

Refrigerator Magnets

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It seems that, these days, the home refrigerator was invented primarily as a venue for displaying children's schoolwork, announcements of up-coming events, phone numbers for pizza and Chinese food delivery, etc. To hold all this important information and evidence of outstanding creativity, some very bright person conceived of the *refrigerator magnet*. Most homes have at least several such magnets commemorating visits to the four corners of the earth and advertising various products and sports teams. Thus, these handy little devices offer quite a rich opportunity for the development of practical, experiments in which students can test out what they have learned in their electromagnetics courses. *Refrigerator magnets* and other simple applications of electromagnetic phenomena can be very helpful in developing the intuition that is necessary to obtain maximum benefit from powerful commercial numerical design tools. It is always helpful to have a simple example with which we can make useful comparisons between the results predicted by modeling and the outcomes of experiments, especially when the experiments cost under \$10.

Refrigerator magnets come in many forms. However, for analysis purposes, we need only consider two of them. There are simple ceramic magnets that are glued to some kind of decorative object, looking basically as shown in the first figure. Magnets are also made by incorporating magnetic materials in with the plastic used to mold the decorative object, as with the magnets that look like the 50 states. For both of these magnets (I will call them type A), the magnetic force problem we need to solve involves only the magnet and the steel skin of the refrigerator door. The second kind of magnet (I will call it type B) has an additional steel piece bent around it as shown in the second figure. The magnetic force problem in this case includes all three components. For both types of configurations we will assume that the magnetization is oriented vertically. Thus, the surface in contact with the door is all one pole, either north or south.

Type B Magnets

The type B magnet can be easily analyzed using magnetic circuit concepts, since the combination of the cover plate and the steel door provides a low reluctance path for the magnetic flux produced by the permanent magnet. Before proceeding with the analysis, it is important to note that type B magnets are usually very close to being two dimensional objects because the plate covers the top and two sides of the magnet, with the front and back sides left open and because the dimension into the page is usually about twice the larger magnet dimension shown. Almost all of the flux will flow through the steel cover, with only a little passing through the air on the uncovered ends. Half the flux flows to the left and half to the right, since the center line is a symmetry line. Assume the following:

- The width of the magnet = w
- The height of the magnet = h
- The depth of the magnet (into the page) = d

- The thickness of both the cover plate and the door = $T \ll h < w < d$
Then (here we will use the fundamental concepts behind magnet circuits, rather than using them directly)

$$\oint \vec{H} \cdot d\vec{l} = H_{plate} l_{plate} + H_{mag} l_{mag} + H_{door} l_{door} = 0$$

Assuming no flux leakage,

$$B_{mag} \frac{w}{2} = B_{plate} T = B_{door} T$$

Also the permeabilities for the door and plate are usually much greater than μ_o . Combining these two equations, we obtain

$$H_{mag} h = -B_{mag} \frac{2T}{w} \left(\frac{w}{2} + h \right)$$

The field produced by the magnet will be given by the intersection of this line with the hysteresis curve of the magnet. The attractive force between the magnet structure and the refrigerator door by evaluating the magnetic pressure on the contact surfaces. The total force is then

$$F_{attractive} = \frac{B_{mag}^2}{2\mu_o} w d \left(\frac{w}{2T} + 1 \right)$$

Note that the force comes mostly from the edges of the cover plate, since $(w/2T) \gg 1$. Thus, the magnets are actually designed to assure simply that contact is maintained at these locations, not at the magnet surface. The magnet is usually riveted or glued to the plate, leaving a gap between it and the door, as shown in Figure 3. The magnetic field is now determined primarily by the gap spacing, because $H_{gap} = (\mu/\mu_o) H_{mag}$.

$$\oint \vec{H} \cdot d\vec{l} = H_{plate} l_{plate} + H_{mag} l_{mag} + H_{gap} l_{gap} + H_{door} l_{door} = 0$$

Which leads to

$$B_{mag} \frac{w}{2T\mu} \left(\frac{w}{2} + h + t \right) + \frac{B_{mag}}{\mu_o} t + H_{mag} h = 0$$

where t is the gap spacing. Since $\mu \gg \mu_o$, the second term in this equation dominates, even though $t < T$. Thus, we have approximately

$$B_{mag} = -\frac{h}{t} \mu_o H_{mag}$$

Since h/t is reasonably large, the magnet will produce a field near its maximum.

