An Investigation into the Use of Linear Generators in the Schneider Hydro-Power Generation System

by

Jaime Sarabia

Submitted to the Department of Mechanical Engineering
in partial fulfillment of the requirements for the degree of

Bachelor of Science

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 1998

Author..
Mechanical Engineering
April 27, 1998

Certified by..
Ernesto Blanco
Adjunct Professor of Mechanical Engineering
Thesis Supervisor

Accepted by..
Derek Rowell
Chairmen of the Undergraduate Thesis Committee
Mechanical Engineering

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Abstract

The Schneider HydroBeaver is a revolutionary idea in Hydro-Power Generation. Conventional dams employ the use of turbines which require a large head to generate the power. The large head is developed through dams, which alter the natural course of rivers, destroying fertile river valleys and ruining the environment for fish. The HydroBeaver plans to develop power through a head of only 3 meters. No dam is required to develop this head. The HydroBeaver unit is small and environmentally friendly. Because no dam is required, no land is destroyed, plus the design allows for safe passage of fish downstream. The purpose of this thesis was an investigation into the feasibility and efficiency of a linear generation unit rather than a rotational generation unit. As is, the Hydro Beaver generates power through a rotational power generation unit placed on one of the axis. The idea is that a linear generation unit would be able to provide more power, more efficiently and in less space. This thesis discovered the governing variables in a linear power generator and briefly describes how to design a linear generator according to these variables. Airgap, magnet size, magnet flux density and field intensity, as well as velocity were discovered to effect power generation. Given the size restraints of the HydroBeaver and limits on foil velocity, it was discovered that a linear power generation unit is an inefficient and not very economic approach to the power generation problem. It will develop power, but only at about 10% of the power desired. This thesis lays the groundwork on the design of a linear generator so in the event of advancement in magneto-solid technology or some other technological advance, this thesis can be referenced or reinvestigated.

Thesis Supervisor: Ernesto Blanco
Title: Adjunct Professor of Mechanical Engineering

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Introduction:

The current method of generating hydropower is by means of dams. Dams have many harmful and undesirable effects on the environment in which they operate. Because of the large head needed for dam hydropower generation, dams require flooding out regions of useful, fertile land, and alter the natural courses of rivers, streams, and lakes. They are expansive in size and expensive in cost. The geographic alteration has a severe impact on the ecological systems of the land. They are significantly decreasing the salmon population, because salmon cannot withstand the extreme pressure drop through the turbines. The high rotational velocity also wreaks havoc on the salmon gills, tearing them apart and cutting off their vital means by which they extract oxygen from the water.

Dams are usually built on land given to Native Americans. The Native Americans rely on the land to cultivate crops and the water to fish for salmon. These dams are pushing the Native Americans out of their land by cutting off their food supplies. The brunt of the negative effects of dams is shouldered by the Native Americans, while they receive little of the positive aspects.

The Schneider HydroBeaver is a revolutionary idea in the realm of hydropower generation. It's small, non-disruptive design makes it an ecologically sound alternative to dam hydropower generation. The basic premise behind the HydroBeaver is linear rather than rotational fluid power generation (see Figure 1).

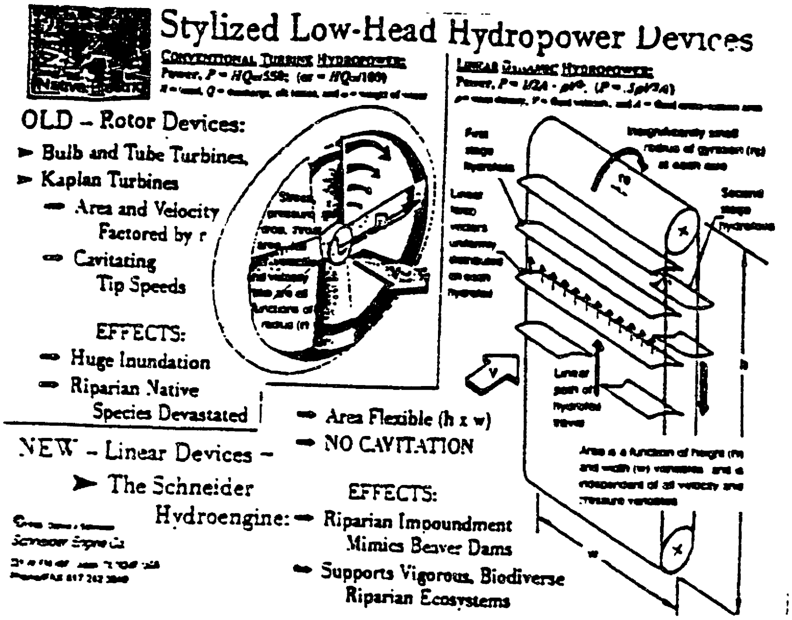
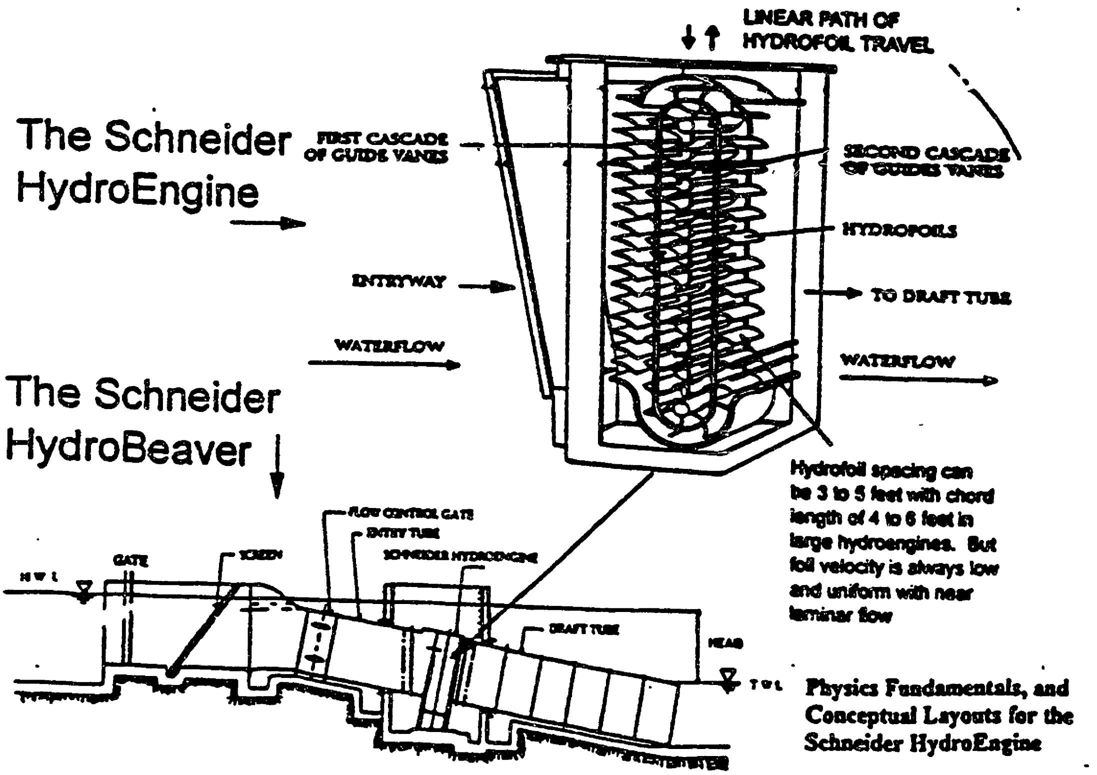


