GWEN SPICER

The How and Why for Reusing Rare Earth Magnets

ABSTRACT

Since the early 2000's, art conservators have been increasing our use of rare earth magnets for all types of conservation work. The small size-to-strength ratio of these magnets has allowed them to be adapted to solve many formerly challenging tasks. The rare earth magnets Samarium and Neodymium are the latest two of the four permanent magnets to be developed, after Alnico and Ferrites. Neodymium is the most commonly used and best suited rare earth magnet for art conservation applications.

However, in the last decade the neodymium rare earth magnet has gone from an inexpensive material to one that has become more costly. In addition, some environmental issues have come to light in the last few years. As with any source of energy or technology, some aspects of their creation and subsequent hazards need to be known, as well as how best to protect the environment. Magnet development and history have long been interconnected with geo-politics.

INTRODUCTION

Whether we came to art conservation with a background in art or from the sciences proper, we've learned the needed basics of physics and chemistry. Yet for many of us, one particular 'puzzle' is the Periodic Table, especially the lower rows of the periodic table, which are often overlooked. The development of rare earth magnets from this row of elements is a story that touches on both early developments from chemistry and from geology. These ultra-strong magnets are well suited for applications in art conservation. Understanding the controversial geo-politics of the development and production of these magnets, and the need for their reuse, versus disposal, is necessary.

Let us be guided by the overall question: Is the use of these new materials sustainable or not?

Presented at the Book and Paper Group Session, AIC's 43rd Annual Meeting, May 13–16, 2015, Miami, Florida

WHAT ARE RARE EARTH ELEMENTS?

Rare earths are also called Lanthanides; they lie along the lower row of the periodic table. They include elements with atomic numbers 57–71 (table 1). At times, scandium (21) and yttrium (39) are also included.

The use of the term "rare earth" is misleading, in that many of these are actually not rare in abundance (Gschneider 2015). Instead, they are difficult to obtain. *Rare earth* is from an archaic nineteenth century term to describe an oxide-type of material (Trout n.d.). This group of elements is notorious for being chemically similar to each other and for many years they were not considered separate elements. In fact, no pure lanthanides are found separately in nature (Kean, 2010). Even the term "lanthanide", which comes from the Greek *lanthaneim*, "to lie hidden" illustrates how challenging it is to isolate one member of this group from another.

The story of their discovery is very confusing and complex. The search for, and discovery of, these elements constituted an integral part of the development of science and technology in the late 19th and early 20th centuries. Due to the complexity and questionable purity of samples, many claims were being made in this time for new elements that later proved false (Trout 1998, 2002; Zepf 2013).

THEIR DISCOVERY

The first rare earth element, ytterbite was discovered and isolated in 1794 in Ytterby, Sweden; initially there was no understanding of their potential use or how to separate these elements from their surrounding material. The small quarry at Ytterby was found to be rich in Lanthanide elements, revealing seven more over time, of which four are named after the community (Kean 2010; Gray 2009). Cerium (58) was the second in 1803 (Zepf 2013).

The similar structure of the rare earths is one reason for their slow separation. In the lanthanide group, each features buried electrons that are positioned more deeply than transition metals (elements located at the center of the periodic table). In the lanthanide group their additional electrons are