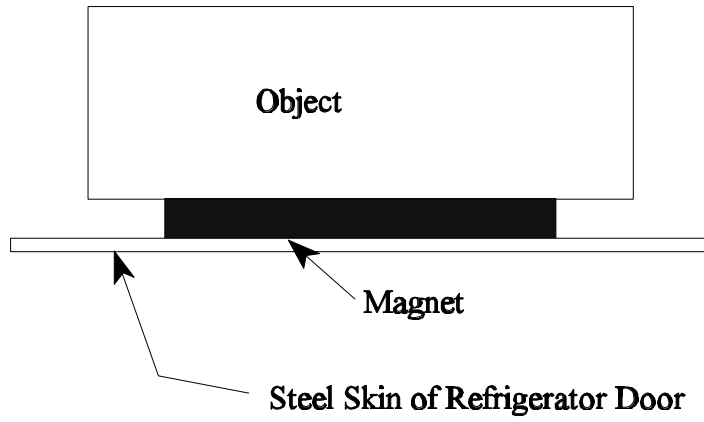
Type A Magnets The usual simple magnet with no cover plate is more difficult to analyze analytically because the flux passing through the air does not follow a simple, nearly straight path, as it does when it jumps a small gap. Thus, we cannot assume that we know the shape of the flux path until we do some additional work -- a task that is best performed numerically if we hope to incorporate the complete structure of the problem. However, we do know that the flux spreads out at an open pole and thus follows a high reluctance path back to the refrigerator door. This causes the magnet to be used near the lower end of its hysteresis curve which greatly reduces the force it can provide. There is a new type of simple magnet -- made using the flexible plastic method -- which works better and is basically two dimensional like the Type B magnet (See Figure 4). Many magnets made to provide advertising for some product are magnetized in an alternating pattern of long thin poles as shown in the fourth figure. To check any magnets you have at home, use the mylar *Magna-view* film available from Edmund Scientific. When such a magnet is placed on the door of a refrigerator, the flux in the air has to follow a much shorter path, which makes the magnetic material more effective.

FLUX2D Solutions FLUX2D can be used to find the magnetic fields and forces for both types of magnets. Shown below are the results for the Type B magnet and its corresponding Type A magnet. The superior performance of the Type B magnet is seen in the ratio of the total forces:

$$\frac{F_B}{F_A} = \frac{28.3}{4.3} = 6.6$$

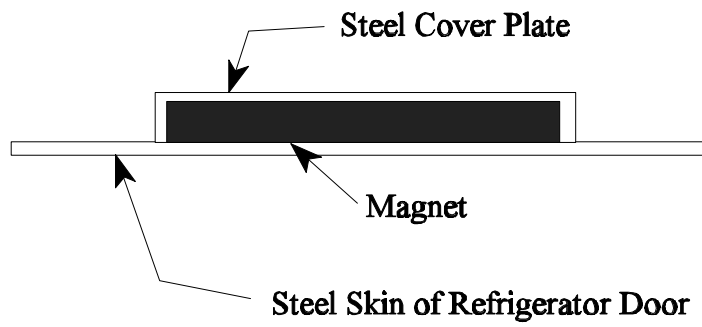
This result was obtained assuming that both magnet configurations are two dimensional, which is not a particularly good approximation for Type A. If you want to do an experiment to check these results, remember that there are probably a lot of effects your model will not include. However, the ratio of the forces should be the right order of magnitude, which we usually find to be the case.

Experiments A few semesters ago, I gave my students a simple design project to add any materials they wished to a simple ceramic magnet with the goal of improving its ability to hold pieces of paper to a refrigerator door. Based on both the analytic and numerical analysis summarized above, improved magnet configurations reduce the reluctance of the flux path outside the magnet. The best designs used large magnets (an obvious way to increase force) capped with steel plates to hold entire phone books in place! Being engineering students, they were smart enough to also realize that a short gap worked best, so they only tried to hold the phonebook cover in place and let the rest of the pages hang below.