Figure 1. Low Head Hydro-Power Device versus Conventional Hydro-Power Device

The equation governing the power of the Hydrobeaver is

$$P = 0.5\rho V^3 A, \tag{EQ 1}$$

where P is power, V is velocity, and A is throat Area. Because power goes with velocity cubed, this design requires low head, therefore does not require a dam. Since there is no dam, there is no physical alteration of the landscape of the region in which it operates. The machine uses the linear motion of the water to lift the hydrofoils. The motion of the water is controlled by the draft tubes which insure laminar flow (see Figure 2).



Hydrofoil spacing can be 3 to 5 feet with chord length of 4 to 6 feet in large hydroengines. But foil velocity is always low and uniform with near laminar flow

Physics Fundamentals, and Conceptual Layouts for the Schneider HydroEngine

Figure 2. Conceptual Layout of HydroBeaver

The HydroBeaver design as is converts the linear motion of the foils to power through a rotational power generation unit. The current design places a rotational power generation unit on one of the axles. The flow induced motion causes the axle to rotate, thus generating power. The design challenge of this thesis was to propose the feasibility of using a linear power generation system to convert the mechanical energy into electrical energy.

The HydroBeaver has been analyzed and redesigned extensively by previous classes and thesis topics. Because it has been so thoroughly analyzed, I will not go too in depth into the fluids and design of the actual unit. I will take many of the parameters as given from previous designs. I will focus most of my investigation on the feasibility, efficiency, reliability, and design of a DC Permanent Magnet Linear HydroPower Generation Unit. I will go through the Physics and Governing Equations that define how mechanical energy is converted to Electrical energy. I will then go in depth into the design of Linear Power Generators, and apply this knowledge to the HydroBeaver. I will then design and analyze a Linear Power Generator and explain why or why not this is a viable option.

Theoretical Analysis of the Fluids of theHydroBeaver:

As stated earlier, the fluid power is generated within the HydroBeaver according to the equation:

$$P = 0.5\rho A V^3 \qquad \text{(EQ 2)}$$

The velocity component of the equation can be solved from Bernoulli's equation:

$$V = \sqrt{2gh} \qquad \text{(EQ 3)}$$

where g is gravity (9.8 m/s^2) and h is the head (about 3 m). Because the water is diverted at a 55 degree angle, the vertical velocity of the guide vanes will be (see figure 3)

$$V_y = V\sin 55 \qquad \text{(EQ 4)}$$

Plugging the values into equation 3, gives a value of V_y=6.3 m/s.

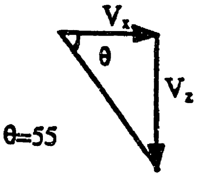


Figure 3. Flow Velocities

The throat area A was found by multiplying the length and width of the HydroBeaver Unit. Assuming a 12ft by 8 ft (specs set by Prof. Blanco) unit you get an area of 96 ft^2 or (8.9m^2). Plugging these values and the density of water back into the Power equation yields a theoretical power of about 1.1 MW. This is the power the water contains as it flows downstream. The only way the HydroBeaver would be able to produce this much power would be if the system was 100% efficient. Because of viscous losses in the water flow, non-zero exit velocity of the water from the second row of foils, momentum not being totally transferred, and friction within the machine, the power output of the Hydrobeaver is significantly less.

Theoretical Analysis of the Mechanics of the HydroBeaver:

Because the linear motion of the water cannot be totally harnessed, some design parameters had to be set. Many HydroBeaver prototypes have been built and tested. A common foil velocity was found to be around 3.05 m/s (10 ft/s). Prof. Schneider stated that 28 kW per end of foil would be desired. Power for a linear mechanical system is given by

$$P = Fv \qquad \text{(EQ 5)}$$

where P is power, $\vec{F}$ is the tension in the belts and v is the velocity. Plugging in 28 kW for power and 3.05 m/s for velocity yields a total force (tension) equal to 9180 N (2063 lbs). Therefore a tension of around 1/2 ton per belt (4590 N/belt), and a velocity of around 10 ft/s (3.0 m/s) will be needed to achieve the desired power output. This is assuming a 100% efficient conversion of mechanical energy to electrical energy.

