

TECHNIQUES FOR EDDY CURRENT REDUCTION IN MAGNETIC DRIVES USING METALLIC CONTAINMENT BARRIERS

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ABSTRACT

Magnetic drive systems, using permanent magnets, are a well known method for transmitting power through a casing or barrier where penetration of that casing is to be avoided. Several magnetically driven pumps are available today which are aimed at the "sealless" pump market where dynamic shaft seals cannot be used. Most of these units use solid metallic barriers which cannot be anything but inefficient, owing to the generation of wasteful eddy currents. With the increased interest in "sealless" drive systems, especially for 50 hp systems and above, a unique magnetic coupling design, using a metallic pressure containment barrier which operates at high efficiency, has been developed. The eddy current problem is reviewed, the new technology is described, and its application is discussed.

MAGNETIC DRIVE SYSTEMS

General Overview

Magnetic drives (or couplings) using permanent magnets are well known for their ability to transmit power through a casing, or barrier, without actually penetrating the casing. In this way, the problems associated with dynamic shaft seals are removed; there is no seal to wear and eventually leak. Whatever seals remain in the assembly are simple static seals.

It is not the intent of the authors to investigate design principals of magnetic drive systems; this is well covered by other literature. However, certain aspects of the design of magnetic circuits will be discussed as they relate to the topic of eddy currents.

With the current interest in the control of "fugitive emissions," where virtually no leakage is permitted [1], a magnetic coupling becomes a very attractive alternative. Many pump manufacturers are making "sealless" magnetically driven versions of their products. These are typically less than 30 hp and use thin metallic barriers between the inner and outer magnet sets, as shown in Figure 1. Some pumps use nonmetallic barriers, and while successful in certain applications, there is no wide ranging acceptance of these materials. Usually, any application in the petrochemical sector dictates that metallic barriers be used.

North American industry standards, such as API 610 [2], require working stress levels in the pump casing, which would include the barrier, that comply with ASME Boiler and Pressure

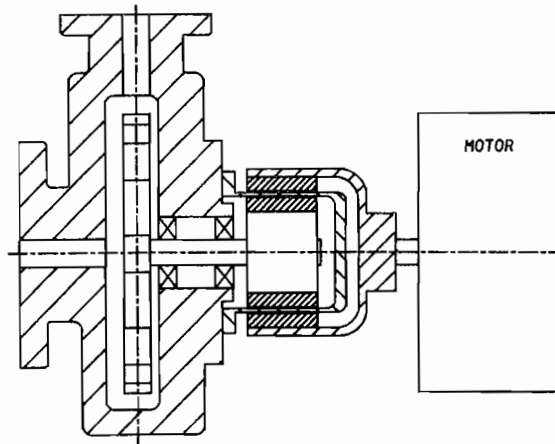


Figure 1. Typical Magnetic Pump Drive.

Vessel Code [3]. This presents a two faced problem in that a thin barrier is required to keep the magnets as close together as possible for maximum torque transmission, but it must also be thick enough that maximum specified stress levels are not exceeded.

However, there is another problem that occurs when using metallic barriers. It is subtle and not well understood. This is the generation of eddy currents. The effect of eddy current generation is to create waste heat in the barrier, which is usually given off to the working fluid. Of course, energy is required to generate these eddy currents. This lowers the efficiency of the magnetic drive assembly by substantial amounts. In a 75 hp drive, for example, a 50 percent efficiency would not be unusual. And it becomes worse as more power, larger size, higher rotational speed, and higher working pressures (requiring a thicker barrier) are considered.

REVIEW OF EDDY CURRENT PROBLEMS

Back to Basics

If you can recall your high school physics days, you will remember "Flemings Right-Hand Rule for Generators," where a conductor moving through a magnetic field creates a current in the conductor. A magnetic field is set up between pairs of poles in the magnetic drive unit, and the conductor is the metallic barrier. There is relative motion between them, but in this case, the conductor (barrier) is stationary, and the magnetic field is moving. The current generated is the subject eddy current.

