The Story of Neodymium

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Motors, Materials, and the Search for Supply Security

Introduction

HOW did Neodymium come to be? That is: why did this rare earth metal come to be the crucial ingredient in high-strength magnets starting in the late 20th Century? It feels like an esoteric question but it holds great importance for the future of motor technology; that's because neodymium-based permanent magnets (PMs) are at the core of today's highest torque motors. From the traction motors that drive hybrid automobiles to marine motors for shipping, neodymium seems to enable high-power motors everywhere.

But it wasn't always like that. What isn't widely remembered today is that neodymium magnets, when they first arrived 25 years ago, were not an incremental technological progression but a materials revolution forced by specific, urgent circumstances.

The answer to how neodymium became the critical ingredient in PM-based motors lies not in science but in… geopolitics. An eruption in a little-known theater of the Cold War halted the supply of the then-critical ingredient in the PMs that enabled high-power motors, and forced a shocked motor and magnetics industry to crash-develop a new recipe for high-strength magnets.

A historical accident, neodymium became both enabler and hindrance. While it set the stage for the late 20th Century's compact, high-power motors, its monopolistic supply, its temperature sensitivity, and the common perception that it's an indispensable ingredient for generating high torque, have become an albatross around the neck of the motor industry.

Chorus Motors' high-torque technology is strategically placed to effectuate a sea change in the motor magnetics space in the coming several years, as neodymium supplies tighten or stall. Using software control instead of special materials, Chorus enables 'Phase II' of the effort that was started 25 years ago by General Motors (GM) and Sumitomo Special Metals Co.: emancipating motor users from exotic materials and unreliable supplies—this time for good.

The key points of this surprisingly non-technical story are here:

- For decades, the highest strength PMs in the world were based on cobalt. Cobalt magnets were the gold standard for delivering high magnetic field strength, and therefore high motor torque.
- In 1978, a Soviet-managed invasion of southern Zaire targeted that country's cobalt production, taking 50-65% of world supplies off the market.
- The cobalt price and supply shock frightened Western industries and governments. In response General Motors and Sumitomo of Japan launched an R&D program aiming for cobalt magnet replacement.
- In 1983 they succeeded: the neodymium-based PM was born.
- Over 95% of neodymium is now supplied by Chinese government-controlled companies, and permanent magnet consumers have become more dependent on China for neodymium than they ever were on Zaire for cobalt.
- Even assuming Chinese political goodwill, <u>a neodymium supply shortage is en route</u>. Demand is high, and producers (even under ideal conditions) lack the capacity to keep up.

Prices are already up over 400% in the last several years.

- Japanese companies and government officials cannot assume Chinese political goodwill. They are already searching for neodymium alternatives, and are more aware than most of the dangers of supply shocks.
- It is commonly believed that neodymium-based motors are the answer to actualizing mass-market hybrid cars. But the unintended consequence is that carmakers, trying to solve the "addiction" to foreign oil by using PM-based motors, are becoming reliant on an even more monopolistic and unstable supplier in China for their critical motor components.
- One company, Chorus Motors, has the technology to make neodymium-based PMs and other exotic materials obsolete in automotive traction and other high-power motors.

Below, the full story of neodymium, and a contextual view of the next step for high-power motors and Chorus technology.

Zaire, Cobalt and the Soviets

Neodymium-based magnets (the $Nd_2Fe_{14}B$ blend that is now the de facto standard) were discovered and developed in the early 1980s by a joint venture of GM and Japan's Sumitomo Corporation.

Before this time, the leading industrial magnets, including those used in high-torque electric motors, were made of a samarium-cobalt mixture. This was considered the leading formula for providing high magnetic field strength, temperature resilience and compactness.[1] The not-yet-famous rare earth element (REE) neodymium was mainly valued as a glass colorant, and was not employed in magnetics at all.[2]

At the time, Zaire (now known as the Democratic Republic of Congo) produced at least 50% of the world's cobalt, with over 90% of that coming from the Belgian-operated (and Zairian-nationalized) Gécamines company mines and refineries around the city of Kolwezi in the metals-rich Shaba province (now known as Katanga). Some estimates are that Zaire was producing 65% of global cobalt output.[3]

But in 1978, something changed.

In the spring of 1978, workers at Gécamines in Kolwezi went on strike. Open market cobalt prices doubled from $6-7/lb. up to $13/lb.