Theoretical Analysis of Design of DC Linear Permanent Magnet Generator:

In order to understand the design of a DC Linear Permanent Magnet Generator, the physics governing the behavior needs to be understood. The basic premise is given by the principle of Electro-magnetic induction.

Faraday's Law states that the induced emf in a circuit is directly proportional to the time rate of change of magnetic flux through the circuit

$$\varepsilon = -N\frac{d\Phi_B}{dt}, \qquad \text{(EQ 6)}$$

where ε is the induced emf, N is the number of turns in the coil, and Φ is the magnetic flux through an area. Magnetic flux is defined as

$$\Phi_B = \int B \cdot dA \qquad \text{(EQ 7)}$$

where B is the magnetic field, and A is the area element over which the field acts. In order to find the power which will be induced in the system, we will need to find the induced emf and then multiply it by the current.

The schematic represantation of the system can be seen in Figure 4. I rotated the unit 90 degrees for ease in conveying information on one sheet of paper. The solid mass above is the conductive material which is wrapped with a coil of N turns, the solid cross-hatched mass below is the permanent magnet. As you can see the motion of the magnet is guided by the guidevane, and the magnet is linked to the belt by a threaded rod to the same coupling that links the foils to the belt.

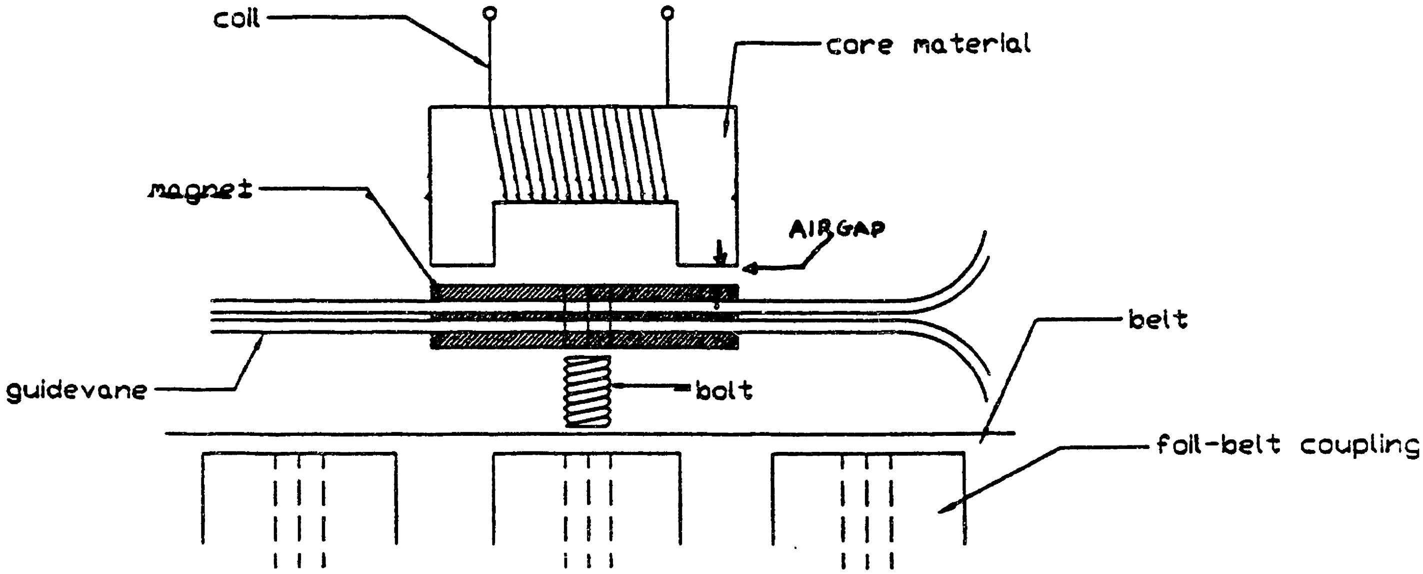


Figure 4. Model of Linear Motor System

Table of Variables

H=magnetic field Intensity
B=flux density
N=turns
i=current
v=velocity
g=airgap
A_m=Area of Magnet
μ_o=permeability of free space
m subscript=magnet
g subscript= airgap
l= length of path
μ_{rc}=permanent magnet recoil permeability=$1.05\mu_0$

To find the power generated by a moving magnet linear generator you must first develop a model. A model of the system showing the flux path through which Ampere's Law is applied is shown in figure 5.