Effect of Induced EMF

The electro motive force (EMF) induced in a straight conductor moving through a magnetic field is given by:

$$EMF = \frac{\delta\phi}{\delta t} \times \text{Length (volts)} \quad (1)$$

ϕ is the flux, and $\frac{\delta\phi}{\delta t}$ is proportional to flux density (B), rpm and radius [4].

As this conductor is now carrying a current and is moving through the magnetic field, a retarding force opposing the motion of the conductor will be set up, requiring energy to overcome it, just as in a generator, and,

$$\text{Force} = \text{Flux Density} \times \text{Length} \times \text{Current}$$

(Flux Density is referred to as B) [4]. (2)

So, from a mechanical point of view, and remembering that, in this case, the conductor is stationary and the field is moving, this retarding force acts against the rotation of the magnets, and,

$$\text{Force} \times \text{Radius} = \text{Torque} \quad (3)$$

This represents a level of negative or "lost" power which must be overcome by the prime mover, and it is obvious how this can lead to the reduction of efficiency of the drive system.

Ohmic Losses

From an electrical point of view, eddy current losses also consist of $I^2 \times R$ losses [4]. These Ohmic losses in a metallic conductor are given by:

$$\text{Watts (loss)} = \text{Current}^2 \times \text{Resistance} \quad (4)$$

Using Ohm's Law, this becomes,

$$\text{Watts} = \frac{\text{Volts}^2}{\text{Resistance}} \quad (5)$$

From these equations, it can be seen that eddy current voltage is proportional to flux density (B), speed of rotation, and the radius; therefore, the losses can also be expressed as:

$$\text{Watts (loss)} = \frac{\text{Function of (B, rpm, radius)}^2}{\text{Resistance}} \quad (6)$$

This shows that changes in flux density, speed of rotation, and physical size (radius) of the drive system all have a *squared function* and have a major affect on the level of watts lost from the overall power throughput. These "golden rules of magnetic drives" are shown in Table 1.

Table 1. The Golden Rules of Magnetic Drives.

A.	Losses go up with the square of the speed.
B.	Losses go up with the square of the increase in drive radius.
C.	Losses go up with the square of the increase of flux density.
D.	Losses are inversely proportional to the resistivity of the barrier material.

Effects of Modern Magnet Materials

In order to obtain as much torque transmission in the smallest space, the strongest available magnets need to be used. The strongest permanent magnet materials today all stem from the "rare earth" family of compounds. Some of the major features of commonly used magnet materials are listed in Table 2.

Table 2. Magnet Material Properties.

SAMARIUM COBALT:

Curie Temp.	:	700°C
Max. Useful Temp.	:	350°C (500°F)
Energy Product, BH max	:	18-32 MGO (Mega Gauss Oersteds)
Temp. Coef. (Loss)	:	0.030-0.045%/°C
Loss of Force/Pole	:	0.089%/°C

NEODYMIUM:

Curie Temp.	:	300°C
Max. Useful Temp.	:	150°C (300°F)
Energy Product, BH max	:	24-35 MGO
Temp. Coef. (Loss)	:	0.090-0.120%/°C
Loss of Force/Pole	:	0.36%/°C

A common method of comparing the relative strengths of differing types of magnets is to look at their "maximum energy product" or $B \times H$ value in units of mega gauss oersteds (MGO). This should only be used as a guide because when designing a magnetic circuit, as shown in Figure 2, it is the value of H (the field strength in oersteds) that is of prime concern. Generally, if H_m is maximized, and because, ideally,