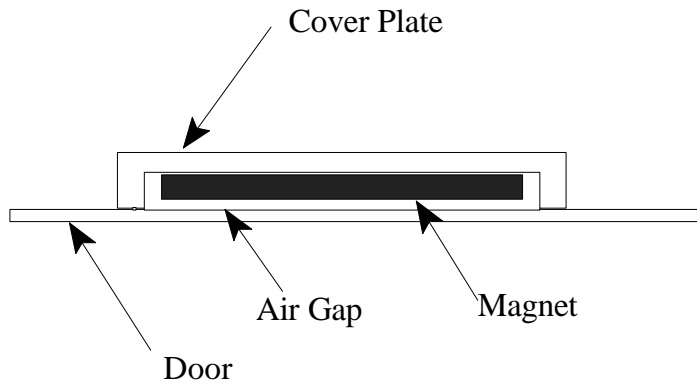
Type A Magnet

Figure 1



Type B Magnet

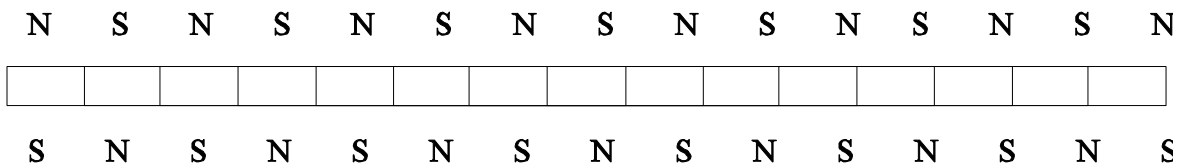
Figure 2



Type B Magnet As Usually Built

Figure 3

Figure 4



End View Of Magnet With Modulated Pole Structure

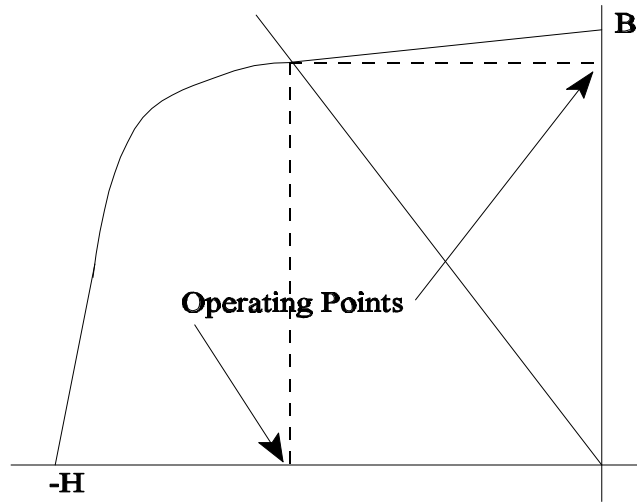
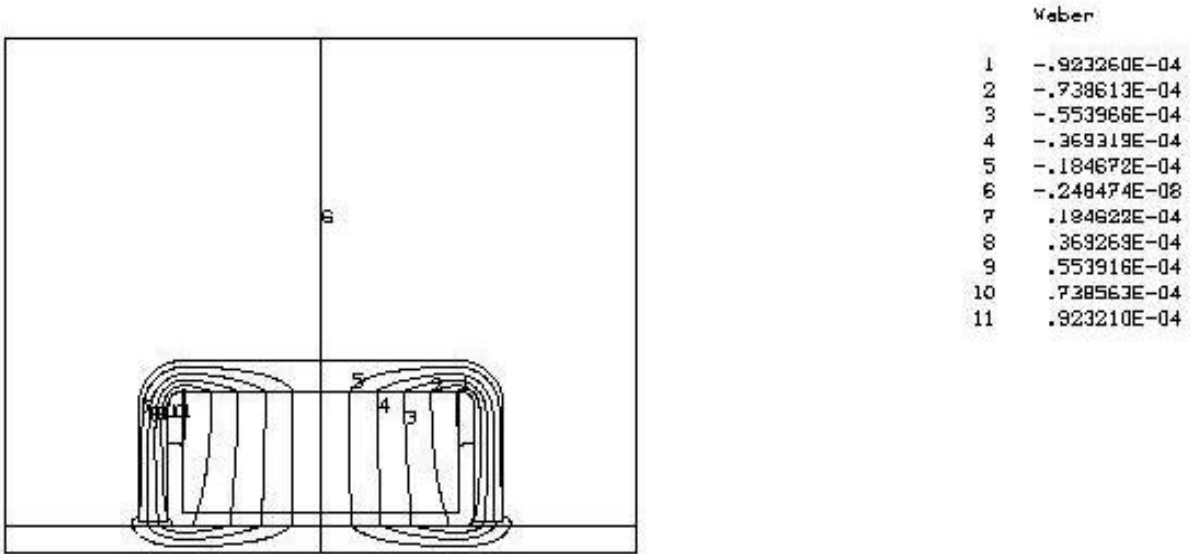
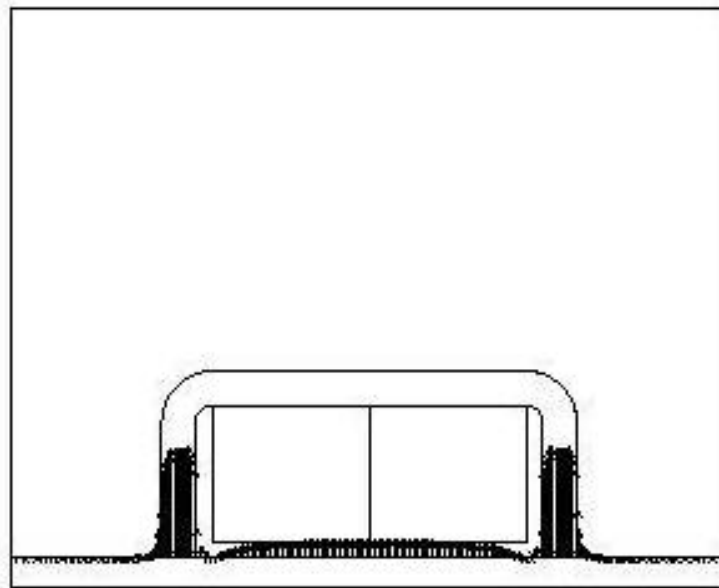


