FERROUS ATTRACTIONS: THE SCIENCE BEHIND THE MAGIC

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ABSTRACT—The question of how to fasten or secure an artifact has long been a focus of art conservators in all specialties. We have stitched and mounted items for decades. With each method, the attempt has always been to keep the conservation treatment as reversible as possible. The relatively recent development of strong permanent rare earth magnets offers the possibility of a new type of reversible fastener. Neodymium rare earth magnets are far stronger than earlier permanent magnets and have only truly entered the market since 1990. They have great potential as a new tool for conservators. Before these new magnets become part of our future, a fuller understanding of how they work is needed. Specifically, categorization of magnetic systems will aid conservators in determining which attributes a magnet should have for each specific project.

This paper describes a workshop held at the 2013 Annual Meeting of the American Institute for Conservation that explored magnetic systems. Participants used "jigs" with various combinations of magnets, metal components, and weights to demonstrate magnetic systems and their parts. Different methods of implementation and the strengths of commonly available magnets were explored. Additional topics included: what makes magnets "permanent", when magnets were developed, and how magnets differ from one another.

ATRACCIONES FÉRREAS, LA CIENCIA DETRÁS DE LA MAGIA—La sujeción de las piezas de arte ha sido un tema central para los conservadores de arte de todas las especialidades. Hemos cosido y montado piezas por décadas. Con cada método, siempre se ha procurado que el tratamiento de conservación sea lo más reversible posible. El desarrollo relativamente reciente de los imanes de tierras raras ofrece la posibilidad de tener un nuevo método de sujeción reversible. Los imanes de neodimio son mucho más fuertes que los imanes permanentes anteriores y recién ingresaron al mercado en 1990. Pueden llegar a ser una gran herramienta para los conservadores. Antes de que estos imanes formen parte de nuestro futuro, debemos saber mejor cómo funcionan. Específicamente, la categorización de los sistemas magnéticos ayudará a los conservadores a determinar qué atributos debe tener un imán para cada proyecto específico.

Este documento describe un taller de exploración de sistemas magnéticos realizado en la Asamblea Anual del Instituto Americano de Conservación 2013. Los participantes utilizaron "guías" con diferentes combinaciones de imanes, componentes metálicos y pesas para demostrar los sistemas magnéticos y sus partes. Se exploraron diferentes métodos de implementación y las fortalezas de los imanes comunes. Otros de los temas abordados fueron: qué convierte a los imanes en imanes "permanentes", cuándo se desarrollaron los imanes y en qué se diferencia un imán de otro.

1. INTRODUCTION

At AIC's 2013 annual meeting a hands-on session on the use of magnets in conservation was presented. Art conservators have been using magnets for many years, but mostly in a very limited way (Dignard 1992; Spicer 2016b). Perhaps a system has not been fully developed or described in literature, it is not part of our training, or it is a practice that is too new to be embraced. This session's purpose was to change that and give conservators hands-on experience with magnets.

Figure 1: Participants at the hand-on session held at 41st AIC Annual meeting in Indianapolis, IN.

The focus of the session was for participants to learn and understand the three main parts of a magnet system: magnet, gap, and receiving material, so that they may use this knowledge in their own practice. Each part of the magnet system works in tandem to achieve the best combination for the artifact. These three parts, in various combinations, were experimented with during the session (fig. 1).

The goal of the session was for conservators to become acquainted with the diverse variables of magnet systems. A range of Neodymium and ferrite flexible magnets were selected as the magnets. Mylar, fabrics, and other materials were included as gap materials. Finally, the ferromagnetic receiving materials included were steel plates and preparations of iron powder in a range of several thicknesses.

The session was divided into parts. First, the types and properties of permanent magnets were described, along with their differences, and the parts to any magnet system developed. This was followed by the hands-on activity and a discussion of observations.