$$H_g L_g + H_m L_m + H_s L_s = 0 \tag{7}$$

H_g and H_s will be determined by the magnetic circuit design

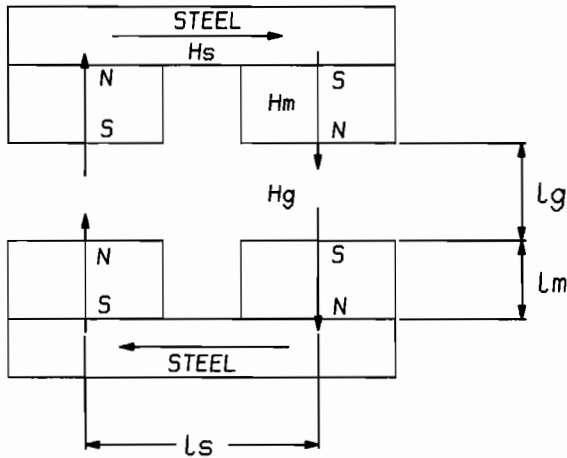


Figure 2. Typical Magnetic Circuit.

The value of H_g will depend on the size of the gap, and the limiting factor is that the steel part of the circuit must be large enough that it always remains below the magnetic saturation level.

It is not always possible to ensure an efficient design of magnetic circuit, i.e., the smallest amount of magnet for the largest value of torque. The driven component, a pump, for instance, is often an existing design, and the magnetic coupling must fit within certain dimensional constraints. In practice, one usually ends up fitting the biggest possible volume of the strongest available magnets in the prescribed space.

Using the strongest available magnets, however, quickly increases the output of eddy currents, as shown by Equation (6), because magnetic flux density between the magnets has increased. Again, a compromise is required, but in reality, using the strongest magnets leads to a necessarily compact design, and eddy current generation is, unfortunately, accepted or overlooked.

The eddy current loss is a pure loss which must be made up by the prime mover to achieve the required output power level.

$$\text{Output Power} = \text{Input Power} + \text{Losses} \tag{8}$$

HOW EDDY CURRENTS CAN BE MINIMIZED

Classical Methods from Electrical Engineers

The classical method for the reduction of eddy currents in many electrical devices is to use insulated laminations [4]. Electrical engineers have used this method in the design of motors, generators, and transformers for many years, and this concept forms part of the design for the new, low loss, pressure containment barrier.

Consider how eddy currents are generated in a segment of the pressure containment barrier. To do this, it is necessary to focus on a small section of the barrier which is affected by the magnet poles, as shown in Figure 3. From Equation (1) the voltage generated along the length of the conductor (barrier) is a function of its length. In this case, its length corresponds to the width of the magnet. Because the adjacent magnet sets have opposite polarity, the voltage created in one part of the barrier under one set of magnets is in one direction, and in the other

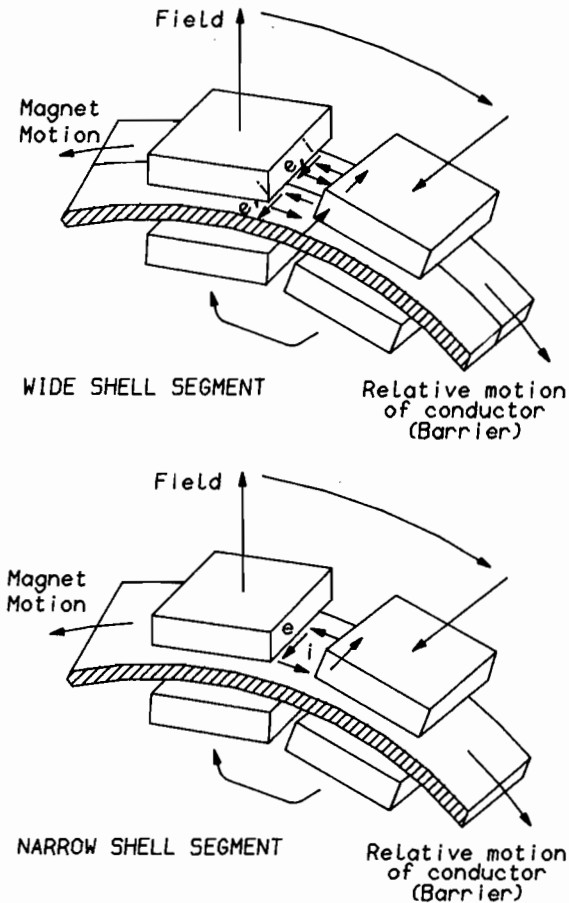


Figure 3. Eddy Current Generation.