Just before summer, things got much worse: a rebel group fighting the rule of Zaire's strongman (Mobutu Sese Seko) invaded Shaba province and made a beeline for Kolwezi—world headquarters of cobalt production.[4]

The mines and refineries were shut as the rebels plowed through the region, killing innocents (including the specialist Europeans who knew how to operate the facilities) and conducting a campaign of rape, pillage and destruction. The surviving foreigners (the ones who weren't murdered or taken hostage) were evacuated to Brussels with the help of Belgian paratroopers and American support.[5]

Belgium and France had already been jockeying for influence in metals-rich Zaire and other mineral-heavy regions of Africa. The jockeying continued as both countries had sent in forces and wanted to secure their 'share' of the region's minerals.[6]

It was quickly recognized that the rebels' attack on Kolwezi, and the attendant flight of civilians and mining specialists, would knock out the region's cobalt production for a minimum of six months.[7] This was immediately seen as a serious economic and technical problem by industrialists, engineers and market analysts.

Things became stranger when it was revealed that the USSR and Communist Bloc governments had purchased huge quantities of cobalt through global dealers in the weeks before the rebels' invasion. The USSR was nearly self-sufficient in cobalt at this time. What was going on?[8]

The answer became clearer as Spanish-speakers rolled into Kolwezi along with the rebels—the Soviet and Cuban governments had trained and armed the rebels (in Angola) for the Zaire invasion and assisted its execution.[9] The rebels' direct strike at Kolwezi, the cobalt capital, was not accidental; it was planned in Moscow. Aside from the rebels' local political goals, Russia aimed to destabilize Western industry by interrupting the supply of a crucial metal while also boosting the value of its own resources.

The market price of cobalt rose to $18/lb. and then $51/lb with intermittent spot prices even higher. Customers were told that for 1979 they would receive at most 70% of what they had ordered the year before. There was nothing that could be done; the supply just wasn't there anymore.[10]

Supply Shock and the Neodymium Response

The cobalt shortage became a matter of strategic anxiety, bordering on crisis, in Western industry. Within months, plans were being drawn for restarting old cobalt mines (first in nearby Zambia), recycling cobalt-bearing scrap, and improving cobalt recovery from existing ore stocks. Western governments immediately began discussions about reestablishing strategic metals stockpiles, and European states tried working out all manner of arrangements to somehow get new cobalt supplies from their African former colonies.[11]

There had been previous interruptions in African cobalt supplies—the 1975 closure of Angola's Benguela railway, for example, blocked the main export channel for Zairian metals—but none had an effect like this. While the 1975 incident temporarily slowed Zaire's cobalt exports, it occurred during a period of lower demand and so did little to impact prices.[12] But by 1978 the demand for cobalt had risen and the metal was now seen as a critical ingredient with limited supply. Even after the Zairian mines began returning to production in 1979, prices moved relentlessly upward.

Rejecting frugality, well-connected manufacturers began hoarding and stockpiling whatever cobalt they could get ahold of—cutting into the available supply and boosting prices yet further.[13] The simple awareness of supply insecurity was proving enough to plunge the market into near panic. Zaire and Zambia, basking in record prices, began *airlifting* some of their valuable cobalt metal out to desperate customers.[14]

Western industries, especially those using magnetics, were shocked. Their cobalt supply lines had crashed and costs increased 800% in the space of a few months. Worse, even if the main cobalt producers were to come back online, the metal's critical industrial role made the market ultrasensitive to even the perception of supply insecurity. Access to economical cobalt was no longer assured.[15]

General Motors and Japan's Sumitomo Corp. launched a response: a secret joint R&D program to design new magnetic materials that would obviate the need for cobalt, and produce PMs strong and light enough for widespread use in automobiles (and not only in traction motors).

The effort was successful, and in late 1983, the neodymium-iron-boron magnet was revealed.[16] The urgently-developed 'NIB' blend allowed the creation of even higher field strength than the old samarium cobalt mixture (though at the price of lower temperature tolerance). And despite the expenses of R&D and initial production, long-term projections indicated that neodymium-based PMs would become cheaper to produce en masse than their cobalt predecessors.

The NIB magnet marked a sea change in the magnetics industry. It opened up new applications, and injected life into the search for new magnetic materials, alloys and recipes.

The Soviet-managed invasion of Kolwezi had forced the leaders of magnet-dependent industries to generate new solutions. The supply shock forced a recognition by PM users, and especially motor builders, that both their financial health and their basic ability to produce were held hostage to a single ingredient coming from a single unstable region itself subject to manipulation by outside powers.