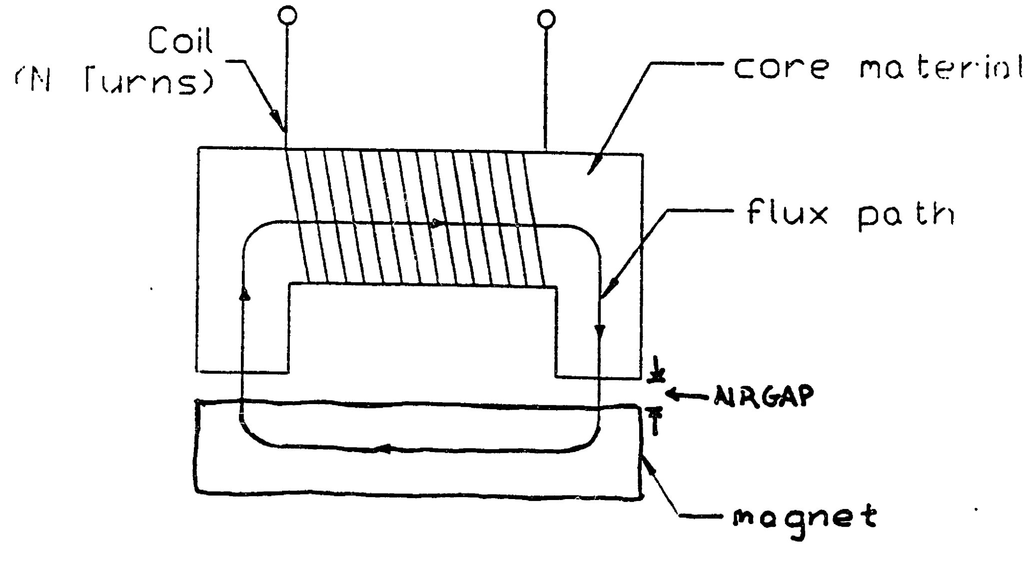


Figure 5. Model of System showing Magnet Flux Path

As you can see the model consist of the moving magnet or primary, the core material or stator, and the coil. A voltage will be induced into the coil because of Faraday's law (see equation (6)). Faraday's Law does not provide a way to quantify exactly how much voltage can be induced according to the system geometry. In order to find the induced EMF in the system one needs to analyze the magnetic circuit of the linear generator system.

To begin this we need to look at the magnetic circuit. In Figure (5), you see a model of our magnetic circuit with coils, core material and an air gap. The line through the material is a path along which the magnetic field travels. Because magnetic and electric circuits are synonymous, we can apply Ampere's Law to the magnetic circuit. Amperes Law states that the sum of the Magnetic Field Intensities along a path equals the current running through that path. In our case I = 0.

$$\oint H dl = H_m l_m + H_g L_g = I = 0 \qquad \text{(EQ 8)}$$

Now to find the induced emf of the system, we need to know the permanent magnet operation flux density B_m. B_m is related to the magnet residual flux density B_r by the relationship

$$B_m = B_r + \mu_{rc} H_m \qquad \text{(EQ 9)}$$

But H_m can be solved using Ampere's Law above. The airgap magnet field intensity H_g is related to B_m by the equation (neglecting saturation and leakage)

$$B_m = B_g = \mu_0 H_g \qquad \text{(EQ 10)}$$

Combining these three equations gives

$$B_m = B_r\left(1 + \frac{\mu_{rc}}{\mu_0}\left(\frac{2k_s g}{l_m}\right)\right)^{-1} \qquad \text{(EQ 11)}$$

Now, knowing the magnet operation flux density, enables us to solve for the induced emf E.

$$E = 4.44 f B_m A_g N \qquad \text{(EQ 12)}$$

where f is the frequency of motion, A_g is the magnet area, and N is the number of turns on the stator. A spreadsheet is attached in the appendices to show how the voltage is affected by the various design parameters.

Some assumptions had to be made before we could calculate the induced emf. First of all the magnets weren't oscillating at a frequency. But since the magnets travel in a train across the stator, I modeled them as coming and going at a certain frequency. Assuming a distance of 10 cm between magnets and given that they travel at 3m/s, yields a frequency of 30 Hz. This is a simplified view of the model, but provides us with a good approximation of the induced emf.

As for magnet dimensions, this is normally solved for using the equation

$$vol = A_m l_m = \frac{B^2{}_g A_g l_g K}{B_d H_d} \tag{EQ 13}$$

where K is the leakage factor. Since our magnet dimensions are constrained by the dimensions of the HydroBeaver, I set their height, length, and depth. I then solved for the induced emf according to these dimensions. Using a spreadsheet provides an easy way of iterating the equations to obtain the necessary induced voltage. The spreadsheet used in this design is attached in the appendix. As you can see, assuming a current of 10 A, it would take quite a hefty magnet to generate the desired 21 kW of Power.

The power output from our generator will be defined by how many volts V it puts out times the current i

$$P = Vi \tag{EQ 14}$$

The current of the system can be found by the relationship

$$V = iR \tag{EQ 15}$$

where R is the resistance of the coils. Assuming copper wires, the resistance can be solved knowing the resistivity of copper. The resistance of copper is a function of the area and length of the wire. To solve for the resistance, I looked up the resistivity of copper in the Metals Handbook. The resistance was a function of wire gage or diameter. Using a spreadsheet to solve for the various resistivities as a function of wire gage and length, we were able to then find the induced current. Plugging the induced EMF and current into equation 14, enabled us to solve for the Power Output. The systems efficiency will be defined by how much of the mechanical power is transduced into electrical power.

$$efficiency = \frac{Vi}{F_e v} \tag{EQ 16}$$

Permanent Magnet and Core Material Selection

A crucial element of the design will be the selection of materials to construct this system out of. The permanent magnet material should meet a list of criteria. It should be relatively cheap, easy to machine, and should have a broad hysteresis loop. (See figure 6).

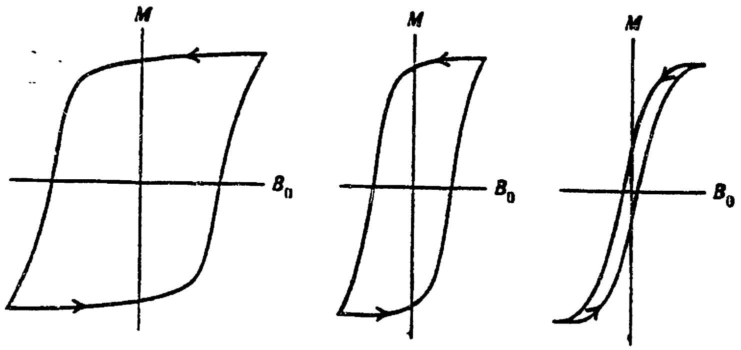


Figure 6: Hysteresis Loops

You also want it to be a material that requires a large reverse field to demagnetize it. Usually steel and alloys such as Alnico, sintered SmCo, and NdFeB are used for permanent magnets. For this application I am afraid to say we will need an especially powerful and expensive magnet to generate the fields desired in our limited area.