2. PERMANENT MAGNETS

Table 1: Types of Permanent Magnets

	Alnico	*Ferrite*	*Samarium*	*Neodymium*
Chemical structure	Al-Ni-Fe-Co	Fe_2O_3	$SmCo_2$	$Nd_2Fe_{14}B$
Date	1935	1951	1965	1985
Method of manufactured	Cast or sintered	Bonded	Sintered	Sintered or Bonded,

Table 1: Types of Permanent Magnets—*Continued*

	Alnico	*Ferrite*	*Samarium*	*Neodymium*
Structure		Face-centered	Hexagonal crystal structure	Multi-phase structure, tetragonal crystal structure
Direction	Isotopic and anisotropic	Isotopic and anisotropic		
Demagnetizing	Can be easily demagnetized. When repetitively placed north pole to north pole ends together, it quickly weakens itself.	Keep away from Rare earth magnets (Samarium and Neodymium).	Can be demagnetized by NdFeB magnets. But they do not weaker others.	Tough to demagnetize. This also means that they can easily demagnetize other classes of magnets like SmCo or Alnico or Ferrite.
Heat Tolerance	Maximum working temperature is 540 °C (1004 °F). The Curie Temperature for alnico magnets is a blistering 860 °C (1580 °F).	Maximum working temperature is 300 °C (572 °F).	Maximum working temperature is 300 °C (572 °F). The Curie Temperature for SmCo magnets is 750 °C (1382 °F). Very respectable for a sintered magnet.	Maximum working temperature is only 150 °C (302 °F). The Curie Temperature for NdFeB magnets is 310 °C (590 °F).
Moisture/ Oxidation	Resistant to corrosion	Resistant to corrosion	Relative resistant to corrosion.	Corrodes easily and requires a coating.
Mechanical Shock	Very resistant	Brittle and chip or crack easily	Brittle and chip or crack easily. Best to separate with a cushioning material.	Brittle and chip or crack easily. Best to separate with a cushioning material.
Common Use	First man-made permanent magnet. —Generators —Engines	Electronic inductors, transformers, and electromagnets. Ferrite powders are used to coat magnetic recording taps.	Hard drives, printers and other computer components	Green energy, hybrid cars, wind turbines, ear phones, cell phones
Trade Comments	Cobalt from Zaire		Cobalt	Rare earths from China
Br(T)	0.6–1.4	0.2–0.4	0.8–1.1	1.0–1.4
Br (gauss)	12,500	3,900	10,500	12,800
Hci	275	100–300	600–2000	750–2000
BHmax	10–88	10–40	120–200	200–440
Tc	700–860	450	720	310–400
Tmax (C) – max temperature of use	540	300	300	150

3. CREATING A MAGNETIC SYSTEM

When using and selecting magnets of any type, three key components are in play.

1. The strength of the magnet itself. Magnetic strength is measured and described in Gauss.
2. The receiving component. This is the material that is magnetized in this system. Magnetized regions of this material impact the magnet's ability to be magnetized
3. The magnetic field distance. This is the space between the magnet and the magnetized metal. It is also called "the gap", as it is created by the layers between the magnet and the receiving ferromagnetic material.

Each of these components is significant in how the magnet behaves and is able to perform the task (Feymann 1964; Livingston 1996; Magnet Story 1998; Spicer 2016a). The balancing of these three parts determines a successful system. No one method appears to be prescribed. Instead each component is adjusted for any particular situation. This is further complicated by the wide variety of needs and requirements of each artifact. It is only by knowing the parts and their interactions that a system can be created for a specific task.

The developed system needs to be strong enough to support the artifact, while not being so strong that it creates damage. Each variable can be slightly altered to reach the desired outcome. Each component is described below along with known alternatives.

3.1 STRENGTH OF THE MAGNET

Magnets are purchased with a set polar direction. The most common magnet has north and south faces located on the largest surfaces of the magnet. These magnets are axially oriented, so the flat surfaces of these magnets have the strongest pull force present. This is because all of the magnetic fields are coming or going from this center spot. The polar direction can also be oriented side-to-side, making diaxially-oriented magnets.

The pull force of a magnet is measured in Gauss both from its center and from its outer surface. This is the amount of force necessary to pull the magnet straight from the surface of a steel plate.

The grade of a Neodymium magnet greatly alters its properties such as, strength, brittleness, Curie temperature, etc (Spicer 2014). Neodymium grades that are commonly used by conservators, are Grade N35, N42 or N52. The grade of a Neodymium magnet can be thought of as the properties of the magnetic material itself and how the behavior is affected. The Neodymium rare earth magnet grades are represented with both letters and numbers. A few suppliers use their own systems. The number represents the strength of a magnet, and generally speaking, the higher the number, the stronger the magnet. An example is N52, which compared to a N42 of the same size is about 20% stronger, and has a higher pull force of its surface field. Also the higher the number, the more brittle the magnet becomes. Breakage can occur easily especially as the magnet becomes thinner. As an example, a N52 magnet that is quite thin will easily break and should be supported if frequently handled. The numbers used by most suppliers correspond to the Maximum Energy Product (MGOe) designation. Therefore the N42 is 40-42MGOe and the N52 is 49.5-52MGOe.