	Cerium Group (1) Light; (more abundant) found in the earth's crust				**(2)**	**Cerium Group**			**Ytterbite Group (3)** Heavy; (less abundant) found in earth's mantle						
Chemical Element	**La** Lanthanum	**Ce** Cerium	**Pr** Praseodymium	**Nd** Neodymium	**Pm** Promethium	**Sm** Samarium	**Eu** Europium	**Gd** Gadolinium	**Tb** Terbium	**Dy** Dysprosium	**Ho** Holmium	**Er** Erbium	**Tm** Thulium	**Yb** Ytterbium	**Lu** Lutetium
Atomic Number	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71
Atomic electron configuration	$5d^1$	$4f^1 5d^1$	$4f^3$	$4f^4$	$4f^5$	$4f^6$	$4f^7$	$4f^7 5d^1$	$4f^9$	$4f^{10}$	$4f^{11}$	$4f^{12}$	$4f^{13}$	$4f^{14}$	4f14 $5d^1$
Radius size	103	102	99	98.3	97	95.8	94.7	93.8	92.3	91.1	90.1	89	88	86.8	86.1
Radioactive					X										
Dates	1839	1803	1885	1885	1942	1879	1896; 1901	1886	1842	1886	1878	1842	1879	(1878); 1907 Isolated in pure form 1953	1906
Named after	Greek, "to lie hidden"	Dwarf planet & Roman Goddess, Ceres	Greek, "Green Twin"	Greek, "New twin"	Titan	Mineral samarskite from which it is isolated	Europe	J. Gadolin (1760-1852)	Ytterby	Greek, "hard to get at"	Stockholm	Ytterby	Thule	Ytterby	Latin for "Paris"
Use	Glass polishing	Lighter flint, polishing glass	Glass blower glasses, blue filter, lasers	Magnets, headphones, Oil filters, disk drives	Compact fluorescent, watch dials	Magnets, electric guitar pickups,	Red color TV, CRT, Compact Fluor.	MRI, Store computer data	Light weight speakers, sonar transducers	Cathode lamps, coating for hard drives,	MRI, Solid state lasers	Fiber optics, lasers, pinkish colorant in sunglasses	Halide lamps, medicine	Lasers, gamma emitter, strengthens stainless steel	High intensity discharge lights, LED lights

Table 1. Rare Earth Elements Facts.

often found two energy levels below (table 1) (Kean 2010). These electrons are located in the 5*d* and 4*f* valance levels with two previously filled levels and 4*f* has 14 places. As you move across the table, each lanthanide is distinguished from the next by the addition of one electron, which results in their wide range of physical and chemical properties (AMC 1999; Gray 2009).

Their discoveries and subsequent separation were directly based on advances in scientific techniques. Separation was first achieved primarily by repeated precipitation or crystallization. Much of the development of rare earth magnets is an evolution of compound manipulation as separation techniques were refined and became less expensive. With each new development, another rare earth could be separated. First came solvent dissolution in 1839 and in 1879 a second technique called surge optical flame spectroscopy. These two techniques led to almost half of the rare earths being identified and isolated (Zepf 2013). The final rare earth, Promethium (61) was not separated until WWII, during the Manhattan Project. The pace of discovery is clearly marked by the appearance of each technique, in total it has taken about 150 years to identify and discover all of the Lanthanides.

A SILENT REVOLUTION

It turns out that our modern world depends on these rare earth elements. Our growing dependency has been termed a "Silent Revolution" (Livingston 1996). One really cannot function today without being in contact with a rare earth element, especially, when it comes to technical devices. Because they have allowed many gadgets to be miniaturized, their use is found everywhere, and they are now an intrinsic part of our modern society. In any smart phone, there are at least 11 rare earth elements (Butler 2012b). Even the simple ear buds sometimes given to you on airplanes (and considered to be disposable) contain Neodymium magnets.

One ironic part of this revolution is that in our attempt to reduce dependency on imported oil, we have turned to "green" technologies that are based on rare earth elements. The predominant industries that use magnets are those producing electric cars, wind turbines, and powerful batteries. All of these use an abundant amount of these elements. The small magnets that are used in conservation do not have the same demands or large supplies as these other industries.

As a side note, each electric Toyota Prius motor requires 1 kilogram (2.2 lb) of neodymium, and each battery uses 10 to 15 kg (22–33 lb) of lanthanum. That number will nearly double under Toyota's plans to boost the car's fuel economy (Gorham 2009; Gorman 2015). The car and turbine industry is also investing in developing methods of recycling the material and how to create the same strengths with less raw ore. Research in the development of nanoparticles, the "next generation" of magnets, are being developed that use less expensive magnetic materials (Jones 2011a & b; Butler 2012b).

Now that their presence in our everyday life is confirmed, we must ask: where do they come from?