It is not accidental that GM was joined by Sumitomo in the effort to develop new magnets and sidestep an unreliable supply line. Japan's 'curse' is its permanent lack of raw materials. For all of Japanese industry's productivity and flexibility, its leaders are painfully aware that such qualities will be meaningless if the necessary raw materials can't be imported first.[17] Independence from these constraints is the aspiration of Japanese industrialists and strategists concerned with economic growth and national security.

Stuck on Neodymium

The critical ingredient for high strength magnets is now even more dependent on a single supplier than cobalt ever was.

Over 95% of the world's neodymium is today supplied by China.[18]

Virtually all of the world's dysprosium — an essential (though lesser known) component of neodymium-based PMs, added at about 5% to increase their resistance to demagnetization — also comes from China; but at even higher prices and in lower volumes.[19] In fact Jiangxi Province, China is currently the world's only commercial source for dysprosium.[20]

Cobalt is also sometimes added to increase temperature stamina. Both cobalt and dysprosium cost more than neodymium, and dysprosium's continuity of supply is uncertain; but the outlook for neodymium alone presents a sobering picture.

The worldwide yield of neodymium oxide in 2006 was 18,000 metric tons. Permanent magnets required virtually all of it: over 20,000 metric tons of all rare earth oxides (REOs) combined, mostly neodymium but also including dysprosium. By 2010, permanent magnets will require about 29,000 metric tons of neodymium oxide alone, and about 4,000 metric tons of other rare earth metals including dysprosium.[21]

That's less than 18 months from now, and it doesn't look like China can deliver.[22]

With an estimated global demand of over 180,000 tons for all REEs combined by 2010,[23] Chinese REE production and exports would have to rise by several hundred percent just to keep pace.

Instead, the opposite is happening. Though neodymium and REE demand *for PMs alone* is rising at an estimated 13% annual rate, China continues cutting its REE export quotas by an average of over 4% per year.[24] At the same time tariffs on neodymium and dysprosium exports have been raised to 15% and 25% respectively.

These policies support a high market value for REEs while also ensuring a constant REE supply to Chinese industry. Aware of their strategic and economic value, China is keeping a close eye on the final destination of these unique resources.[25]

Moving forward to 2014, Chinese industry alone is projected to require 160,000 metric tons of rare earth metals – swallowing all of China's projected REE production, and leaving none available for the exports upon which Japanese and Western industry are now dependent.[26]

The Chinese central government's ongoing consolidation of REE mining and marketing concerns indicates its commitment to maintaining tight resource control and preventing deviations from central policy — such as over-quota production.

As BCC Research, a leading industrial and technical market research firm, observes, both the economics of REE production and the available raw production capacity dictate an impending supply crunch or outright shortage. The problem is not situational or transient, but fundamental; it is the very chemistry of REEs that dictates the economic boundaries of production.

"The fact that rare earths are co-produced creates a situation where one or two elements that are in particular demand require that other elements be mined as well. The co-produced elements will then potentially create a glut in supply, that is, they will be produced in amounts that exceed demand.

"Neodymium is one element that appears to create this situation, due to its use in Neo magnets and its presence in some of the less-processed mixed element products (such as those used in catalyst and glass applications). With neodymium averaging approximately 16% of the total REO (Rare earth oxides) content of the majority of the ores, its demand would require an annual total REO production of approximately 175,000 metric tons in 2010. This demand cannot be met by the current supply sources." [27]

[emphasis added]

In other words: rare earth elements are chemically similar and so tend to be grouped together in deposits. Producing one REE necessitates the production of the attendant REEs that are found in that deposit.

But given the concentrations of neodymium in REO ores, producing sufficient neodymium just to meet demand would require flooding the market with other rare earth elements, lowering the prices to uneconomical levels for producers. Either way, current REE producers don't have the raw capacity to meet the forecast neodymium demand even if they wanted to.

In light of that rising demand, and China's tightening of control over REE exports, it is increasingly apparent that non-Chinese companies will need to develop new strategies for securing supplies of neodymium and other REEs. By 2007 Roskill, a UK-based metals and minerals consultancy, bluntly described the need for non-Chinese sources of these materials as "urgent".[28]

There are other potential sources of neodymium that may come online in the next several years. They are finite and known: Lemhi Pass, Idaho; Mt. Weld, Australia; Mountain Pass, California; Hoidas Lake and Thor Lake, Canada. These projects will be very profitable if current supply/demand trends continue. But they are not yet delivering REEs to market, and they will only supplement, not supplant, China's tightly controlled neodymium exports when they do.[29]

It is not accidental that the new prospective REE projects are all located in Western countries. The first Western REE producer to come online will become the only geopolitically stable supplier of neodymium on the planet.

