

## Energetics of Ferromagnetism by Leon Dragone

When a permanent magnet is placed inside a coil, and the current in the coil is turned on, the coil's field can aid or cancel the PM's field. If the coil cancels the PM's field, the magnetic energy of this field is lost from the environment. Where does this energy go? To answer this question, let us describe the permanent magnet in terms of its circuitual Amperian currents,  $I_a$ .

Consider a cylindrical permanent magnet which is magnetized along its axis as shown in figure 1a. It is customary to describe the PM as if it were a solenoid having many turns around the cylinder's lateral surface and carrying an effective current  $I_a$ . See figure 1b. In this case one can describe the PM's field energy by the formula  $\frac{1}{2}L_m I_a^2$ , where  $L_m$  is the effective inductance of the PM as if it were an actual coil carrying the current  $I_a$ .

Now suppose that we put this PM inside of a coil as shown in figure 2. We switch the coil on in such a way as to cancel the PM's field. The field energy for this situation can be written as

$$W_{\text{mag}} = \frac{1}{2}L_m I_a^2 + \frac{1}{2}L_c I_i^2 - M I_a I_i,$$

where  $L_c$  is the inductance of the coil,  $I_i$  is the current put into the coil, and  $M$  is the mutual inductance between coil and PM which is to be thought of as a solenoid. When the coil is turned on, the PM acting as if it were really a coil driven by current  $I_a$ , should be aided by an induced

emf so that the current  $I_a$  should increase. However,  $I_a$  is atomic origin and cannot be altered. Thus by the reciprocal relation which exists between coil #1 and permanent magnet acting as coil #2, this induced emf must end up in coil #1. Therefore the induced emf acts to build up the current  $I_1$ . This makes sense since we start with the magnetic field of the PM and end up with no or almost no magnetic field. The field energy that disappears from the  $S_z$  system must appear in some other form. Differentiating (1) with respect to time we get the input power

$$P_{in} = \dot{W}_{in} = L_c I_1 \dot{I}_1 - M I_a \dot{I}_1$$

It is seen that this can be negative if  $I_1$  and  $\dot{I}_1$  vary within a certain range. From this we can compute the coil's input voltage as

$$V_{in} = L_c \dot{I}_1 - M I_a \dot{I}_1 / I_1$$

If  $I_1 = 0$ ,  $W = \frac{1}{2} L_m I_a^2$  and  $\dot{W} = 0$  so that no back emf can exist in an unexcited coil near a PM. But if  $\dot{I}_1 > 0$ , the back emf  $V_{back} = -M I_a \dot{I}_1 / I_1$  begins to build. In any practical demonstration of this effect, we must include the  $I_1 R$  drop so that

$$V_{in} = L_c \dot{I}_1 + R I_1 - M I_a \dot{I}_1 / I_1$$

gives the input voltage to the coil. For certain values of  $I_1$  and  $\dot{I}_1$ ,  $V_i < 0$ .

For a numerical example, suppose  $I_1$  goes from 0 to 30mA in .1sec. If  $L_c = 2,000H$  and  $R = 20,000 \text{ ohms}$ , then  $V_1 = 2,000 \times .3 + 20,000 \times .03 = MI_a \times 10$ . We can only estimate  $M$  and  $I_a$  but typically  $I_a$  is tens of thousands of times  $I_1$ . Further,  $M \approx K\sqrt{L_c L_m}$  which itself is at least an order of magnitude. Since we know that magnetic field energy disappears, we know that  $V_1$  must be negative and judging from the order of magnitudes of each of the terms in  $V_1$ , is itself at least three orders of magnitude. Thus for the numbers given, we would expect the input power of between  $-30W$  to  $-300W$  or so. Thus  $V_1 < 0$  but within a certain range of values for  $I_1$  and  $\dot{I}_1$ . Also,

$$P_{in} = L_c I_1 \dot{I}_1 + RI_1^2 - MI_a \dot{I}_1 < 0$$

The interesting observation to be made here is that the PM's field <sup>in  $S_2$</sup>  can be "SHUT OFF" by outputting its energy into the external circuit. If at the same instant  $t_0$  the external circuit were removed, we have no closed circuit. However, we can predict the final result: the PM field will again be present and the current in the coil will cease. But how can the isolated coil-PM system  <sup>$S_2$</sup>  gain back the PM's field energy when it has been cut from the external circuit? The situation appears as in figure 3. What happens in the transient phase?