WORLD PRODUCTION AND TRADE

Access to materials has been an integral basis of permanent magnet production. The impetus for the shift to more uses of the ceramic magnet occurred during a shortage and subsequent price inflation of cobalt (a main component of Alnico, the first permanent magnet) during the Zaire wars in the

early 1970s. Rare earths, just like cobalt in the 70's, are part of present conflicts and trade issues.

Early commercial mining for rare earths started in Brazil where the ore is found mixed with the sands. This work grew especially after the discovery of a newly invented incandescent lantern mantle using Thorium, an element exhibiting low-level radioactivity (Gray 2009; Zepf 2013).

In the mid-20th century mining took off. Mountain Pass in California was the world's major source of lanthanides from the 1960s to the 1980s (Long *et a.* 2010). One of the significant products of this mine was used to produce the reds in color TVs. Domestically we supplied all of our needs, but that began to change in the early 2000s. Two influences caused the Mountain Pass mine to close: one was the decline in prices of materials imported from China, but also the mine was cited for environmental infractions (Margonelli 2009). Mountain Pass demonstrated that even in our country, where we have strict mining practices and environmental regulations, the risk for potential pollution is high.

CHINA'S RISE

During the development of rare earth magnets, especially Neodymium since the 1990's, China has become the predominant source for the rare earth ore with the largest deposits in Southeast China and Inner Mongolia (Humphries, 2013). Other countries that had mined ore could not compete with the lower prices at which China was exporting. But with the low price came the environmental hazards due to poor controls on mining methods inside China (Trout 2002; Bradsher 2009). This low cost only stayed until a 90% market hold was reached by China. But since, 2010 there has been a sharp rise in cost.

With the increase of prices, China has also now begun limiting exports, favoring their domestic customers (Inoue 2012; AP 2015). Three of their eight major mines, one of which produced 40% of China's production (Jones 2011b), have stopped production. These changes in prices and restrictions may have a silver lining. It is hoped that the newer mine locations in other countries will have better restrictions and tighter safety standards when it comes to mining and production. Searches for alternative mining locations are ongoing in Australia, Brazil, Canada, South Africa, Greenland and the US. Many of these countries were original producers, before China's current monopoly (Bradsher 2009; Gambogi 2013; Humphries 2013).

Keep in mind that there are two parts to the production of rare earth magnets. One being the mining or extraction, the other is the processing. Each has environmental repercussions that involve release of toxic chemicals, including radioactive materials and air pollution.

This global geo-political situation is how this author became aware of these issues. It is the knowledge of the processing practices and trade issues of rare earth elements that is necessary to understand that our changing shift away from fossil fuels and towards our miniaturization world may not be as "green" as we think.

ENVIRONMENT AND MINING

The environmental implications of mining and processing are immense, especially if the situation continues without properly imposed regulations. Potential environmental damage is particularly worrisome when it comes to illegally or marginally supervised mining. Various forms of lanthanide elements are found together, unfortunately also along with mildly radioactive materials, like thorium and uranium. Furthermore, the separation requires the use of toxic acids to extract the rare earth ore from the surrounding soils, and then from each other. For every ton of rare earths mined, 19 lbs fluorine, 28 lbs dust, and 2650 cubic feet of acidic wastewater result (Bradsher 2009; Cressey 2010; Hurst 2010; Butler 2012a).

All aspects of mining, refining, and recycling require proper management to retard any environmental consequences. The run-off from mining and subsequent tailings and other waste materials is known to affect farmlands below. It has been found that a mine might produce for a few years but the effects last for decades (Bradsher 2009)

Recent developments have moved some of the processing to poorer countries. An example is Australia, which has mines in several locations, recently got approval to ship their ore to Vietnam for processing. It has become a conflict between the 1st and 3rd world, the market identifying countries that are willing to accept the environmental difficulties. Another approach being considered is seeking out less populated areas like Greenland, the sea and even the Moon! (Jones 2011b; Veronese 2015 a & b)

But at what environmental cost do we obtain our supply of rare earth elements?