The letter represents both their manufacturing method, as well as their formulations. Sintered magnets are represented as N, M, H grades and bonded magnets as BDM grade. Bonded magnets should be considered if the potential of high humidity conditions exist. Additional alloys in mixture with Neodymium, like Terbium and Dysprosium, are added to maintain a magnet's magnetic properties at higher temperatures (Brown 2004, Jones 2011) and are represented by other letters.

3.2 RECEIVING COMPONENT (THE MAGNETIZED MATERIAL)

The receiving component is also an important factor in the strength of a magnet's pull force (Spicer 2015). Metals are divided into three groups; ferromagnetics are very attractive, paramagnetics are weakly attractive, and diamagnetics are opposed to magnetic fields. The system will not function fully if the receiving component is not properly considered, as the full strength of a magnet will only be achieved with sufficient ferromagnetic material.

Ferromagnetic metals that are most attractive to magnets include nickel, cobalt, and iron. Within the structure of these materials are small regions or domains that are aligned by permanent magnets, as shown in this illustration (fig. 2). The amount of alignment within the domains or saturation enables the strength of the magnet to be optimized. This is how the receiving substrate becomes a temporary or "soft" magnet. For a given sized magnet, there is a corresponding thickness at which the steel is saturated. If you use a steel plate that is thicker, you should not see any real increase in the pull force. However, when you attach a magnet to thinner steel sheets you will see diminished pull strength and the magnet will behave as a lower strength magnet.

This occurs because the ferromagnetic material will not become magnetically saturated. This means that the receiving material can't hold all the magnet's flux (the amount of magnetic field passing through a given