The Situation

Geopolitics forced a revolution in magnetics by prompting the invention of neodymium magnets. The 1978 invasion of southern Zaire, and the subsequent market panic, brought magnet producers and consumers face-to-face with the realities of single-source supply chains.

When the sole source of a critical material can't be relied upon to ensure the continuity and economy of supply, a dependent company's entire enterprise exists at the mercy of any force that might interfere with that supply. That fact of business applies whether the source is Zaire, China or any other producer.

Today, one unreliable single-source magnet supplier has been replaced by another. Any political instability in China, or new tariffs, export restrictions or taxation imposed by the government will impact the world's only source of critical materials for the highest-strength magnets. Automakers that use PM-based motors, like Toyota and Honda (and an increasing number of other major players), are now completely dependent on Chinese neodymium supplies.[30]

In fact, the Western world's entire effort to free itself of gasoline for ground transportation depends on a generous, predictable stream of Chinese neodymium to be incorporated into automotive electric motors. In lieu of relying upon a cartel of foreign nations to supply fossil fuels, however, Western economies are now becoming reliant upon a single foreign nation to supply their vehicles' most critical ingredient.[31]

The Japanese economy is permanently short of raw materials, and perennially concerned about China's intentions. It is not accidental that Sumitomo Corp. led the development of neodymium magnets with GM, nor that Japanese industrialists openly volunteer their uneasiness with China's total control of neodymium supplies.

In 2007 the Japanese government announced a strategic program—managed at the cabinet level—to find alternate suppliers for REEs and to identify substitutes for the materials themselves. In fact several such initiatives are now active.[32] In the tense, resource-competitive geopolitical environment of East Asia, Japan knows better than most that the constancy and security of materials imports cannot be taken for granted.

Because of its geographic location and its sensitivity to resource trends, Japan tends to respond sooner and with longer range planning to developments that soon impact Western nations as well. The Japanese development of hybrid automobile technology as a response to tightening oil supplies is a well-known example. In this case and others, it has been the first to chart the course that must of necessity be followed in time by other developed economies.

A supply crunch in neodymium is en route. While neodymium prices declined modestly during 1H 2008, they remain about 400% higher than in 2005. If new supplies come to market, the Chinese government can reduce its own production, increase export tariffs, or simply redirect the output to the country's voluminous internal consumption (devoted to electronics, automobiles, and millions of motor-driven bicycles annually).

China's month-long halt in REE production in early 2008—designed to raise prices following an unexpected slide—followed by its late summer announcement of an enormous new REE stockpile—several times larger than the country's entire annual production[33]—are only the most recent reminders of the government's strategy to harness and direct REE production in the service of China's broader economic and geopolitical interests. To China, REEs like neodymium are keys to global technology and energy progress, valuable generators of foreign currency and tools of national influence.[34]

Even if new suppliers come on line, Chinese domination of supply and production coupled with rapidly growing global demand dictate the advent of near- or outright shortage conditions within several years. "*This demand cannot be met by the current supply sources.*"

Delivering the Prize

The next several years, as neodymium supplies tighten, are a natural time to effectuate the next turning point in electric motor technology. The motor industry began its reduction of supply risk by switching from cobalt to neodymium in the 1980s. But as can be seen in the early 21st Century, that was only Phase I. There is now an impending shortfall in neodymium, which is controlled by a single party that can redirect its production at will.

One company has developed and demonstrated the technology to generate the peak motor power typically associated with neodymium, but without relying on exotic materials or a monopolistic supply line. Chorus Motors' patented motor design and software control unlock extremely high torque in motors made of nothing more exotic than iron and copper.

Because of Chorus's licensable technology, it is uniquely positioned to take advantage of emerging resource conditions—the impending shortfall in neodymium supplies—and enable high-power motor builders to thrive in them.

Chorus is ready to provide motor makers and motor users with 'Phase II', the completion of the supply-security process that began over 25 years ago; to step away from specialty magnet materials once and for all.

Chorus is offering complete supply emancipation: instead of relying on imported neodymium to supply magnetic fields to motors, the next stage of motor development will rely on the classic electromagnets of induction machines—but with the twist of Chorus high-phase-order drives that generate far higher peak torque.