From what we know about coils and back emf's, something must happen within the coil that will allow the PM to again become uncovered; i.e. obviously the current in the coil will go to zero. From an energetics point of view, a field

of energy  $\frac{1}{2}L_m I_a^2$  will appear and the coil current must relax in such a way that this energy which was formerly dumped into the external circuit, will be retrieved from the coil-PM system<sup>5a</sup> as now isolated. Two cases occur: a) The coil is shorted immediately upon removal of the external circuit; and b) The coil is left open. In either case the end results are the same: after transients, the PM's field returns and the coil becomes passive.

In case b), we need not worry about the coil's  $I^2R$  losses or about the coil itself during the relaxation process. We can then think of this transient phase as follows: imagine the coil to be a ferromagnetic sample and the PM is to act as a magnetizing agent. The coil, acting as a ferromagnet, has a remnant field which at  $t_0$  just cancels the PM's field. As the transient process begins, the PM field must unmagnetize the coil. Remember, the coil is acting like a ferromagnet with a remnant field. At the end of the process, the net field will be  $H_0$  which was what the PM's field was before the coil was excited. The graph for this process is as shown in figure 4. Clearly, the energy for this process is given by  $E = \int H dB$  as it is in any magnetizing process. For the curve shown,  $E = \int H dB > 0$ , so that the PM is doing work ON the coil. The energy required for the PM to so act on the coil comes from the Amperian circuital currents or from the PM's internal energy. Hence, these circuital currents suffer an energy loss on an atomic level. But it is impossible

for the circuital currents to diminish because quantum conditions within the atom are far more stringent than the little perturbing force of the coil. The loss of energy will then be drawn from the PM's thermal energy on the level of  $kT$  and within the PM itself. The thermal energy of the PM will thus decrease and so the PM will cool. This latter phenomenon occurs because we assumed that the PM does not change during the entire process; i.e. the coil's field, on or off, does not alter the PM's domain structure. This is a fact which is known to be practically attainable. Further, we can always choose a range of  $I_1$  values so that the whole process will lie on a Barkhausen jump where the  $B$  of the PM remains constant while the  $H_{coil}$  changes provided the current  $I_1$ , so chosen, and its rate  $\dot{I}_1$ , also lie in the negative input power range. Also, by making the coil physically large, the remote part of the PM's field can be canceled without undue stress on the  $B$  field near the PM. Thus large amounts of magnetic field energy can be canceled from the coil-PM system and this energy dumped into the external circuit without stressing the PM to change internally.

The entropy of the PM will remain constant during the the switch on process. During relaxation however, the entropy of the PM will decrease because its internal energy will drop as it drives the "remnant" field out of the coil. Cooling means an entropy drop even though there is no change

in the PM's domain structure. The PM will not drive the coil to positive magnetization since at  $B_{\text{coil}} = 0$ , the coil becomes passive and all currents within the coil cease.

The final state, after transients, is of course, identical to the initial state. Therefore this process can be repeated cyclically. During each cycle an amount of heat  $Q$  will be absorbed by the PM so that it can remain in thermal equilibrium with the surroundings. The entire cycle would require from 10 to 100 millisecc so that from 10 to 100 cycles can be made per sec. The numbers chosen herein are typical of the orders of magnitude that I have experimented with. Obviously, they are not critical with the exception of the large coil because its relaxation time is long enough to switch off at time  $t_0$ . If the switch off time  $dt$  is of the same order of magnitude as the coil's relaxation time, the negative power will be dissipated in the switch or retrieved by the coil from the external circuit.

Since the energy dumped into the external circuit is equal to the energy that disappears from the PM's field, we can also calculate the "free energy" directly from the part of the PM's field cancelled. If  $B_0$  is the value of the PM's field, the energy of its field is given by

$$E_{\text{mag}} = 1/2\mu \int B^2 dv$$
 where the integral is over all space. Far from the PM,  $B^2 = B_0^2/r^4$  and typically  $B_0$  is  $1w/m^2$ .