direction under the other set of magnets (Fleming's right-hand rule again). This causes current to flow in a loop in the surface of the barrier, and, as mentioned above,

$$\text{Watts (loss)} = I^2 \times R \tag{9}$$

If this segment of barrier is cut in half, and both halves are fit together such that they are insulated from each other, as in Figure 3, the length of the conductor (barrier) is now halved. This halves the voltage, and hence the current. But because W is a function of I^2 , W is not halved, but quartered.

$$\left[\frac{1}{2}\right]^2 = \frac{1}{4} \tag{10}$$

By cutting these rings in half again, the length of the conductor is now a quarter of what it was originally, so that voltage and current are proportionally reduced, and now:

$$\text{Watts (Loss)} \text{ is } \left(\frac{1}{4}\right)^2, \text{ or } \frac{1}{16} \text{ of what it was} \tag{11}$$

So, by cutting the barrier into a series of narrow rings and reassembling them into their former cylindrical shape with an insulator between each ring, eddy current losses can be controlled. This, then, forms the basis of a concept for a low loss barrier.

Application to Magnetic Drives

The "laminated barrier" and "low loss" concepts, and their application to synchronous magnetic drives has been developed and patented by Taiani [5, 6].

It is clear that using a series of rings in the barrier would help to control eddy currents. They can also support the hoop stresses caused by system pressure inside the barrier. Because the barrier will also experience axial stresses, each ring will try to move away from its neighbor, creating gaps which would cause leakage. Therefore, something must be done to resist these axial loads.

If the series of rings can be placed end to end and fitted inside another cylinder, then such an assembly could form the wall of a barrier; the rings supporting hoop stresses, and the outer cylinder restraining axial stresses. This outer cylinder is now a source of eddy currents and so it also must be "treated." Because it is only taking care of axial stresses, it can be slotted parallel to the axis, and of course, the more slots the lower the rate of eddy current generation.

This, then, forms the construction method for the wall of the barrier; inner rings taking hoop stress, and an outer, axially slotted cylinder, taking axial stresses, as shown in Figure 4. As is usually found in most designs, this solution is a compromise and offers some disadvantages, the main one being that the total thickness of the barrier wall is more than it would be if a normal solid barrier were used. Construction is also difficult and special techniques are required for assembly. A typical design of a laminated barrier magnetic drive is shown in Figure 5.

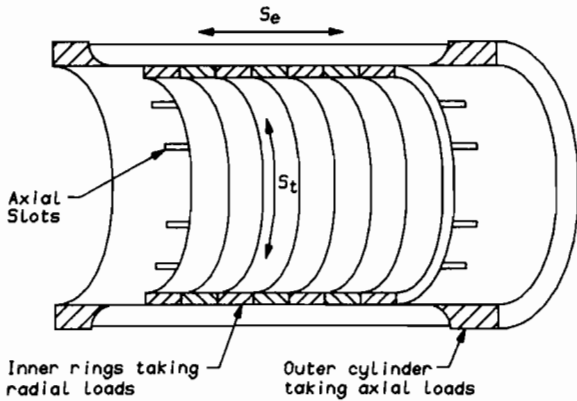


Figure 4. Laminated Barrier Construction.