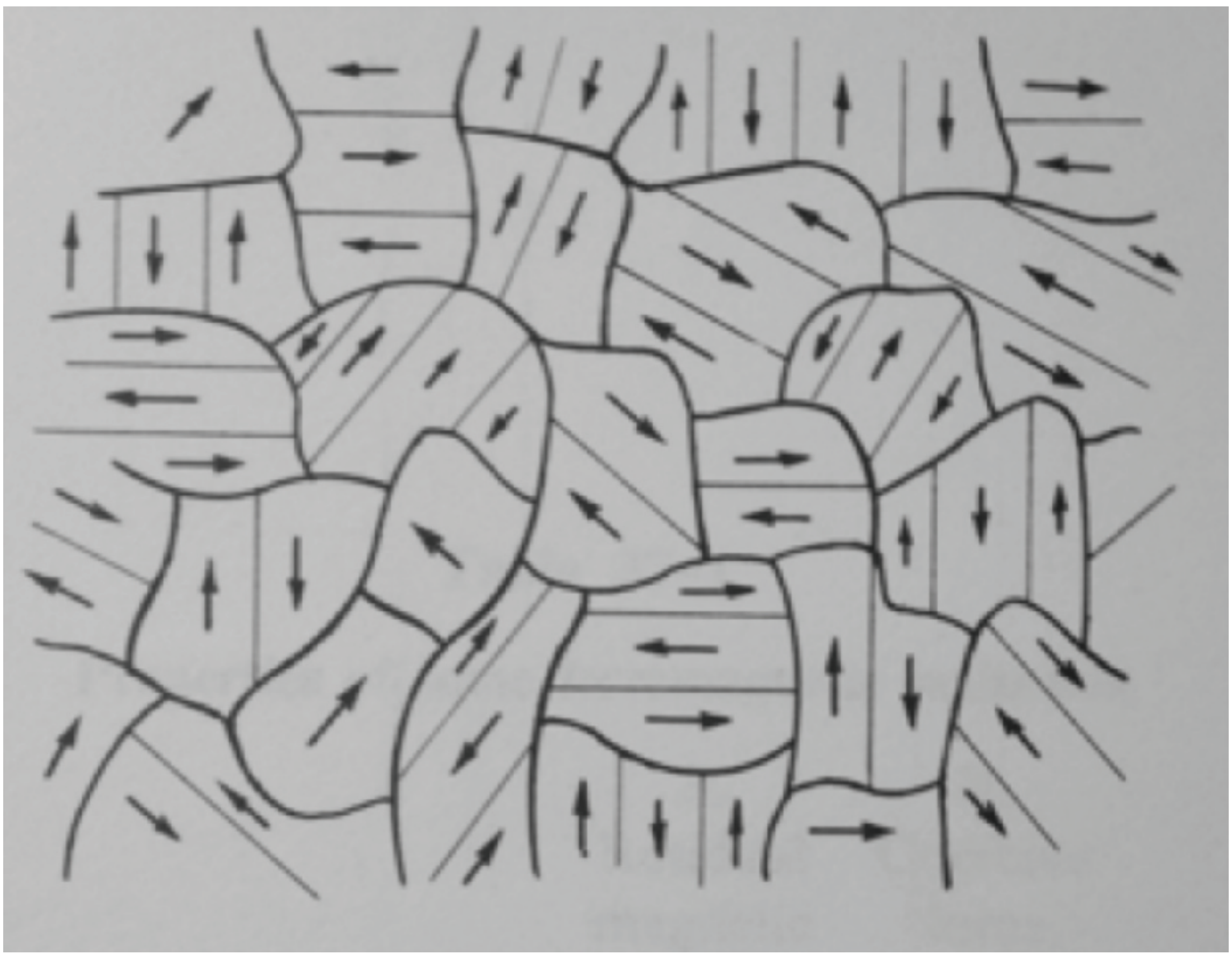

Figure 2: Domain regions within a ferromagnetic material.

surface). To utilize 100% of the magnet's pull force, you would with a thicker plate. When this is the case, some of the magnetic field will extend behind the steel, because the steel isn't thick enough to shield it all. If another ferromagnetic material is placed behind it, this too will be attracted and become a soft magnet. In this way the force field can travel to several neighboring layers of ferromagnetic materials, increasing the magnetic force as needed. However, if the ferromagnetic material is thicker than the magnetic field's strength, then the reverse side of the metal shows no magnetic attraction.

When using rare earth magnets the lowest and most minimum gauge steel plate to use is 24-gauge. A 22-gauge or thicker would be more optimal (note: the lower the number, the thicker the steel). The ferromagnetic metal is an important, but often over-looked component of a magnetic system. It was only a few years ago that the gauge of a steel sheet used was first mentioned in conservation literature (Halbrow and Taira 2011; Hovey 2012). It is only through control of all the variables: the magnet, the ferromagnetic material, and the layers between, that a system can be reproduced and adapted to any situation.

3.3 THE MAGNETIC FIELD DISTANCE OR THE GAP

The magnetic field distance, also called the gap, is composed of the artifact along with various materials used as padding, and barriers. When the layers between the magnet and the receiving metal is widened, the magnetic force is dissipated. The strength of the magnetic field falls off inversely with the cube of the distance from the magnet's center. This can also be calculated from the magnet's surface area. Determining the possible gap of any particular type of magnet is based on its strength, size, and shape. The size and grade of the magnet contributes to its pull force as stated earlier, which is measured by surface of coverage. If the receiving side is outside the magnetic field of the magnet, it results in very weak, or zero, attraction between the two surfaces. In essence, as the space between the magnet and the receiving side increases, the magnetic field decreases (Feymann 1964; Livingston 1996; Spicer 2010; Spicer 2016a).

Organic materials that are commonly used to soften the hard surface of the mount and even the magnet itself, have a variety of density, loft, compactness, and friction. The materials used in the gap can add or subtract to the performance of the system. Not all gap materials behave the same way. Thus a system that is designed for one material might not work the same way for another.

4. THE HANDS-ON SESSION

Following the introduction to magnets and magnetic systems, participants were divided into groups. Each group received one of five different magnetic system variations. All groups received the same gap materials: cotton fabric, paper, Mylar, two thicknesses of polyester batting, and an ultra suede. Each of the materials was chosen to represent the various materials of an artifact, mount, or barrier layer. The Mylar was included because conservators frequently incorporate it as a barrier.

Each group was given a "jig" made with ¾" PVC pipe for the legs and an upper horizontal aluminum "L" piece (fig. 3). Wooden blocks with secured magnets or ferromagnetic materials were made to act in two ways: to rest on the upper edge of the aluminum bar and to independently support a small weighted bucket. In this way, participants were instructed to add weight to their given system and record the weight at which their particular configuration of magnets, gap material, and receiver failed. Each group was given a set of pre-weighed sand bags, starting with an eighth of a pound. These jigs tested the sheer strength of the magnetic systems (fig. 4).

