light Ship Weight	4400 LT	7.63 lbs.
Ballast Capacity	6470 LT	11.22 lbs.
Total Disp, (Target Vol.)	336917 ft^3 SW	0.267 ft^3 FW
Total Disp. (Target Wt.)	9626 LT	16.69 lbs.
Form Coefficients:		
Midship Coefficient	0.980	0.980
Block Coefficient	0.683	0.683
Prismatic Coefficient	0.697	0.697
Waterplane Coefficient	0.762	0.762
Resistance and Propulsion:		
Wetted Surface	38760 ft^2	3.32 ft^2
Speed Maximum)	15.50 Knots	1.49 Knots
		2.52 ft/sec.
EHP / SHP	0.78	NA
EHP	4680 HP	0.46 Watts*
Installed Power	6000 SHP	1.40 Watts*
Propeller Diameter	19 ft.	2.11 in.
RPM	92 RPM	NA
Stability and Trim (at target darft of 18' ship, 2' model)		
LCG (rel. to midships)	5.25 ft. fwd.	0.58 in. fwd.
KM (18' draft)	26.10 ft.	NA
KG (above baseline)	22 ft.	1.75 in. est.
GM	4.10 ft.	NA
KB	9.54 ft.	1.10 in.
BM	18.83 ft.	26.90 in.
KG	22.00 ft.	1.75 in.
GM calc. est.	6.37 ft. (est.)	26.25 in. (est.)

* See appendix on propulsion for derivation of model power.

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The model faithfully follows the lines of the parent hull so that displacement, resistance and propulsion can be scaled exactly using the laws of comparison and similitude.

Fixed ballast was cast to fit in the double bottom. This submerged the light ship hull to the correct waterline while increasing stability to support rotor.

Forward ballast & ballast compartment

Forward ballast installed

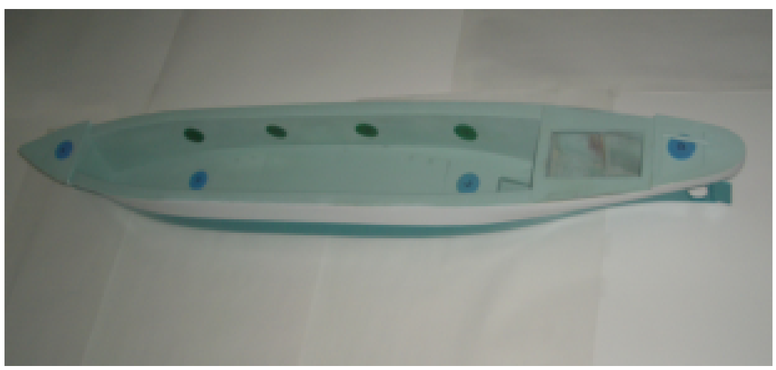
Model with fore and aft fixed ballast installed in double bottom

The model was fitted with a conventional propeller aperture and steering mechanism for radio-controlled testing.

Double-hull construction was used to increase longitudinal strength, to build in buoyancy chambers and trim compartments and to improve watertightness. The hull is coated on the outside with marine epoxy resin and fiber-glassed on the inside.

By the end of the second year the model hull was completed.

Trim tanks were fitted in addition to the fixed ballast.



Rotor mockups were fitted to control space allocation.

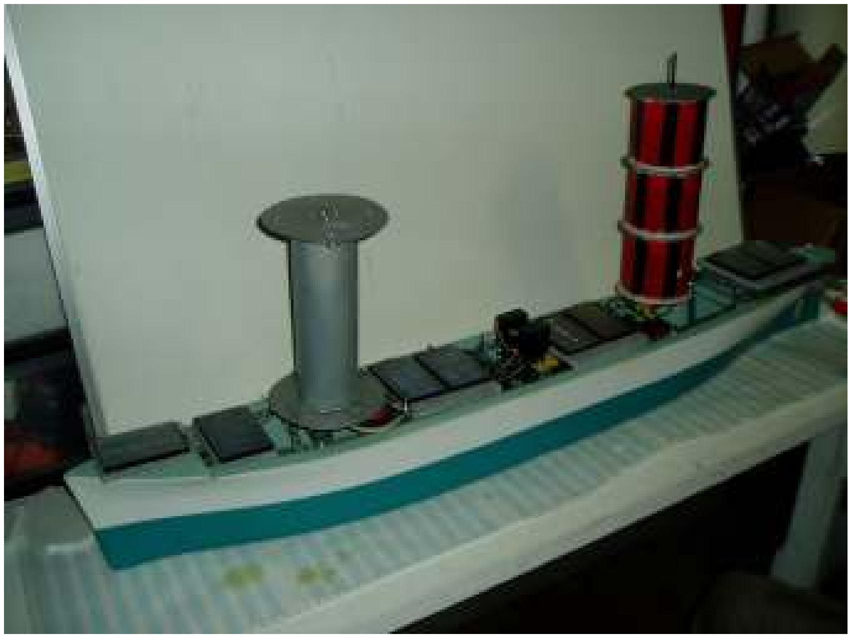
In the third year an easy-to-remove steel cage was fitted to facilitate future machinery and electronics installations. This also minimizes the number of fastenings into the wood hull.