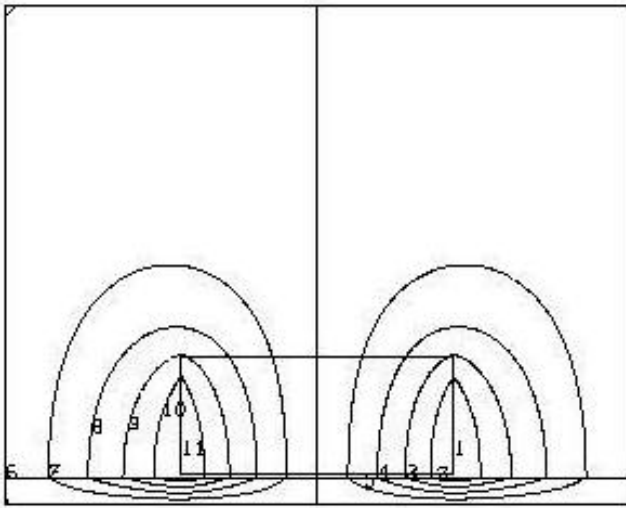
Figure 5 BH Curve For Magnet



FLUX2D Magnetic Field Solution For Type B With Gaps
Figure 6

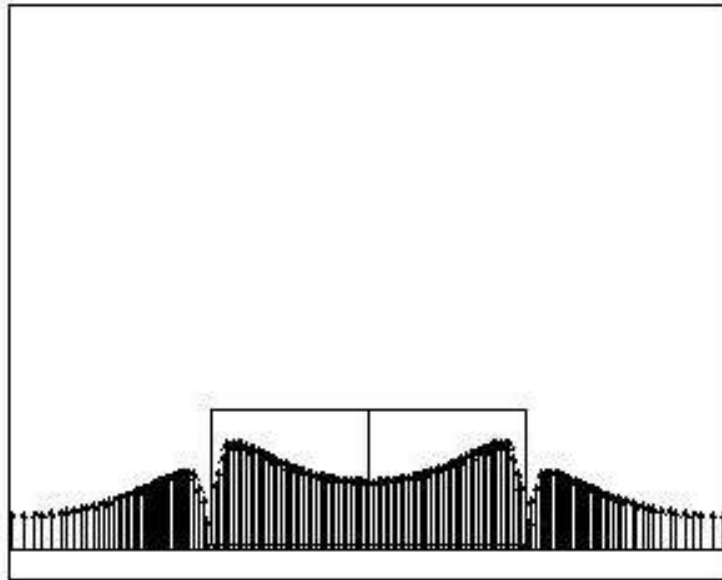


Max Vector Length Corresponds To 0.06 n/mm^2
FLUX2D Solution For Type B Magnet Force Vectors
Figure 7



	Weber
1	-.401409E-04
2	-.321127E-04
3	-.240845E-04
4	-.160563E-04
5	-.802806E-05
6	.153705E-09
7	.902937E-05
8	.160566E-04
9	.240848E-04
10	.321130E-04
11	.401412E-04

FLUX2D Magnetic Field Solution For Type A Magnet With Gap
Figure 8



Maximum Vector Corresponds To 0.002 n/mm^2
FLUX2D Force Vector Solution For Type A Magnet
Figure 9