The Chorus technology represents a paradigm shift for motor designers and customers, using unique software to generate the kinds of peak torque that previously depended on exotic materials and permanent magnets. Due to the well-known strengths and weaknesses of typical induction solutions, motor makers are often surprised to learn that Chorus technology enables the creation of extremely high power in such a small envelope.

Supply shocks are ephemeral things. The motor and magnet industry's memory of the early 1980s cobalt PM shortage has faded, just as Western carmakers' and drivers' memory of the 1970s oil shocks faded in the 1980s and 90s.

It may be difficult to alert some motor makers to the inherent unreliability of neodymium supplies until a price increase or shipping delay hits them 'in the gut'. Indeed, for its part cobalt served the motor magnetics industry quite adequately… until its supply unexpectedly dried up, necessitating a crash program to find alternatives. Now there is an impending neodymium crunch, and Chorus Motors can offer forward-thinking motor makers insulation and immunity from that crunch.

While the impressive temperature resilience of Chorus eliminates one of the critical shortcomings of neodymium PM-based motors,[35] motor customers will also find that Chorus's improved reliability doesn't come at the cost of impeding high power when it's needed. On the contrary, as demonstrated by the Chorus-based WheelTug system, the technology enables unprecedented power density.[36]

Far from being a 'second-best' or 'contingency' solution, Chorus enables remarkable peak torque production in settings and applications that PM-based motors could never enter—whether it's taxiing a full-size commercial aircraft on the runway, or powering a fully loaded work truck or family sedan up a steep incline at highway speeds.

The idea that supply security can arrive together with improved quality and reduced costs is an unexpected win-win proposal—but it is in fact why neodymium magnets supplanted cobalt in the 1980s. And it's why Chorus is now ready to supplant neodymium. ■

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Notes

[1.] A useful survey of cobalt's magnetic properties, and its 20th Century introduction into high-strength magnets, is provided by the Cobalt Development Institute (http://www.thecdi.com/general.php?r=U6ENJWAVAL).

The well-known Alnico alloy, still employed in updated varieties today, was developed in the early 1930s and was thereafter presumed to hold the key to producing high-field strength PMs. (see Hubert, A., & Schäfer, R. (1998) *Magnetic Domains: The Analysis of Magnetic Microstructures*. Springer Verlag.)

A particular variety of cobalt magnet, the elongated single-domain (ESD), came to be viewed as virtually 'perfect' among magnetics specialists. "At their time ESD magnets were fully competitive.... This class of magnets fascinated researchers because it appeared to represent an ideal of artificial materials tailored to maximum quality as guided by theory." The crash introduction of neodymium made these "ideal" magnets obsolete. (ibid., p. 557)

[2.] Two accessible summaries of early neodymium usage are available at http://www.corrosionsource.com/handbook/periodic/60.htm and http://en.wikipedia.org/wiki/Neodymium. Neodymium remains a widely-used glass colorant today and has also found a valuable contemporary application in lasers. (see Hecht, J. (1999) *The Laser Guidebook*. McGraw Hill, and Chapter 22, *Neodymium Lasers*.)

[3.] See, for example, Sullivan, C. (1978, May 23). Halt to Copper Mining Seen as Crippling Zaire. *The Washington Post*, p. D8; Lewis, P. (1978, May 23). Belgians Fear French Intervention in Zaire is to Expand Influence. *The New York Times*, p. A14; also Borrell, J. (1978, May 22). Rebels' brief hold on Kolwezi could upset Zairian economy. *Christian Science Monitor*, p. 4.

[4.] See Inside Kolwezi: Toll of Terror. (1978, Jun 05) *TIME Magazine*, available (October 2008) at http://www.time.com/time/magazine/article/0,9171,916174,00.html. Also Southerland, D. (1978, May 18). Cuban Step-up in Africa Tests U.S. Hands-off Stand. *Christian Science Monitor*, p. 1; and Spence, A. (1978, May 18). Free-Market Cobalt Prices Rise Sharply Due to Rebel Invasion of Southern Zaire. *Wall Street Journal*, p. 36.

[5.] Claiborne, W. & Oberdorfer, D. (1978, May 19). Zaire Rescue Mission Launched. *The Washington Post*, p. A1.

[6.] For some contemporaneous accounts of European resource-jockeying in Africa see, for example, Kandell, J. (1978, Apr 29). French Seeking New Role in Africa With Troop Aid. *The New York Times*, p. 4; Koven, R. (1978, May 9). France's New Role: Africa's Gendarme. *The Washington Post*, p. A13; Pond, E. (1978, May 17). Zairian's visit reflects Bonn's interest in Africa. *Christian Science Monitor*, p.7; Lewis, P. (1978, May 23). Belgians Fear French Intervention in Zaire is to Expand Influence. *The New York Times*, p. A14; Browning, J. (1978, May 22) French rescue move tells Soviets 'Hands off Africa'. *Christian Science Monitor*, p.4.