Recently, a conventional Flettner rotor was fitted in the forward rotor position.

A more advanced rotor fitted with intermediate gates (as well as end disks) was fitted in the aft rotor position. This rotor uses a carbon fiber mast instead of brass tube to reduce weight. Also, the bearings of this rotor are lighter, also to reduce weight.

Because this is a working experimental model, it is unlikely the rotors will be perfectly matched any time soon since TransTech is following a strategy of "leapfrog" improvements. The rotors are separately controlled and relatively easy to change out.

The model has recently been fitted with solar panels connected in a combination to increase voltage and amperage. The solar panels recharge the main battery which powers the rotors.



The model has also been fitted with a radio-controlled steering servo.

Closure

All systems (except screw propeller and drive motor, see below) have been bench-tested and the model floats very close to her marks with little need for trim ballast.

The model will be field-tested when suitable propeller and drive motor are obtained. Just as a full-size rotor ship must have a conventional screw propeller for safety when the wind is not blowing, so should the model have secondary "get home" capability.

Field-testing is planned to begin in spring 2012, by which time a sufficiently lightweight variable geometry rotor (see Appendix 2) should also be ready for testing.

The field-test program is planned to study model performance under a number of different wind conditions and model headings over known distances. Measurement of model speed and energy consumption under rotor propulsion, screw propulsion and combinations thereof will enable quantification of the net energy savings contributed by rotors.

The rate at which the "rotors-as-wind-turbines" replenish the battery will provide insight into whether convertible / transformable rotors are worth the higher investment and maintenance cost, given that their use as wind turbines is limited to when the ship is in port and today's merchant ships spend far more time at sea than in port.

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VGER:

Variable Geometry Energized Rotor for Marine Propulsion

Final Report - Appendix 2:
Variable Geometry Rotor Design

Introduction

The appeal of a “variable geometry” Flettner rotor for ship propulsion that can convert into a vertical-axis wind turbine (VAWT) to generate electricity when the ship is in port is intuitive:

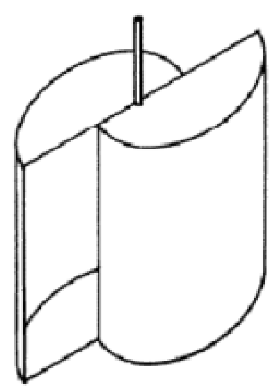
- Obviously, a ship does not need propulsive thrust when it is in port. But it still needs power for the “house” load, and in some cases the machinery for loading and unloading cargo is also run off of ship’s power. In the case of an “all-electric” ship, energy generated in port by rotor / wind turbines could be stored in batteries for later use at sea.

- There are morphological similarities between a conventional Flettner rotor and some types of vertical axis wind turbines, suggesting that it might not be too great a stretch to integrate the technologies.

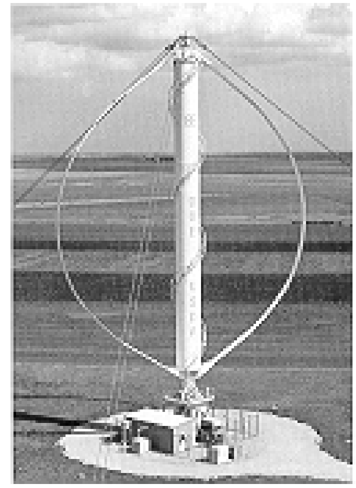
Initial Investigation:

An initial investigation was undertaken to examine which types of VAWTs are most amenable to the dual role. VAWT technology divides along two lines:

1. “Push” (or drag) based VAWTS: This type of wind turbine originated in ancient Persia where sails were mounted on a boom which was attached to a vertical shaft. They machines were used primarily for milling grains and corn and spread across North Africa and eventually to Europe where the technology changed only slightly over two millennia. In the early part of the 20^{th} century, Finnish inventor Sigurd Savonius improved the VAWT by “splitting an oil drum” into two opposed scoops. Though less efficient than more modern VAWTS, they remain popular because of their relative simplicity. All drag based VAWTS like Savonius machines share the common characteristic of not spinning very fast (tip-speed ratio, or TSR, which is the ratio of rotational speed of a point on the outer periphery of a VAWT to the wind speed, rarely exceeds 1.0), so their higher torque is more efficiently used to perform mechanical work, like pumping water, rather than to produce electricity through a gear box.