OPEN PIT MINING AND TAILING PONDS

Ore is typically mined with an open pit process. Three types of minerals are sought during this process: Placer sands, Monazite and Bastnasite, and recently Lujavrite now found in Greenland (Zepf 2013; Vahl & Kleemann 2014; Veronese 2015 a & b).

Consider the processing and separation of the ore to create the rare earth. The resulting wastewater from this process is held in tailing ponds containing acids and radioactive materials (Engles 2014 a & b; Payne 2015). Populations in nearby regions of China are believed to suffer from cancers and shorter life expectancies (Margonelli 2009; Butler 2012). China is able to operate about 1/3 the cost of US production because of lax environmental standards.

However, on a positive note, in the last few years companies in Japan and elsewhere have been working hard at making rare earth technologies more efficient (Inoue 2012; Gimurtu

	Alnico	***Ferrite***	***SmCo***	***Neodymium***
Use keeper for Horseshoe shape	X			
Wrap to prevent abrasion		X		
Group by size		X	X	X
Stack, orienting North-to-South		X	X	X
Place separator between			X	X
Moisture and RH sensitive			X	X
Mechanical Shock tolerance	Very resistant	Brittle and chip or crack easily	Low. Brittle and chip or crack easily. Best to separate with a cushioning material.	Very low. Brittle and chip or crack easily. Best to separate with a cushioning material. Continual snapping will lead to demagnetizing.
Demagnetizing Field (H_{ci})	Can be easily demagnetized. When repetitively placed north-pole-to-north-pole ends together, it quickly weakens itself, but can be re-magnetized.	Keep away from Rare earth magnets.	Can be demagnetized by NdFeB magnets. But they do not weaken others.	Tough to demagnetize. This also means that they can easily demagnetize other classes of magnets like SmCo or Alnico or Ferrite. Shock can demagnetize. Cannot be re-magnetized.

Table 2. Storage of Permanent Magnets by Type.

2013; Gorman 2015). Also General Electric is reverting to Alnico magnets for use in wind turbines. Scientists are also developing improvements on techniques that create less waste (Midgley 2015). These directions point to a positive resolution of our global environmental issues.

STORAGE / SAFE HANDLING OF NEODYMIUM MAGNETS

As conservators, our daily use of rare earth magnets in conservation is very limited.

In 2011, an electronic survey of ten questions was implemented, with an incredible response from all conservation specialty groups and conservators from around the globe. One question was directed at how magnets were being stored and the responses indicated a particular lack of understanding in this area. This topic will be addressed in the remainder of the paper (Spicer 2016b).

All permanent magnets require special attention for optimal and continual performance (table 2). As with any equipment, one should use them with care. Areas of concern are mechanical shock, heat, moisture, and a demagnetized field. All of these are issues of handling and environment, which conservators are especially suited to understand. Depending on the class of magnet, the care will vary slightly, but, with proper care, little decay should be noticed (fig. 1).

Coercivity (Hc) is the process where a magnetic field is reduced or eliminated. Each permanent magnet has its own coercivity rating. The higher a magnet's Hc, the greater the resistance to demagnetization (The Magnet Story 1998). Understanding the Hc of permanent magnets and other material and equipment that surrounds us is necessary when working with strong magnets. Rare earth magnets currently have the highest coercivity values. Industries that work exclusively with rare-earth magnets are quite concerned about their coercivity.

One of the survey questions focused specifically on how conservators stored their magnets. As a response, here are a few rules of thumb:

Fig. 1. Solutions for storage of rare earth magnets, showing a range of box sizes and styles. Ethafoam sheet lining placed in the boxes provides cushioning of the magnets.

- Separate the rare earths from all other types of permanent magnets.
- Provide cushioning between the magnets and prevent any shock.
- Keep away from all heat sources.