We thus have  $E_{\text{mag}} = 1/2\mu \int B_0^2/r^4 r^2 \sin \theta dr d\theta d\phi$  or  $4\pi \times 1/2\mu B_0^2 \int 1/r^2 dr$ . Since the angular part gives  $4\pi$  and  $\mu = 10^{-2}$ , and we are going to choose  $R_0$  to be larger than the physical dimensions of the PM, we can write  $E_{\text{mag}} = 2\pi/10^{-2} B_0^2 1/R_0$ . Using  $B_0 = 1\text{w/m}^2$ , and assuming that the PM's size is but a fraction of a meter so that  $R_0 = 1\text{m}$  is far from the PM, we can estimate  $E_{\text{mag}}$  to be  $200 \times \pi = 614\text{J}$ . If only 1/30 of this field energy is cancelled by the coil, about 20J of energy will be dumped into the external circuit per cycle. For 10 cycles per second, we get 200W output. This means that  $Q = 200\text{W} = 50\text{cal/sec}$  will be the rate that the PM will draw in heat from the surroundings. For a 100 lb coil-PM system, we get  $50\text{cal/sec} = \Delta T \text{SM} = \Delta T(.11\text{cal/g})(100\text{ lb})(454\text{g/lb})$  or  $\Delta T = 50/4994 \text{ }^\circ\text{K/sec}$ , where we have assumed an average specific heat of .11cal/g. For an adiabatic process, the coil-PM system must suffer a temperature drop of 1/100 of a degree Celsius per second. Operating adiabatically for five minutes should cause the system's temperature to drop  $3.0^\circ\text{C}$ . Temperatures of this order of magnitude have been actually observed on the Electro-Entropic motor. Of course, the motor's coil-PM system was not thermally isolated so that a continual drop in temperature with time was not observed.

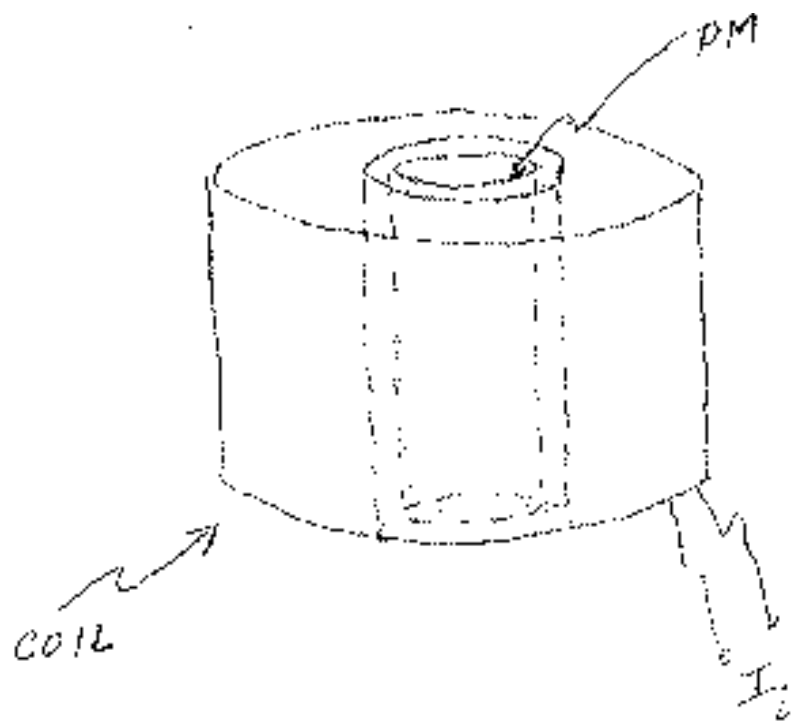
It struck me that when big coils were switched, sometimes very large arc back would occur at the switch and other times virtually no arc back was observed. The previous discussion clarifies these qualitative behaviors. For certain values of  $I_1$  and  $\dot{I}_1$ , the negative power was being

lost in the switch other times it was not. Of course, I was dealing with a rotating PM and was not controlling  $I_i$  or  $\dot{I}_i$  at all. It was by chance that the correct combinations of current, current rate, and cycle time were combined. This explains why high efficiencies were measured only under certain operating conditions. For the Electro Entropic motor efficiencies of 2000% were measured. The measuring process was a no load situation and the only load was the accelerating 5 Kg armature. The cooling effect was also best noted under these operating conditions. Also no regard was given to the polarity so that sometimes the motor operated by repulsion as in the Jones' motor, and sometimes by attraction. Clearly, negative power and cooling requires attraction between coil and armature. Most of the tests made were with an eye toward toward repeatability. I therefore used various input voltages, currents, and polarities without noticing what they were inasmuch as I was getting the cooling effect repeatably. Now I will renew these tests with an eye toward these differences. Again, and for the record, the E-E motor has an efficiency of 20 to 1 in a no load situation. I think this motor should be looked at by the Institute and this over unity effect can be verified first hand by you.