Figure 3: The jig is made of 3/4" PVC pipe for the legs, and an upper horizontal aluminum "L" piece. Wooden blocks with secured magnets, or ferromagnetic materials, are made to rest on the upper edge of the aluminum bar and support a weighting bucket (Woods, 2013; Spicer, 2014).

Figure 4: Wooden blocks with secured magnets or ferromagnetic materials made to rest on the upper edge of the aluminum bar and support a weighting bucket.

Several of the systems were based on configurations previously described in conservation literature (Potje 1988; Ritschel 2011; Heer 2012; Migdail 2012; Spicer and Owens 2013; Stein 2013; Spicer and Dunphy 2015). They were included for participants to see not only how they worked, but more importantly, how they could be altered for different situations. Since more has begun to be written about magnets, much of the tests focused on the variations of ferromagnetic material. The magnet selection was more constant.

Below, each test is described. The Neodymium magnet for all cases were disc, grade N42, 1/8" thick, and in a range of diameters. The poles were all axially oriented.

4.1 TESTS

The five tests were performed to test the sheer strength of the magnets. Each of the tests was performed by four different groups (see table 2). Some of the materials used in the tests needed additional information and is included below.

4.1.2 Metallic Cups

Several suppliers sell metallic cups in which rare earth magnets fit. The cups are designed to be embedded into wood, in order to have a flush relief, and are secured with a screw. The cups are made of steel with a nickel-plated coating. While the type of metal used enhances the magnetic power as previously described, it is the presence of the additional vertical sides of the cups that increases and focuses their magnetic fields, creating added strength.

4.1.3 Flexible magnets

The flexible magnet is a type of ceramic magnet where the magnetic material is dispersed in a binder, such as vinyl or rubber, when the magnet is formed. The pull force is quite weak, but in order to increase the strength, the polar directions are arranged as a Halbach Array (fig. 5). It is this alternating polarity that creates a modest attraction. Thickness of the flexible material is in direct relation to the pull force of the magnet. Flexible magnet specifications are simple: The thicker the sheet, the stronger the magnet. The weak strength of this material was confirmed by all test groups.

4.1.4 Iron Powder

As an experimental receiving agent, iron powder, commonly known as "Magnetic Paint", was prepared in three different ways. First, it was mixed with an acrylic paint according to the manufacturers directions. Second, it was bulked with epoxy and applied directly to a wooden block. Third, it was bulked with epoxy but forced into needle-punched polyester batting. The varying amounts of the iron powder were added to modify the variables in the kits.

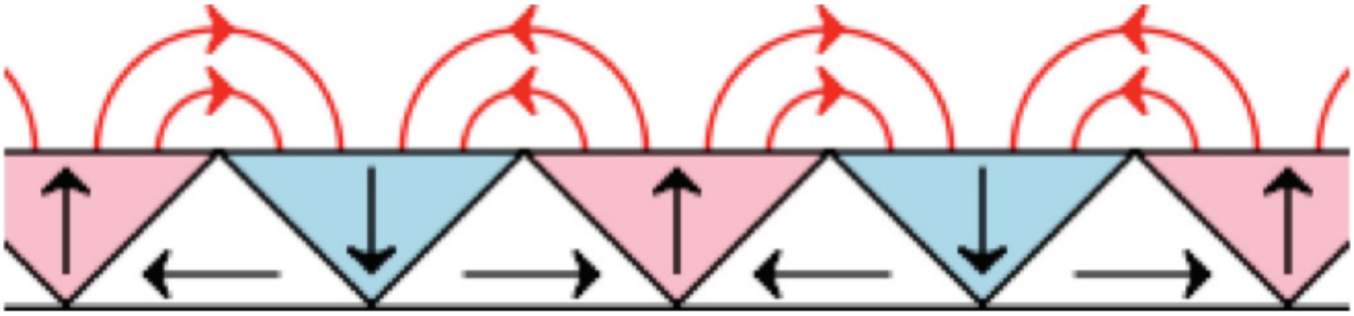

Figure 5: Halback array-alternating polar direction to increase pull force.