The limited amount of available resources made inter-power competition and distrust endemic.

[7.] *Supra* note 5, "Belgians Fear French Intervention In Zaire Is to Expand Influence." Also, Browning, J. (1978, May 30). As French exit, Zaire economy faces test; Major cobalt, copper mines knocked out for six months. *Christian Science Monitor*, p. 3; Nossiter, B. (1978, May 24). Soviets Reportedly Bought up Cobalt Before Zaire Invasion. *The Washington Post*, p. A15; Nossiter, B. (1978, May 24).

[8.] Ibid. Also see Browning, J. (1978, May 22) French rescue move tells Soviets 'Hands off Africa'. *Christian Science Monitor*, p.4; and Spence, A. (1978, May 18). Free-Market Cobalt Prices Rise Sharply Due to Rebel Invasion of Southern Zaire. *Wall Street Journal*, p. 36.

[9.] See Mowrer, R. (1979, Jan 16) Moscow's maneuvering in Africa causes cobalt shortage in West. *Christian Science Monitor*, p. 6; Southerland, D. (1978, May 18). Cuban Step-up in Africa Tests U.S. Hands-off Stand. *Christian Science Monitor*, p. 1. Also see *supra* notes 3 and 7.

(For an extensive, academic survey of former Communist Bloc interests in this region, see George, E. (2005) *The Cuban Intervention in Angola, 1965-1991*. Routledge.)

[10.] "Major Cobalt Producers Raise Prices Nearly 50%" (1978, Jul 25) *The Wall Street Journal*, p. 38; Valentine, J. (1978, Sep 28) Cobalt Price Rises as Problems in Zaire Threaten Supplies, and Demand Climbs. *The Wall Street Journal*, p. 38 ("Cobalt is becoming a precious metal."); Salpukas, A. (1978, Jun 12) Key Industries Scouring for Supplies of Cobalt. *The New York Times*, p. D8; Spivak, J. (1978, Nov 21) Severe Cobalt Shortages Seen Worsening As Zaire's Production Continues to Fall. *The Wall Street Journal*, p. 38. Also see *supra* note 8 (Spence), and notes 11 and 12 below.

[11.] Spence, A. (1979, Jan 19) Sharp Rise in Cobalt's Price Spurs Plans for New Mines, Better Recovery From Ore. *The Wall Street Journal*, p. 20; "French Bureau Buys Zairian Mining Interest from Indiana Standard" (1979, Jul 16) *The Wall Street Journal*, p.8; Spence, A. (1979, Feb 26) European Countries Stockpile Minerals In Case Unstable Nations Cut Deliveries. *The Wall Street Journal*, p. 24; Spence, A. (1979, Jul 9) European Nations Move on Two Fronts to Secure Supplies of Strategic Materials. *The Wall Street Journal*, p. 24.

[12.] For a good summary of the impacts of this closure—and an example of how deeply demand levels determine the impact of such events—see *Strategic Materials: Technologies to Reduce U.S. Import Vulnerability*. (Washington DC; U.S. Congress, Office of Technology Assessment, OTA-ITE-248, May 1985), esp. beginning p. 97. Available online

(September 2008) at: http://www.cbo.gov/ftpdocs/51xx/doc5126/doc29-Entire.pdf.

13. Ibid. esp. p. 99. Also, *Cobalt: Policy Options for a Strategic Mineral*. (Washington DC; U.S. Congress, Congressional Budget Office, September 1982), esp. p. 7.

The decision by those cobalt customers with money and access to begin stockpiling was painful for the broader cobalt market but logical and urgent from a business perspective. Companies dependent on an 'irreplaceable' material were left with no better choice.

(At least one prominent industry consultant is already imploring magnet makers and consumers not to repeat this pattern as they assess the impending neodymium crunch. "Don't purchase 'hedge' inventories—this doesn't help the supply-demand equation!" See Benecki, W. *Why Rare Earth Prices are Likely to Continue Their Upward Trend*, presented at Magnetics 2007 conference, April 4-5, 2007, Chicago, IL. Available (October 2008) at: http://www.waltbenecki.com/uploads/Why_Rare_Earth_Prices_are_Likely_to_Continue.pdf.