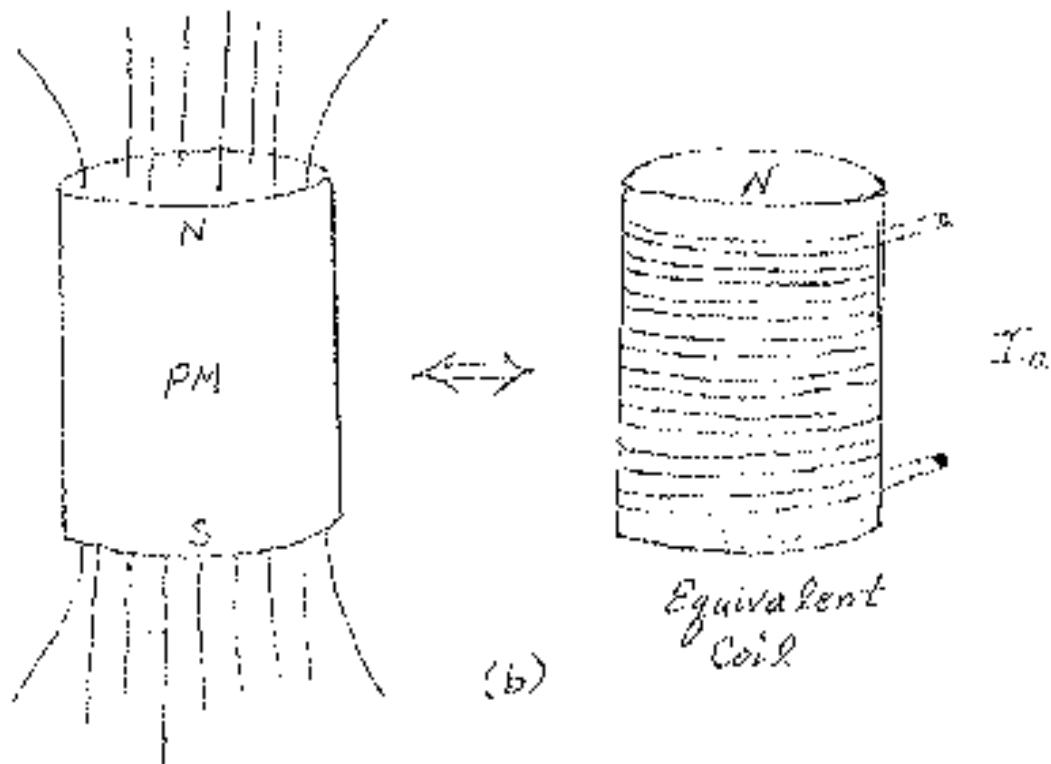
The "black box" device was my attempt to do away with the moving armature of the motor. As I mentioned, this device had an over unity efficiency for the two tests I performed.



Further tests are needed. However, from this device can be gleaned the arc-switch. This switch and a few simple circuit components, can control  $V_i$ ,  $I_i$ , and guarantee fast current off times. Even solid state devices have difficulty in turning OFF large currents in short times. The arc switch has a shut off time of 5 microsec for a current of 60 Amps as demonstrated on the scope.