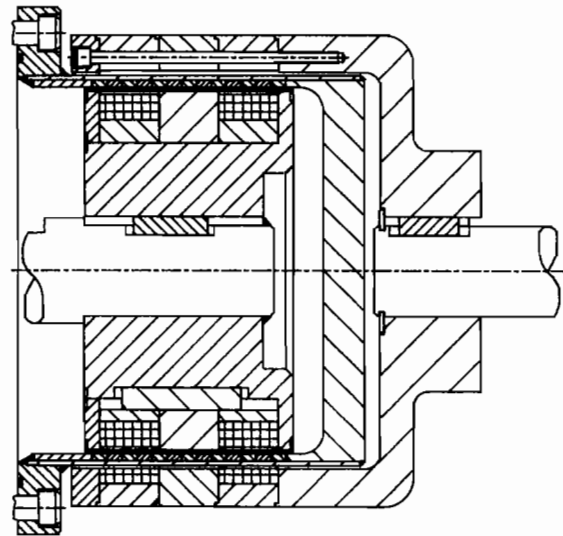
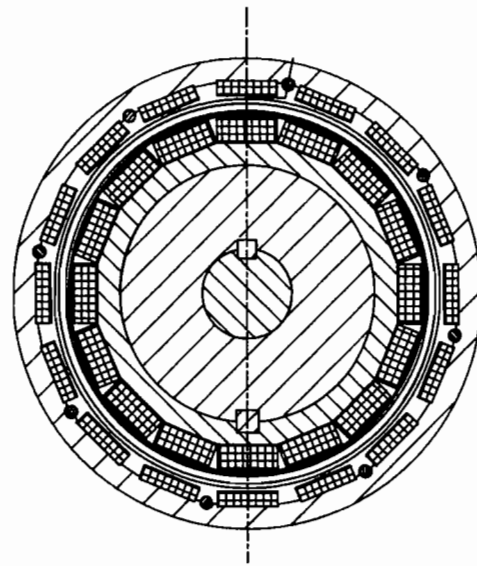


Figure 5. Laminated Barrier, Typical.

APPLICATION OF THE NEW TECHNOLOGY

The Operational Envelope

A graphic presentation is shown in Figure 6 of the normal operating region of magnetic couplings using solid metallic barriers, and the expanded operating region is shown for the laminated barrier system.

In any magnetic coupling system, the three controlling parameters are speed, system pressure, and torque. The combination of torque and speed will result in a developed horsepower.

The three axes shown in Figure 6 are speed, pressure, and horsepower. Consider a theoretical case of a magnetic coupling operating at point B. At a speed of OA, developed horsepower is OC. This point of operation requires zero pressure containment, so the barrier can be infinitely thin. Here, torque is at a maximum because an infinitely thin barrier allows driver and driven magnets to be very close together. Speed is also at a

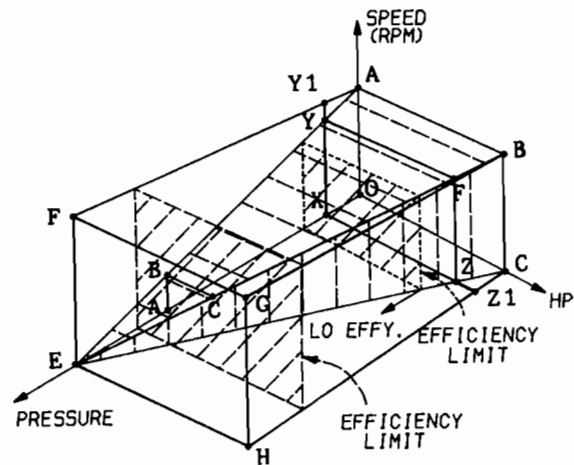


Figure 6. The Operational Envelope.

maximum, because no eddy current losses can be developed in the infinitely thin barrier.

In a practical situation, of course, pressure containment by the barrier is an essential feature. If the pressure level is OX, and a conventional solid metallic barrier is used, because of barrier thickness, the driver and driven magnets must be farther apart, resulting in reduced torque. As the barrier now has thickness, eddy currents will be generated as a function of speed. In this situation, speed must be limited to XY, and the resulting horsepower output is reduced to XZ.