MECHANICAL SHOCK

Several magnet types are brittle and can easily fracture. This is especially the case with rare-earth magnets, when impact and tensile forces affect them. Many suppliers do not guarantee against poor handling due to this fact. Brittleness increases as the grade number increases. Since a sharp hammering, or any physical shock, can cause demagnetization, it is necessary to prevent magnets from quickly jumping to one another or dropping to the floor from a raised height. Once a magnet is broken or cracked, it is highly susceptible to moisture and corrosion. Do not attempt to use them by positioning them together or gluing them together. Chipped or cracked magnets with peeling or spalling surfaces should not be used since the protective coating has been disrupted (Campbell 1994). When a higher grade is used, a smaller size magnet might be preferred.

HEAT (TC)

Each permanent magnet has a Curie temperature (Tc) that identifies the point where the material's magnetism is eliminated. Neodymium magnets are very sensitive to temperature and have the lowest Tc of the permanent magnets; Alnico and samarium have the highest Tc values. This is one of the reasons why Alnico magnets are still used. Be sure to stay below the working temperature of each permanent magnet used.

MOISTURE

Neodymium is easily oxidized. The presence of an oxidized surface lowers the pull force of the affected layer, which allows the region to demagnetize more readily (Campbell 1994, Drak & Dobrzanski 2007). A coating of nickel-plating, or epoxy, is critical to prevent this from occurring. Blistering and spalling of the surface can be seen, more readily with two-layer copper nickel plating (Drak & Dobrzanski 2007). Even during the manufacturing process, oxidation prevention measures are required, often using a vacuum or argon gas environment. A sintered magnet is less stable than a bonded magnet against oxidation induced demagnetization corrosion (Campbell 1994; Trout n.d.). The same multiphase structure is responsible for its good magnetic strength, and also for its poor corrosion resistance. If a neodymium magnet is used in a known raised relative humidity location, a bonded-type over a sintered magnet is recommended (Drak & Dobrzanski 2007).

DEMAGNETIZING FIELD

Some types of permanent magnets influence or weaken other magnets. One such case is when ceramic (including flexible type) or samarium magnets are demagnetized by neodymium magnets. As a result, neodymium rare-earth magnets should always be stored away from other magnet types. Similarly, electronics systems that rely on magnets to hold information, such as hard drives and disks, can be altered or demagnetized by a neodymium magnet that is placed nearby. Magnetic strips on credit cards and other cards can also be affected.

Ferrite magnets can be demagnetized when their poles are alternated, a reason to carefully stack the magnets. This is especially the case with the bonded flexible type; sliding a magnet side-ways perpendicular to the polar rows demagnetizes the array. Alnico type magnets are unique in that they can be re-magnetized by realigning the internal domains via another strong magnetic field. This is not the case with other magnets, especially neodymium ones, where once demagnetized, the magnetism cannot be recovered.

Each type of permanent magnet should be segregated and spaced well outside other magnetic fields. As more magnets are concentrated together, the field increases. A safe approach is to separate each type in the work area.

REUSE OF A MAGNETIC SYSTEMS

Any successful magnetic system uses three key factors that include: 1) the strength of the magnet itself, Magnetic strength is measured in *Gauss*, the amount of force necessary to pull the magnet straight from the surface of a steel plate. 2) The receiving ferromagnetic metal. This is the material that is magnetized in this system. Magnetized regions of the receiving metal impact the magnet's strength. 3) The magnetic field distance, "the gap", is the space created by the layers in between the magnet and the receiving ferromagnetic metal (Spicer 2010, 2013a, b, c, d, 2015, 2016 a & b).

A magnetic system needs to balance the selection of key factors, while also protecting the magnet itself. A successful method is placing rare earth magnets on mounts or within materials. Keeping the magnets surround by materials aids in their longevity, preventing demagnitization from both shock and heat. These embedded magnets or ferromagnetic materials can be placed on top or within an artifact as well as used as a point fastener or as continuous pressure (FN).

Embedding magnets into a stiff material like mat, or corrugated board is an obvious approach (Ellis 2008; Holbrow & Taira 2011; Hovey 2013). At the Asian Art Museum, they have mastered including magnets within an outer boarder that supports the artifact while on display (Holbrow & Taira 2011; Spicer 2013a; Migdail 2015, 2016). They have created a modular system where block-shape magnets are embedded into strips of mat board, positioned outside of the magnetic field and become the finishing outer perimeter of the display mount and are placed over the outer edge of the artifact (fig 2).