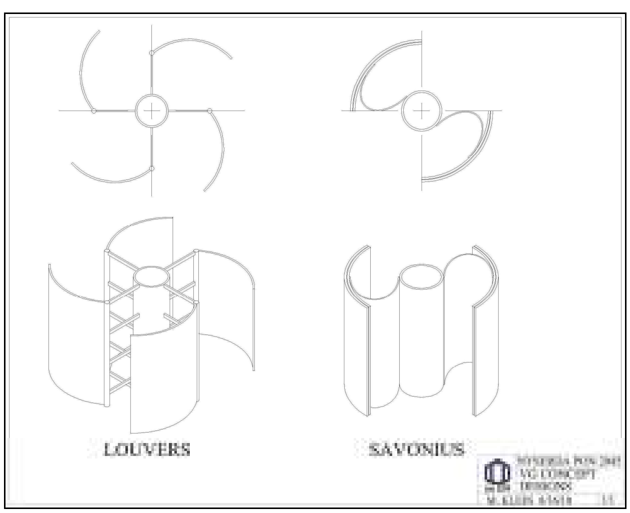
2. “Pull” (or lift) based VAWTS: This type of VAWT uses thin, often curved, aerofoil-type blades that produce lift to “pull” the vertical shaft about its axis. They are more efficient than drag-based VAWTs. Georges Darrieus invented the machine that bears his name in the 1930s and there are several variants that go by other names. Lift-based VAWTs have TSRs far in excess of 1.0 (4.0 to 5.0 is common) which, coupled with low starting torque, makes them better at generating electricity than performing mechanical work. The machines are subject to greater stresses due to higher speed and lighter construction.



TransTech’s investigation of VAWTs revealed there is promising on-going research and development on both drag and lift-based technologies occurring in many countries. The R&D is directed towards improving efficiency, reducing weight and extending robustness. An unanticipated finding of TransTech’s research is that because VAWTs are being “reinvented” in so many new ways, it could well be the case that it will be easier to transform one of the new designs into a Flettner rotor, rather than transform a Flettner rotor into a VAWT.

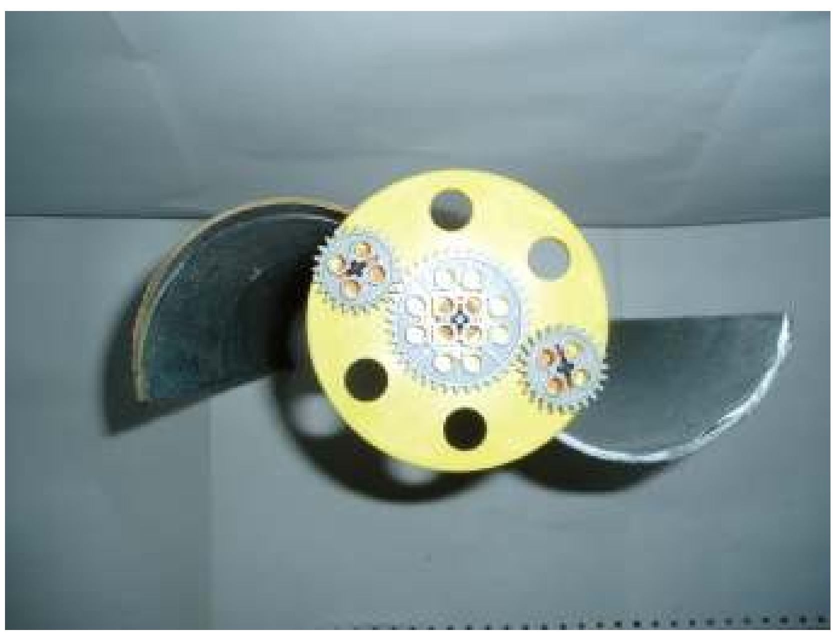
Building a Prototype:

There are conceivably dozens of ways a Flettner rotor might transform into a vertical-axis wind turbine. Louvers and a Savonius machine were selected as the final candidates based on their relative simplicity (and the fact that gear boxes have improved that could gear up their RPMs to generate electricity). The overriding consideration was that the VAWT component of VGER should impact the rotor propulsion component as little as possible.



A Savonius machine was decided upon as simplest of all to build, since transformation from a rotor requires the fewest moving parts.

A system of gears was designed that can be engaged by an external motor to open and close the rotor / Savonius machine.



When fully opened, the rotor resembles a conventional Savonius machine. .

Preliminary Findings:

As rotor complexity increases, so does weight gain and the weight increase is marked, even when close attention is paid to controlling it. This is due to the fact that there are more components and some of them are heavier by nature, such as gears that must be ruggedly built. The prototype variable geometry rotor shown in this appendix was not installed on the test model. It is currently being evaluated to explore ways to reduce weight and lower its VCG (vertical center of gravity).

As alluded to earlier in this appendix, an unanticipated finding of TransTech's research was that it might prove easier / more efficient to transform a VAWT to a propulsion rotor, than vice versa. A modern elastic material might, for instance, be used to sheath a wind turbine to create a propulsion rotor. When the rotor is to be transformed back into a wind turbine, the area beneath the rotor end disks creates a natural space to "furl" the sheathing material. This is an area for further study by a team that should include materials science expertise.

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