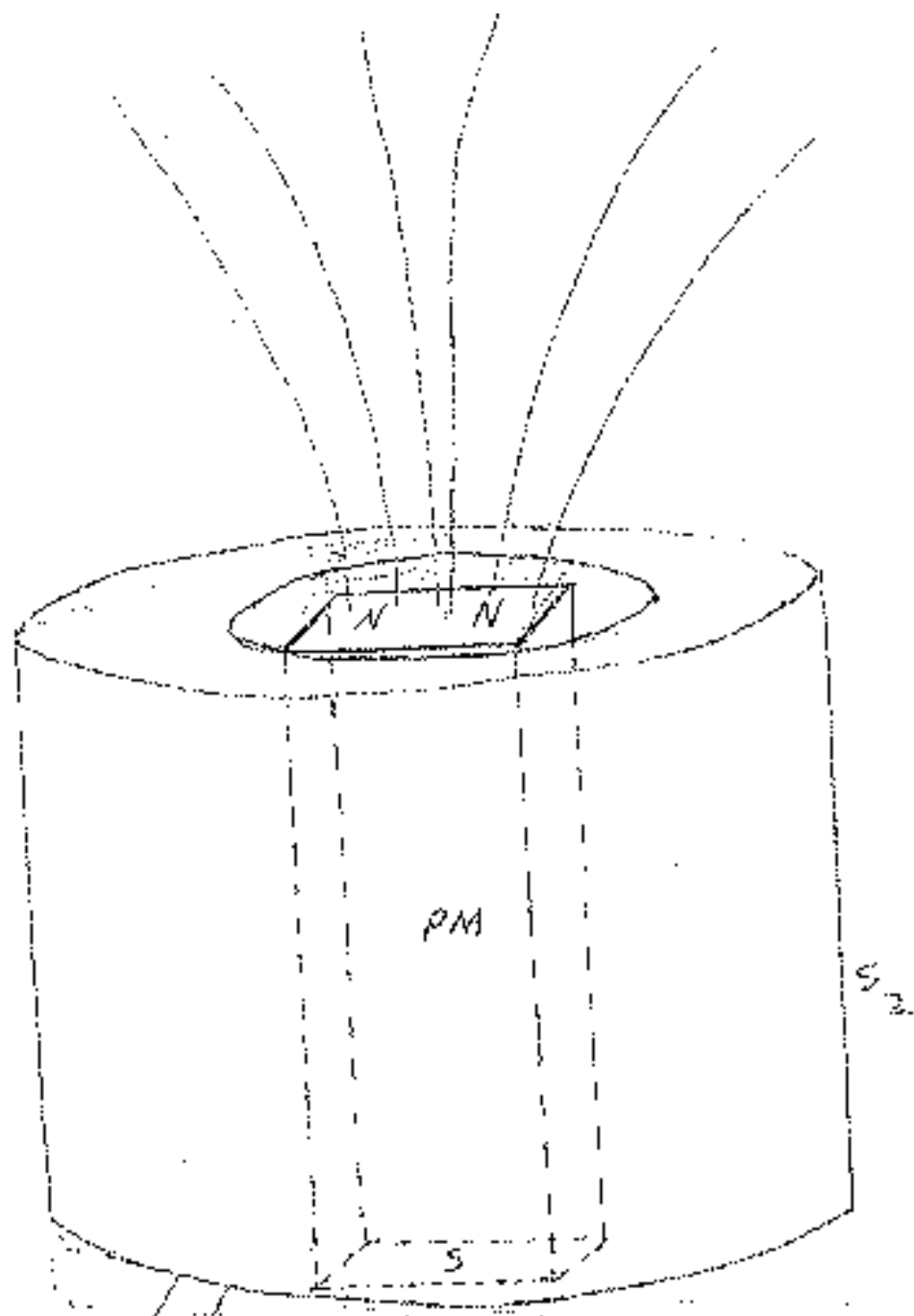


(a)



(b)

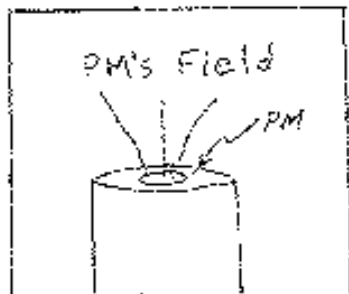
FIGURE 1



Power Supply  
S<sub>1</sub>

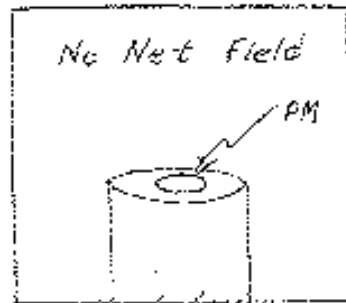
- ① POWER SUPPLY = SYSTEM S<sub>1</sub>
- ② COIL - PM SYSTEM = SYSTEM S<sub>2</sub>
- ③ ALL SPACE WHERE MAGNETIC FIELD ENERGY IS NON ZERO AND INCLUDING S<sub>1</sub> AND S<sub>2</sub> = SYSTEM S<sub>3</sub>