14. *Strategic Materials: Technologies to Reduce U.S. Import Vulnerability*, op. cit., p. 99.

15. For one example of the concerns induced by this recognition see Knight, J. & Washington, P. B. (1981, Mar 15). In U.S., Strategic Minerals Acquire New Prominence. *The Washington Post*, p. H1; "Why the U.S. Can't Rearm Fast" (1980, Feb 10). *The Washington Post*, p. D1; and Lowenstein, R. & Shao, M. (1981, Apr 15) Vital Ingredients; Investors, the Military are Keenly Interested in 'Strategic Metals'. *The Wall Street Journal*, p. 1.

The shortage of cobalt soon raised awareness of other resources whose supply could be disrupted. See, for example, Thatcher, G. (1980, Jan 25) Will Rhodesia play politics with scarce metals? *Christian Science Monitor*, p. 7; and Middleton, D. (1980, Feb 6). Soviet, Though Self-Sufficient, Is Reported Buying Some Strategic Metals. *The New York Times*, p. 11;

The American Geological Institute asserted that the US was now the target of a *bona fide* "resource war, conducted by the Soviet Union, whose goal is to interrupt or deny this country access to strategic and critical materials." See "Is There a Resource War?" (1980, Sep 20). *The Washington Post*, p. A18.

16. Koten, J. (1983, Aug 29). GM, Sumitomo Race To Develop Magnet To Reduce Cost and Size of electric Motors. *The Wall Street Journal*, p. 6. (Also see below, note 34, for an interesting postscript.)

17. For an early 20th Century view see Hunter, J (1933). *Industrial Labour in Japan*. Geneva: International Labour Office, esp. Chapter 4, *Economic Structure of Modern Japan*. (Republished in 2000 by Routledge in *Japanese Economic History; 1930-1960*). Japan's resource plight had global economic and geopolitical implications throughout the 20th Century.

For early 2008's manifestation of this problem see Ujikane, C (2008/04/17). Japan's Economy Threatened by Raw-Materials Costs. from *Bloomberg News* Web site: http://www.bloomberg.com/apps/news?pid=20601101&sid=aiW8.7IRn6Ng. For late 2008's, see The *Yomiuri Shimbun* (2008/08/14). 18 tril. yen lost to resource costs / Rising prices for raw materials causes national cash outflow, from *Yomiuri Shimbun | Daily Yomiuri* website: http://www.yomiuri.co.jp/dy/business/20080814TDY04302.htm. (Both available as of October 2008).

18. Lifton, J. (2008). *Ninja Neodymium Investors*. retrieved September 2008 from Resource Investor. http://www.resourceinvestor.com/pebble.asp?relid=41879; Frequently Asked Questions. Retrieved September 2008 from Great Western Minerals Group Ltd. website: http://www.gwmg.ca/rare-earths/faq. Mavin, D (2008/09/11); Demand For Rare Earths Escalates. *National Post*, http://www.nationalpost.com/related/topics/story.html?id=784203; and Alper, A. *Great Western Minerals Poised for Rare Opportunity*. Available (October 2008) from Metals News Web site: http://www.metalsnews.com/featured.aspx?ArticleID=39473.

> *"China produces over 97% of the world's rare earth elements, with 77% of world production coming from one mine. There are no longer any REE producing mines outside of China. Moreover, by 2012, China is expected to need all its REE to feed its own rapidly growing industries, with none to spare for the rest of the world."*

Also see Graham, W (2007, March). Nolans bore life of Arafura party [sic]. *Resource Stocks Magazine*, 40-41. Available (October 2008) at: http://www.arafuraresources.com.au/documents/CorporateProfileResourceStockMarch07_000.pdf.

And the U.S. Geological Survey's 2007 Mineral Commodity Summary for Rare Earths (retrieved September 2008) (http://minerals.usgs.gov/minerals/pubs/commodity/rare_earths/rareemcs07.pdf) for illustrations of Chinese overall REE production in 2005 and 2006 compared to other nations'.

19. See Campbell, P (2008/02). Supply and Demand, Part 2. *Magnetics Business & Technology, 7(1)*, text available (September 2008) from Dr. Peter Campbell at http://www.magnetweb.com/Col05.htm.

See also Hedrick, P (2006). *2006 Minerals Yearbooks—Rare Earths* at U.S. Geological Survey website (October 2008): http://minerals.usgs.gov/minerals/pubs/commodity/rare_ea rths/myb1-2006-raree.pdf.