As system pressure is increased, barrier thickness must increase, and speed and torque decrease, giving reduced horsepower levels. So, for solid metallic barriers, the operating envelope is limited by area OABCE.

In the laminated barrier system, the metallic barrier is constructed in such a way that eddy current levels are very low. This means that for the same system pressure and torque level, speed can be increased to XY1, resulting in higher developed horsepower, OZ1. It can be seen then, that when using a laminated barrier system, a larger operating envelope, OABCEFGH, is available.

In practice, overall coupling efficiencies are 95 to 99 percent efficient. Current designs are using torques in the 200 ft-lb range, speeds to 5000 rpm, and pressures to 10,000 psi.

TECHNOLOGY APPLICATIONS

The development of a high efficiency magnetic drive will help solve most of the dilemmas that face their use with one exception. The exception, of course, is the problem of bearings that must run within the pumpage. There appears to be some very significant advances being made in this area. The significance to the magnetic drive area is that the type of high efficiency barrier being discussed does not lend itself to a steady bearing being placed at the end of the barrier. Designs that utilize an overhung shaft with very low end loads are the most successful with this type of barrier.

Problems of high torque, high speeds, and high barrier pressures can all be dealt with in a reasonable and economic manner. When you are dealing with a drive efficiency that can be better than 99 percent, there are plenty of interesting refit opportunities, as well. Some of the very important aspects of high efficiency include:

- The ability to refit a field pump and utilize the same motor. Doubling the size of pump motor usually requires a large investment in increased electrical supply, starters, motor, etc.
- Simplified pump design, since there will be little or (usually) no requirement for pumpage to cool the barrier. Thus, there will be no "hot spots" if the barrier is run vertically and no complicated pump flow through the barrier, except as required by bearings. In fact, many designs can be completely cooled by air flow alone. (This also opens up the use of magnetic drives for blower applications.)
- Big increases in the economy of operation of pumps with high efficiency barriers are available. A comparison of various barrier types in a typical 60 ft-lb coupling are demonstrated in Figure 7 and Table 3. At 35 hp and 3550 rpm, the stainless steel one could not even be used. The solid Hasteloy can would cost approximately \$44,000 more to operate in three years, assuming a ten cent kilowatt hour, at even a 66 percent duty cycle.
- The area of very large magnet gaps, which are required for very high pressure cans, can also be dealt with effectively. Current designs have 99 percent efficiency for a 15,000 psi barrier, with 25 hp and 4500 rpm.
- The limit on horsepower can be extended. Present designs have 99 percent efficiency for a 150 hp, 3550 rpm drive, with a

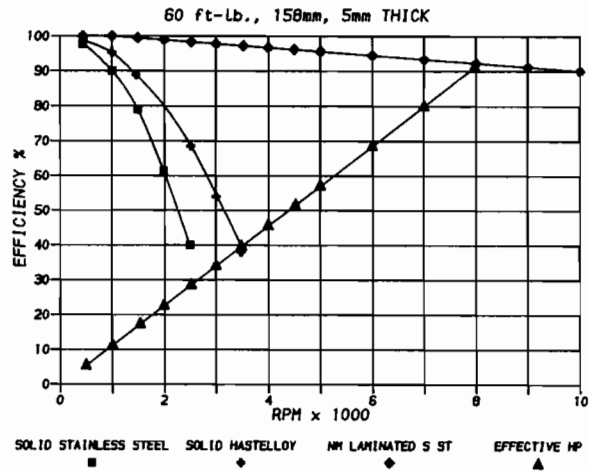


Figure 7. Graph of Efficiency, Laminated vs Solid Barriers.

working temperature of 400°F. There is no reason why horsepower in the range of 1000 hp cannot be dealt with.