When selecting the core material, ferromagnetic materials are widely used. These materials are good because they induce relatively high currents for a given magnetic field. For this application a relatively narrow hysteresis loop is desired because hysteris is what dissipates the energy. The area under the curve is the work generated during hysteris. You want to minimize this because energy dissipation is in the form of heat, which is often the cause of failure or burn out in motors. It is also a source of loss within the generator. Keeping the hysteris loop narrow reduces the amount of heat generated in the motor/generator, and provides for a robust design. However our generator will perform underwater, so we can accept a broader hysteresis loop for better performance. since it will be constantly convectively cooled by cool flowing water.

When dealing with electromagnetic devices, you must account for the energy dissipation within the material itself. These losses are called core losses and are due to losses within the material due to eddy currents forming and hysteresis loss. The loss due to hysteris is the area under the curve times the frequency

$$P_h = k_h f B_m^{1.5-2.5} \qquad \text{(EQ 17)}$$

where k_h is a constant, f is the frequency and B_m is the maximum flux density.

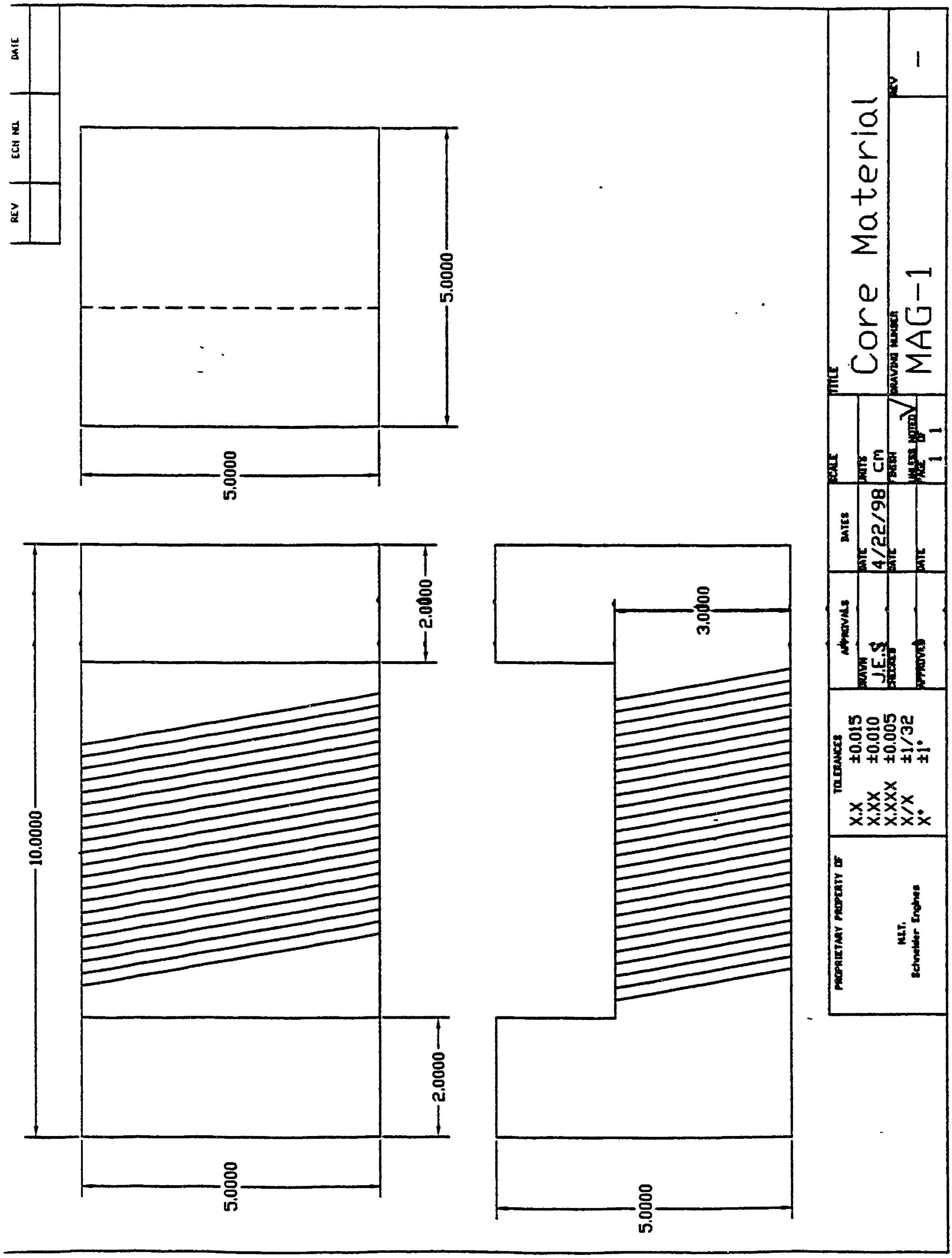
The losses due to eddy current formation is calculated using the following equation

$$P_e = k_e f^2 B_m^2 \qquad \text{(EQ 18)}$$

where k_e is another constant proportional to the lamination thickness, and B_m is the maximum flux density. One way of reducing eddy current loss is to sandwich the magnet with thin layers of electrical insulation. The more layers you sandwich, the more you reduce eddy current power loss.