Table 2: Overview of All Tests

Team	Receiving Side	Magnetic side	Weights		Notes
Green: Local Spots *Publication:* Potje 1988; Keynan et al 2007; Spicer 2009; Ritschel 2011; Hovey 2012; Spicer and Owens 2013	fender washer thicker steel washer metallic cups, ½" and 1" in cups	½" ½" in cup 1" 1" in cup	(lbs) 1 ½ 1/4	# 3 4 4	This test has two thicknesses of steel washers and three Neodymium magnets (grade N42). Two ½" diameter magnets are in a steel cup. Test various combinations of magnets and washers. Record observations and weight amounts. Return test recording sheet to presenter. **The larger magnets in this test are very powerful. Great care in handling is necessary. Avoid having magnets hit one-another abruptly, shock can demagnetize them.**
Blue: Iron Powder *Publication:* Sheesley 2008; Stein 2013	Iron powder "Magnetic" paint • painted on surface • mixed with epoxy • embedded into batting	½" ½" in cup 1" 1" in cup	(lbs) 1 ½ 1/4	# 1 2 4	This test has three thicknesses and methods of applying the iron powder and two Neodymium magnets. Each option has increasing amounts of iron powder. One ½" diameter magnet is in a steel cup. Test various combinations of magnets and iron powder samples. Record observations and weight amounts. Return test recording sheet to presenter.
Orange: Steel Gauge *Publication:* Halbrow and Taira 2011; Hovey 2012	.001 .025 (24 gauge) ½" in cup	¼" ½" ½" in cup	(lbs) 1 ½ 1/4	# 5 2 4	This test has two thicknesses of steel bar and three Neodymium magnets (grade 42). Two ½" diameter magnets are in a steel cup. Test various combinations of magnets and steel bars. Record observations and weight amounts. Return test recording sheet to presenter.
Red: Flexible Magnets *Publication:* Heer 2012; Migdail 2013	foil tape (.001) steel (0.01) steel (.025), (24 gauge) flexible magnet (0.06)	*Flexible magnet:* (0.03) (0.06) (0.125) ½" dia.	(lbs) ½ oz 1/8 1/4	# 4 2 4	This test has three thickness of steel bar and three thicknesses of flexible magnets. A second strip of 0.125 flexible magnet is provided. In the literature, Mylar was used as a separating barrier. Test various combinations of flexible magnets and steel bars. Record observations and weight amounts. Return test recording sheet to presenter. **Keep the one rare earth magnet separate from the flexible magnets.**
Yellow: Velcro Alternative Idea *Publication:* Wood 2012	"*Slat*" *Side* • Steel bar (24 gauge) • 3/4" diameter magnet attached to aluminum • Empty cups, 3/8" & 5/8"	*Removable Side* • webbing sleeve with pockets for ½" magnets • powder-coated steel (24 gauge) • 2 webbing sleeves	(lbs) 5 1 ½ 1/4	# 1 4 2 4	This test has two 24-gauge steel bars, one on a block and the other powder-coated and which slides into a prepared webbing sleeve. Neodymium magnets are both attached to an aluminum bar and loose. A second prepared webbing is provided to test various magnet placements. Test various combinations of magnet, steel and webbing sleeves. Record observations and weight amounts. Return test recording sheet to presenter.

5. OBSERVATIONS

The final section of the session was when, as a group, we discussed our observations of the various trials. Each group was allowed to speak while a volunteer recorded the comments. The recorded comments are collated in table 3. The observations are divided into comments about the test and the gap materials. Expressed observations were mainly related to the gap materials used by participants.

5.1 DISCUSSIONS OF THE TESTS

Any discussion relating to weighted tests, as in this hands-on session, requires a mention of static and dynamic forces. Static can be described as a load that moves slowly, as opposed to one having acceleration. The method of weight placement in the bucket by any one group can greatly affect the results. Therefore a weight that is gently and slowly placed will have a higher weight result than a dynamic test where the weights are dropped.

Table 3: Comments recorded during session

Test	***Test Comments***	***Gap Comments***
Green	One group recommended, "buy the cup!" While, they also mentioned that it left a mark or impression on the paper.	The felt/batting diminished the strength of the magnet's strength. This observation represents the whole ideas of the thicker the gap, the weaker the pull strength.
Blue	The powdered iron embedded into the batting created the best results. Groups clearly saw that the increase in the concentration of iron powder held better. The 1" disc magnet in a cup did not hold more weight than the ½" disc in a cup on average. This was seen on all tests.	Mylar on the outside was better than when placed on the inside. This was noticed by other groups too. Nap-to-nap surface was better. Alluding to the fact that friction is playing a role in the system.
Orange	The thin foil (.001) steel did not even hold the bucket. (The average weight was 40 grams) 24 gauge steel held the cup.	When the Mylar was next to the steel, it failed at ½ lb. where as, when the fabric was placed next to the steel, it stayed at ½ lbs. Other groups also noticed this. Best results were when the suede was between and in the gap.
Red	The overall concession was that Flexible magnets do not hold much weight. One group was able to hold as much as 1-½ pounds using the 0.125 thick magnets.	All felt that the strongest was with the suede in the gap.
Yellow	Not a lot of sheer strength Magnet needs to be smooth when using the cup Mock-up is essential Discussion of how to adjust the lower lip of the "L" slat.	None