However, conservators have also found methods for easily inserting disc shaped magnets by cutting the hole with a drill bit (Ku & Chen 2013). Their use of magnets was along the upper edge, which is especially useful for large artifacts and pair them into short section of mat board. The benefit of the smaller sections is that they can allow adjustments to the artifact during mounting.

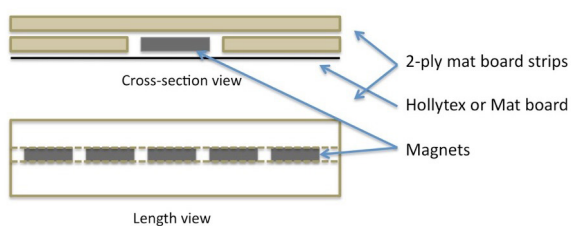

Fig. 2. The block-shaped magnets are embedded into strips of 2-ply mat board. Three sizes of mat board strips are cut; one for the top layer and two for the center layer. The center layer is composed of two longer strips with a row of alternating magnet and mat board. The layers are secured with PVA and wrapped with Hosokawa paper (Holbrow & Taira 2011).

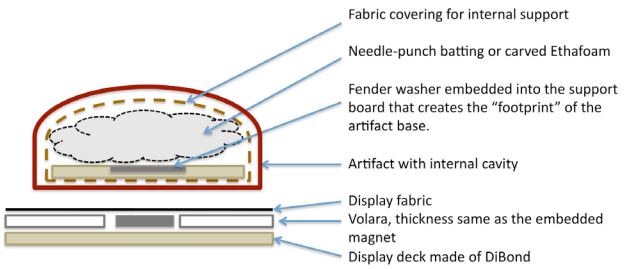

Fig. 3. The mount is made of DiBond covered with an upper layer of Volara and then covered with display fabric. The magnets are embedded into the Volara layer. The selected thickness of the magnet matches the thickness of the Volara layer (*Uncommon* Threads, Maine State Museum 2009); Inside of the artifact is an internal structure filled with batting and covered with stockinet. The footprint of the support is made with acid-free board with a metal fender washer (Carrel *et al.* 2005; Spicer 2013).

Hovey describes embedding magnets into corrugated board that then act like padding that fits inside folds or creases that are accessible. These modular shaped devices can be treated as removable and thus reusable exhibiting tools. Several other conservators have created great methods of positioning magnets within internal padding. Such devices can be made universal and used and reused (fig. 3) (Carrel *et al.* 2005; Hovey 2012; Spicer 2013a). Such approaches can also be used with sturdy materials like baskets or wooden boxes to secure to a mount. One just needs to ensure that including the thickness of the artifact and its internal support as well as supports for mounting does not take the system outside of the magnetic field distance (Maltby 1986, 1988; Carrel *et al.* 2005; Hovey 2012; Spicer 2013a).

Any modular system, during use and in storage, will benefit from having the poles of all the magnets in the same orientation. An inexpensive compass can be used to quickly show the pole direction.

CONCLUSION

The jigsaw puzzle that was started over the holidays was completed by filling in the Lanthanides. It is hoped that this introduction will entice all conservators to put another tool— rare earth magnets—in their tool box. Perhaps this will encourage conservators to develop systems to reuse magnets better, and to create reusable standardized systems for mounts. The field of art conservation will benefit greatly from using rare earth magnets. As we do so, let us in this, and in other aspects of our work, be aware of "best environmental practices" just as we do our best to follow best practices in our treatments. (fig. 4)

Fig. 4. The author after having completed the Periodic Table puzzle.

ACKNOWLEDGEMENT

The author would like to thank the organizers of the Sustainability Session at AIC 43rd Annual meeting, Mary Haude, Robin O'Hern and Melissa Tedone, and the paper conservation community who felt that this topic was important to publish.

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GWEN SPICER
Spicer Art Conservation, LLC
Delmar, NY
gwen@spicerart.com