- New cost effective sealless designs can be implemented in areas that were previously thought impractical. Since the high efficiency barrier deals with speed well, magnetic couplings can be designed that transmit horsepower at higher speeds for less money than lower speeds, simply because there are fewer expensive magnets involved. As well, the physical size of the coupling is reduced, allowing lower manufacturing costs.

See Table 3 for a look at the cost projection for operating solid barriers and a laminated barrier for a typical 60 foot-lb magnetic drive.

CONCLUSION

By utilizing classic engineering solutions to solve the eddy current problems associated with magnetic drives, users can now enjoy the benefits of substantial ASME rated barriers without rewiring for larger motors. Pumps may also have drastically lower operating costs and simpler designs. They can also deal effectively with higher operating pressures, speeds, and horsepower.

NOMENCLATURE

- B magnetic flux density at the gap, teslas (1T = 10Kgauss)
- E electro motive force (EMF), volts
- F force between conductor and flux, newtons
- H magnetic field strength, oersteds
- H_g magnetic field strength in gap, oersteds
- H_m magnetic field strength in magnet, oersteds
- H_s magnetic field strength in steel, oersteds
- I current, amperes
- L length of conductor, metres
- L_g length of gap, metres
- L_m length of magnet, metres
- L_s length of steel, metres
- R resistance of conductor, ohms
- V relative velocity between conductor and flux, metres per second
- W power lost to heat, watts loss
- Φ flux
- t time

Table 3. Cost Projections for Typical 60 ft-lb Drive.

	<<<<<<< 1750 RPM >>>>>>>			<<<<<<< 3500 RPM >>>>>>>		
	SOLID SS	HASTELOY	LAMINATED SS	SOLID SS	SOLID HASTELOY	LAMINATED SS
Barrier Thickness (m.m.)	5.08	4	5.08		4	5.08
Efficiency	0.51	0.792	0.99	N/A	0.5	0.976
Loss Watts	12855	5430	159		13055	627
33% Loss \$, 1 Year	\$3,368	\$1,423	\$42		\$3,420	\$164
66% Loss \$, 1 Year	\$6,736	\$2,845	\$83		\$6,841	\$328
Equivalent HP Required	39	25	20	N/A	68	35
Run Watts	28962	18650	14920		50967	26110
Additional Hardw. \$ Required	\$5,000	\$3,500	\$0		\$7,000	\$0
Run \$ @ 33%, 1 Year	\$7,588	\$4,886	\$3,909	N/A	\$13,353	\$6,841
% Increase	194	125	100		195	100
1 Year Additional Cost	\$3,679	\$977	\$0	N/A	\$6,512	\$0
3 Year Additional Cost	\$11,037	\$2,932	\$0		\$19,537	\$0
Run \$ @ 66%, 1 Year	\$15,176	\$9,773	\$7,818	N/A	\$26,707	\$13,682
% Increase	194	125	100		195	100
1 Year Additional Cost	\$7,358	\$1,955	\$0		\$13,025	\$0
3 Year Additional Cost	\$22,075	\$5,864	\$0		\$39,075	\$0
Approx. Cost of Magnetic Drive	\$7,400	\$7,700	\$9,200	N/A	\$7,700	\$9,200
Total extra 3 year cost, compared to laminated barrier with electricity and hardware costs considered.						
33% Duty Cycle	\$14,237	\$4,932	\$0	N/A	\$25,037	\$0
66% Duty Cycle	\$25,275	\$7,864	\$0		\$44,575	\$0

Cost Projections for a Typical 60 FT-LB Magnetic Coupling

Pump requires nominal 20 hp at 1750 rpm and 35 hp at 3500 rpm with magnetic barrier. The three barriers compared are a solid stainless steel unit, a solid Hasteloy alloy units, and a patented, laminated stainless steel unit.

Two duty cycle premises are 33 percent for one year and 66 percent for one year with an average electricity cost of 10 cents per kilowatt.

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