Design Ideas

The design phase of this thesis involves incorporating the components of the DC Linear Permanent Magnet Generator into the existing design. We want to do this in as small a space as possible and do not want the design to change any of the dimensions of the HydroBeaver. The following drawings are ideas on how to design the system to be integrated into the existing HydroBeaver. As you can see the magnet will be attached to the same fixture that attaches the foils to the belt by a The magnets will be shaped of a geometry seen in the picture to provide a way of maintaining the crucial air gap. The fins will run along the guidevanes. The guidevanes will be constructed of a strong lightweight material, that doesn't conduct well with magnets. That way there will be minimal reduction in force due to magnetic attraction. The entry end of the guide vane will flare out to guide the magnets into their railway. The tolerances on the width of the rail and the dimension of the fin on the magnet will need to be on the order of.0005". I am not sure that is within machinability limits. If it is, it will be costly.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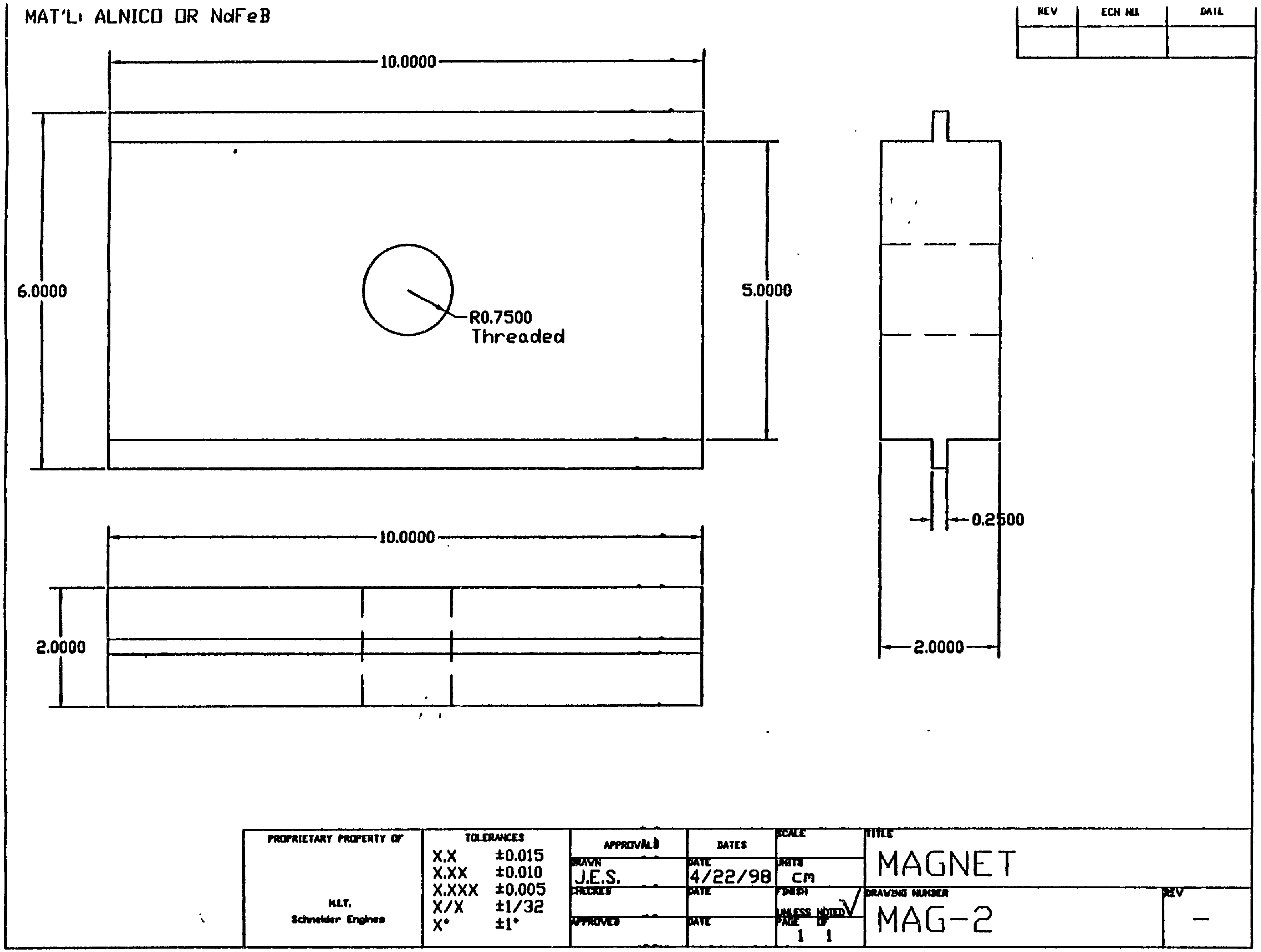
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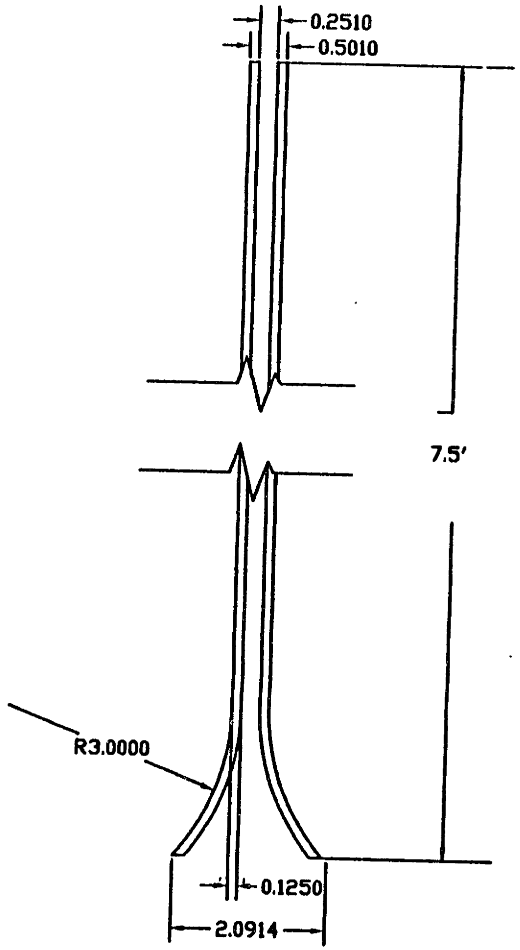