FIGURE 2



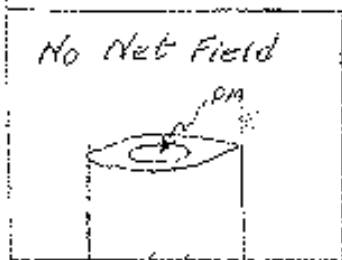
$I_1 = 0$

(a)



$I_1 > 0$

(b)



At  $t = t_0$ , Coil-PM System Cut From External Circuit and left Isolated

(c)

?????  
TRANSIENT PHASE



(d)

FIGURE 3

DEMAGNETIZATION OF COIL BY PM

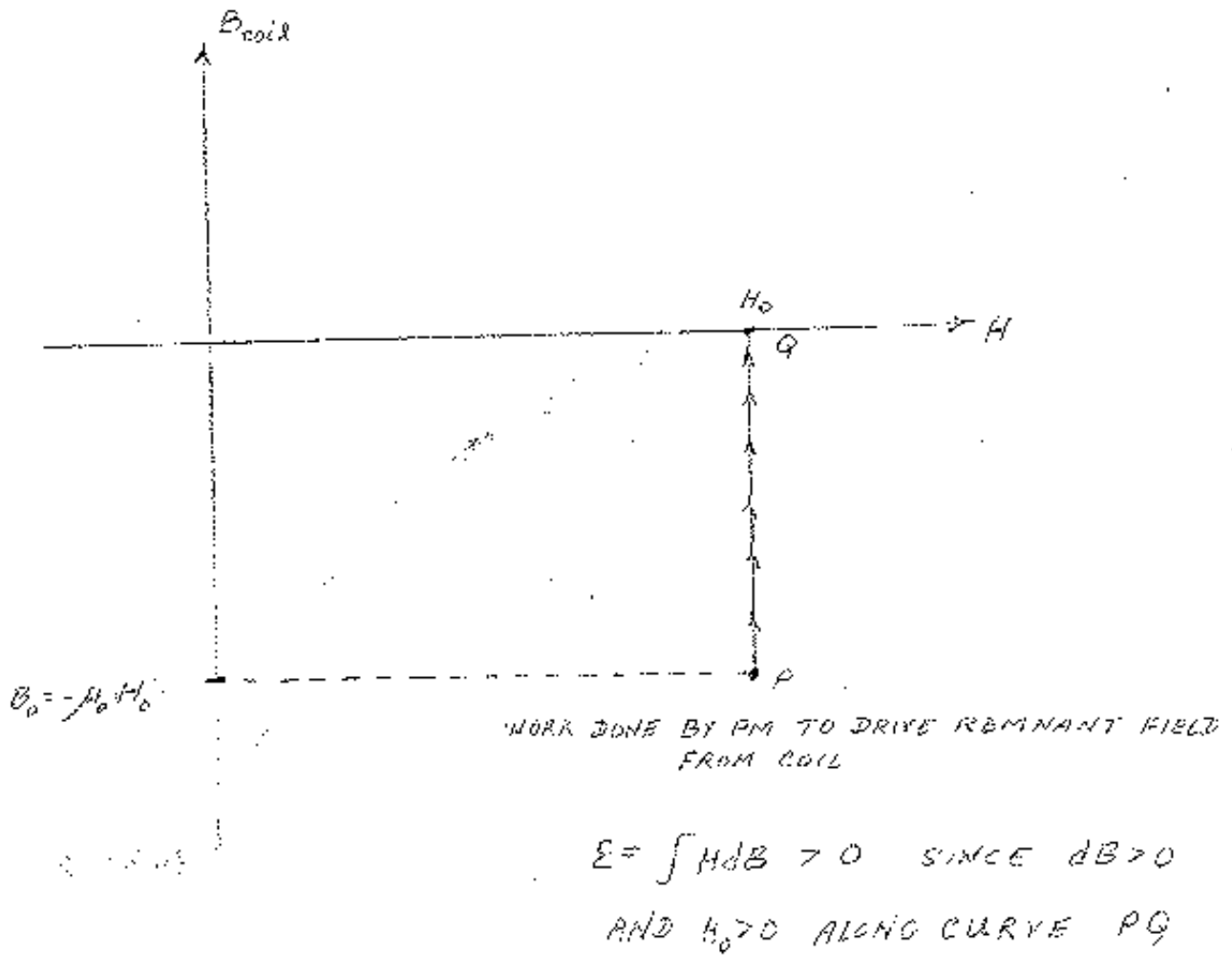


FIGURE 9

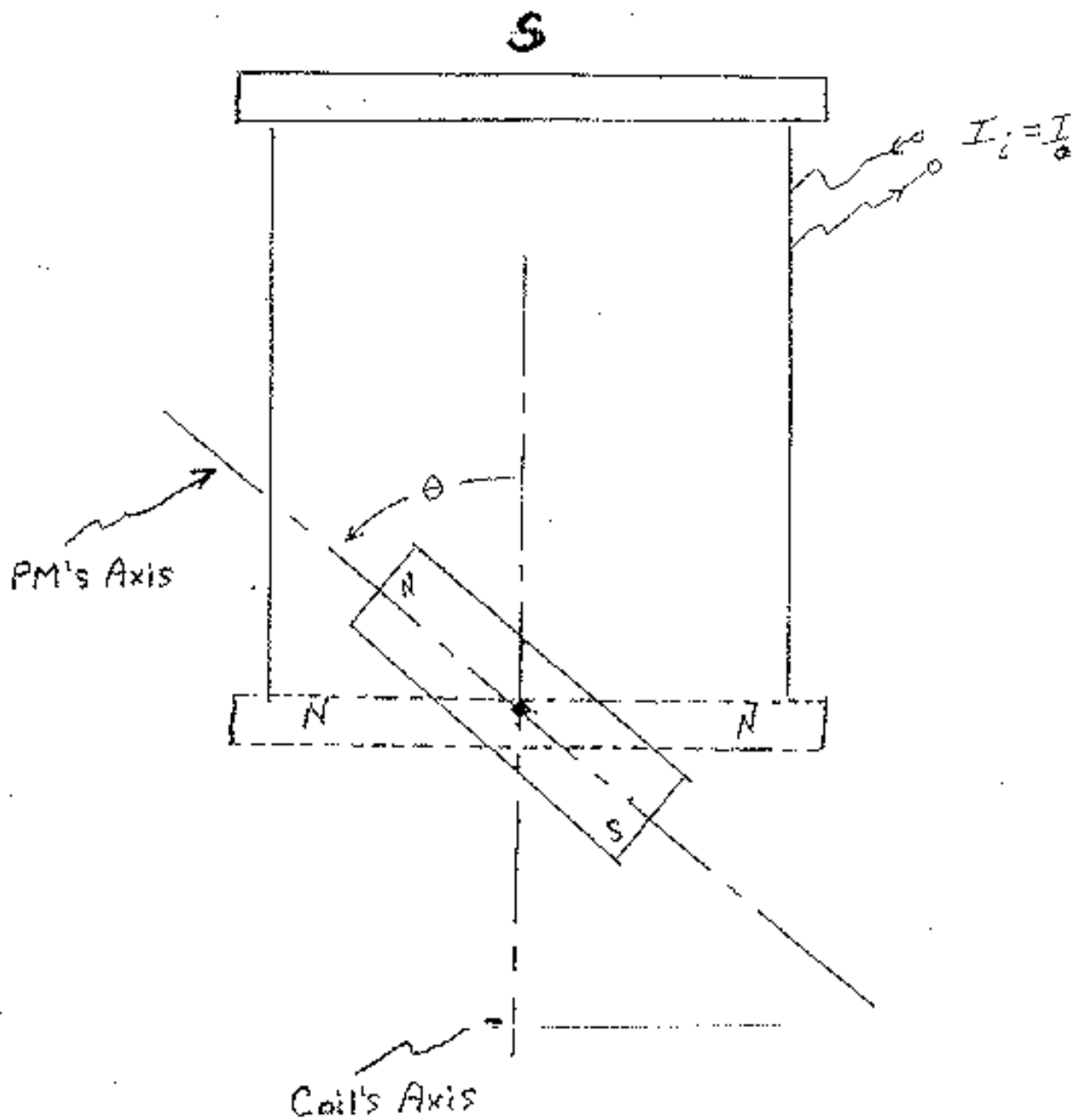


FIGURE 5