Table 4: N 42 1/2” disc. × 1/8” thick with all of the ferromagnetic options

.001 steel	***.01 steel***	***.025 steel***	***Fender***	***Thick washer***	***Painted***	***Epoxy mix***	***Embedded batting***
Less than 40 grams	½ lbs	1 1/8 lbs	¾ lbs	1 lb	Less than 40 grams	~40 grams	1/8 lbs

Participants quickly found that the amount and thickness of the ferromagnetic materials greatly affected the strength of the magnets. This was seen regardless of what form of ferromagnetic material was used: washers, steel sheet, or powdered iron. Neither the foil tape (0.001), nor the powdered iron in the paint medium was found to be strong enough to hold the bucket with any of the magnets. Large differences in magnet size did not affect the pull strength (1” to ½” was the same) (table 4).

In all groups, the same ratio of decrease in pull force of any test was seen. In essence, as more layers were placed between, and the thickness of material was increased, the pull force decreased. Besides the distance that affects the force field, surface quality and area of the materials are also at play. The physical properties (smoothness, friction, or static) all contribute to a small degree (table 5). Participants noticed differences with the suede and Mylar layers. These contributing forces need more investigation. Friction, as with other mounting systems, works the same; the smoother the surface of the gap material, the lower the hold. When developing a magnet system, the types of materials selected to be surrounding the artifact (i.e. the materials in the gap) can play a role in the success of the system and when in close proximity, they can have the ability of added attraction. With more grab between the layers, less pull force is necessary, and hence the chance for damaging of the artifact due to compression can be reduced. The presence of the pull force applies the necessary pressure to lock the fibers together. Slippage is hence reduced (SmallCorp 2012).

It is common for conservators to use Mylar as a barrier, but this might need to be reconsidered when it comes to magnetic systems. Mylar is often used as a barrier in order to prevent unwanted materials to transfer to the artifact (Heer 2011; Migdail 2012). As a barrier, Mylar does quite well, however, as its smooth surface works counter to the holding powers of the magnetic pull force. Static charge that is builds up with Mylar does not affect the magnet itself or the ferromagnetic material. But the static can have a role with the other materials and the artifact. During this hands-on training session, participants noted a marked difference depending on where the Mylar layer was located. One might want to rough up the surface in the location of the magnet.

Table 5: Gap material characteristics

	Static	***Friction***	***Surface***	***Cotton***	***Acrylic***	***Polyester***	***Thickness***
Paper			s	x			0.0036
Mylar	x		s		x		0.003
Fabric		x	r/s	x			0.011
Batting		x	r			x	0.095
Suede		x	r				0.025
Webbing		x		x			0.02

KEY: s-smooth, r-rough

6. CONCLUSIONS

The activity was designed as a learning experience while also serving as a fun introduction to magnetic systems. It appears that both were achieved. Participants were able to deal with many of the issues in creating and altering magnetic systems.

Tests were quickly performed. This could have altered the results, as the weights were added more quickly or heavy-handedly than might have been done if more time had been provided. This gives a less precise result than in a more "controlled" experiment. However, none of the group observations mentioned this type of phenomenon. Most significantly, the importance of the ferromagnetic materials and the gap materials in a magnetic system was demonstrated. This allowed for a fuller understanding of the all the parts of a magnetic system.

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SOURCES OF MATERIALS

Disc Neodymium with nickel-plating, ¼", ½", and 1", Grade 42; Flexible magnets: Ferrite bonded strips with synthetic rubber, style 0.03, 0.06, and 0.125; Cups for magnets: Steel, ½" and 1"; Steel washer 1 1/8"

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www.lyt.com, magmag@stargate.net,

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Buffalo, NY 14224
(716) 674-7990, ext. 207
www.buffalofelt.com

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(212) 219-0735
http://www.talasonline.com

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