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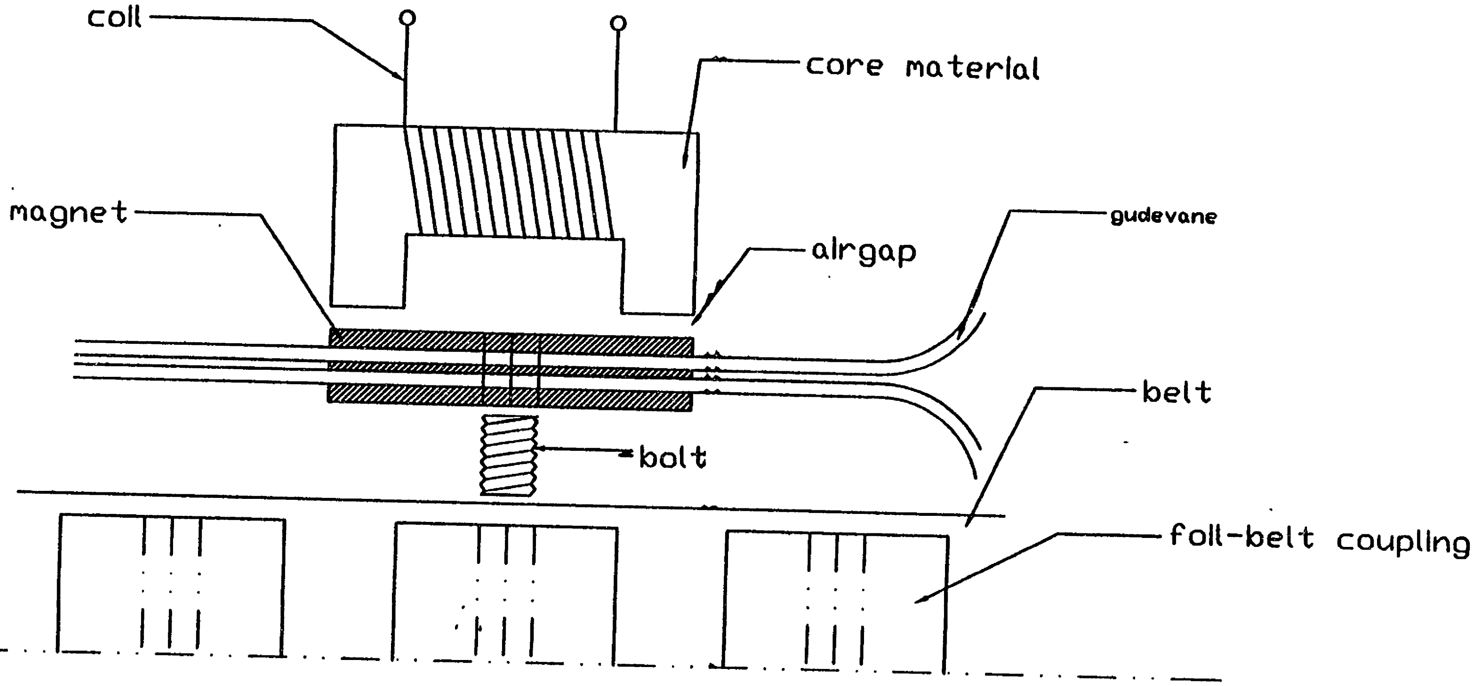

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Conclusions and Recommendations

A DC linear Permanent Magnet Generator would not be a viable option to generate HydroPower. In order to generate the desired output one would need magnets on the order of one meter square. The magnetic field intensity and flux density of existing permanent magnet materials need to be significantly improved before this type of generator could be a realistic option. Maybe if the speed (therefore frequency) could be increased, this a realistic option.

If you look at the Power Generation and Efficiency spreadsheet in Appendix B, you will notice that the efficiencies are high only for the 4 gage wire. The problem is that 4 gage wire is too thick to make the coil out of, plus at that current you would burn the wire up. You would need something in the range of 12-20 gage wire. If you scan the efficiencies of these wire gages for the two coils of 50 and 100 turns you will notice that they are only 11% efficient at best. And that is under ideal conditions.

Some recommendations I would like to make for future research topics, would be to think of ways to increase the frequency. Maybe by altering the geometry of the magnets, or the dimensions by which they are separated you could increase the power output.

Also since this was only an investigation into the feasibility of a permanent magnet linear DC power generator, it did not go too in depth into the design once it was discovered that it was not a viable option. There could be analysis of the viscous damping between the magnet and stator. There could also be some analysis performed on the shear generated between the magnet fins and guidevanes. Another subject could be an investigation into what sort of effect the mechanical vibration of the system will have on magnetic performance over time.

Another design idea could be in a design that maintains the tight.001" airgap to a tolerance required to get any significant power out of the system.

Finally a more detailed and complete design of the incorporation of a linear DC Permanent Magnet generator could be investigated. This could involve all the necessary technical drawings. The design would need to encompass everything from shape, size, and integration of the individual parts. The assembly design and how it is incorporated into the existing design would also need to be extensively researched.

Appendix A: Induced Emf Spreadsheet:

Magnet length	Magnet Width	Magnet Depth	Frequency	PM operation Flux Density	Residual Flux Density	Permeability ratio	Airgap	Induced EMF	Turns
0.1	0.05	0.02	30	1.0751637	1.1	1.05	0.001	35.802952	50
0.1	0.05	0.02	30	0.98610489	1.1	1.05	0.005	32.837293	50
0.1	0.05	0.02	30	0.33232628	1.1	1.05	0.1	11.066465	50
0.1	0.05	0.02	30	1.0399433	1.1	1.05	0.0025	34.630111	50
0.1	0.05	0.02	30	1.0751637	1.1	1.05	0.001	35.802952	50
0.1	0.05	0.02	30	1.0751637	1.1	1.05	0.001	71.605904	100
0.12	0.08	0.02	30	1.0751637	1.1	1.05	0.001	68.741667	50
1	1	0.02	30	1.0751637	1.1	1.05	0.001	7160.5904	50
0.1	0.05	0.02	30	1.0751637	1.1	1.05	0.001	716.05904	1000
0.1	0.05	0.02	60	1.0751637	1.1	1.05	0.001	71.605904	50
0.1	0.05	0.02	30	1.0751637	~~1.1~~	~~1.05~~	~~0.001~~	~~35.802952~~	~~50~~
0.1	0.05	0.02	30	0.51044084	1.1	1.05	0.05	16.99768	50
0.1	0.05	0.02	30	0.24636058	1.1	1.05	0.15	8.2038074	50
0.15	0.055	0.025	30	1.0751637	1.1	1.05	0.001	59.07487	50
0.12	0.052	0.025	30	1.0751637	1.1	1.05	0.001	89.364168	100
~~0.05~~	~~0.05~~	~~0.02~~	~~60~~	~~1.0751637~~	~~1.1~~	~~1.05~~	~~0.001~~	~~35.802952~~	~~50~~
0.1	0.05	0.02	30	1.0751637	1.1	1.05	0.001	35.802952	50
0.1	0.05	0.02	30	1.0751637	1.1	1.05	0.001	35.802952	50
0.1	0.05	0.02	30	1.0751637	1.1	1.05	0.001	35.802952	50

Appendix B: Power Generation and Efficiency Spreadsheet

Gauge	Turns	Length	Resisitivity (ohms/1000ft)	Resistivity (ohms/m)	Resistance	
4	50	80	0.2584	0.00084776903	0.067821522	
8	50	80	0.6532	0.0021430446	0.17144357	
12	50	80	1.65	0.0054133858	0.43307087	
16	50	80	4.18	0.013713911	1.0971129	
20	50	80	10.6	0.034776903	2.7821522	
24	50	80	33.7	0.1105643	8.8451444	
28	50	80	67.8	0.22244094	17.795276	
32	50	80	169	0.55446194	44.356955	
36	50	80	431	1.414042	113.12336	
40	50	80	1122	3.6811024	294.48819	
44	50	80	2696	8.8451444	707.61155	
Gauge	Turns	Length	Resisitivity (ohms/1000ft)	Resistivity (ohms/m)	Resistance	
4	100	160	0.2584	0.00084776903	0.13564304	
8	100	160	0.6532	0.0021430448	0.34288714	
12	100	160	1.65	0.0054133858	0.86614173	
16	100	160	4.18	0.013713911	2.1942257	
20	100	160	10.6	0.034776903	5.5643045	
24	100	160	33.7	0.1105643	17.690289	
28	100	160	67.8	0.22244094	35.590551	
32	100	160	169	0.55446194	88.713911	
36	100	160	431	1.414042	226.24672	
40	100	160	1122	3.6811024	588.97638	
~~44~~	~~100~~	~~160~~	~~2696~~	~~8.8451444~~	~~1415.2231~~	
For Copper Wire (50 Turns)						
gauge	resistance	Emf	Current	Power	Power	efficiency (%)
4	0.067821522	35.802952	527.89956	18900.363	18900.363	68%
8	0.17144357	35.802952	208.83228	7476.8121	7476.8121	27%
12	0.43307087	35.802952	82.672271	2959.9113	2959.9113	11%
16	1.0971129	35.802952	32.633791	1168.386	1168.386	4%
20	2.7821522	35.802952	12.868797	460.74091	460.74091	2%
24	8.8451444	35.802952	4.0477521	144.92147	144.92147	1%
28	17.795276	35.802952	2.0119358	72.03324	72.03324	0%
32	44.356955	35.802952	0.8071553	28.898542	28.898542	0%
36	113.12336	35.802952	0.31649477	11.331447	11.331447	0%
40	294.48819	35.802952	0.12157687	4.3528108	4.3528108	0%
44	707.61155	35.802952	0.050596901	1.8115184	1.8115184	0%
For Copper Wire (100 Turns)						
gauge	resistance	Emf	Current	Power	Power	efficiency (%)
4	0.13564304	35.802952	263.94978	9450.1813	9450.1813	34%
8	0.34288714	35.802952	104.41614	3738.4061	3738.4061	13%
12	0.86614173	35.802952	41.336135	1479.9557	1479.9557	5%
16	2.1942257	35.802952	16.316896	584.19302	584.19302	2%
20	5.5643045	35.802952	6.4343984	230.37046	230.37046	1%
24	17.690289	35.802952	2.0238761	72.460737	72.460737	0%
28	35.590551	35.802952	1.0059679	36.01662	36.01662	0%
32	88.713911	35.802952	0.40357765	14.449271	14.449271	0%
36	226.24672	35.802952	0.15824739	5.6657235	5.6657235	0%
40	588.97638	35.802952	0.060788434	2.1764054	2.1764054	0%
44	1415.2231	35.802952	0.025298451	0.90575921	0.90575921	0%

Bibliography and References

1. Boldea, I and Nasar, Syed A. Linear Electric Actuators and Generators. Cambridge University Press, Cambridge 1997.

2. Basak, Amitava. Permanent Magnet DC Linear Motors. Oxford University Press, Oxford 1996.

3. Moon, Francis. Magneto-Solid Mechnics. John Wiley and Sons, New York 1984.

4. Boldea, I and Nasar, Syed A. Linear Motion Electric Machines. John Wiley and Sons, New York 1976.

5. Young, Hugh D. University Physics. Addison Wesley Publishing Company, Reading, MA 1992.

6. Moskovitz, Alexander D. and Korn, Naomi S. "Analysis and Optimization of the Schneider HydroEngine." Unpublished B.S. Mech E. Thesis, MIT 1997.

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