20. *Supra* note 19, and ibid. esp.: "Existing production is currently not sufficient to meet increases in world consumption, and shortages exist for neodymium and dysprosium for magnet alloys and europium and terbium for phosphors."

An unusually frank discussion of dysprosium's criticality in enabling hybrid vehicle motor function was offered by the CEO of Neo Material Technologies, Inc., a major neodymium and dysprosium producer, in March 2008:

> *"…[R]ight now we are the biggest producer of dysprosium in the world. Again we don't like to advertise that; we try to fly under the radar. But if, for example, in this room we decided to send everybody in the company on a two months holiday,* ***I think the hybrid industry would be very hard pressed. Every hybrid car has these very large electric motors under the hood that [sic] dysprosium is one of the key ingredients that keep them operating.***
>
> *"So…* ***if China shut it down—its dysprosium output— or we shut it down—our dysprosium production—I think there'd be an army of Toyota folks trying to knock our door down.*** *There are certain key industries that are very dependent on rare earths.* ***The hybrid industry is very dependent on dysprosium as well as neodymium and neodymium-iron-boron magnets.***
>
> …
>
> *"I think the Japanese centered, neodymium-iron-boron magnet industry has been trying for a number of years to deal with the dysprosium requirement for [enabling] higher operating temperature magnets. I think the best they can do [is] somewhat reduced dysprosium levels—but these levels are not drastically different from what's being done now…. [W]hen I talk to our material scientists they really don't see a replacement for dysprosium. Not a replacement in any way that's cheaper or that works better."*
> [emphasis added]

Neo Material Technologies, Inc. *Q4 2007 Earnings Call*. (2008, March 07). Uncorrected transcript available (September 2008) at: http://seekingalpha.com/article/67658-neo-material-technologies-inc-q4-2007-earnings-call-transcript.

Japan's Institute of Science and Technology Policy (see below, note 32) concurs:

> *"[T]he importance of not only the main component neodymium but also dysprosium and terbium… added to increase the coercive force and magnetic flux density in the high-temperature region, has also increased. Dysprosium is a particular element that has become essential for enhancing these characteristics. Presently, no groundbreaking substitute magnets that can rival its high performance is [sic] found even in research stage."*

The report concludes that "it is highly unlikely that technology for substituting dysprosium…will become available in the short-to-mid term future."

21. See, for example, Arafura Resources Limited. (September 2007). *Rare Earths: An Industry at the Crossroads*. Kingsnorth, D. Available at: http://www.arafuraresources.com.au/documents/DJK-REsAnIndustryattheCrossroadsR5.pdf; Hampton, M (2008, September 18). The Realpolitic Of Rare Earths, Supply Constrained "Green" Elements. *Minesite*, Retrieved September 2008, from http://www.minesite.com/nc/minews/singlenews/article/the-realpolitic-of-rare-earths-supply-constrained-green-elements/41.html; *Great Western Minerals Group Ltd. | About Rare Earth Elements - Frequently Asked Questions*. Retrieved September 2008, from Great Western Minerals Group Ltd. Web site: http://www.gwmg.ca/rare-earths/faq;

22. See, for example, Campbell, P (2008/02). Supply and Demand, Part 1. *Magnetics Business & Technology*, *6(6)*, text available (September 2008) from Dr. Peter Campbell at: http://www.magnetweb.com/Col04.htm; *Nolans bore life of Arafura party*, op. cit; Also, Campbell, P (2008/08). Cost Benefit of Additives for NdFeB. *Magnetics Business & Technology*, *7(4)*, text available (September 2008) from Dr. Peter Campbell at: http://www.magnetweb.com/Col08.htm; also notes 23, 24 and 25 below.

The same conclusion can be found in virtually all current analyses of the neodymium and REE markets.

23. See Roskill Information Services. (2007). *The Economics of Rare Earths and Yttrium* (13th ed.). London: Summary available (October 2008) at: http://www.roskill.com/reports/rare. "With high prospects for growth in rare earth's end-use sectors, and forecast demand growth of 8-11%py, there is a pressing need for new non-Chinese capacity in the next 3 to 4 years."

Others believe that the 180,000 tonnes/year watermark will be reached in 2011 or 2012. See, for example, *Lynas Corporation Limited: Rare Earth prices off to a Gebeng*, Patersons Securities Research, (2008, May 22) accessible at http://www.lynascorp.com/content/upload/files/PSL_Brokers_Report_220508.pdf; see also Lynas Corporation. (August 2007). *Diggers and Dealers Presentation*, p. 8, accessible (Sepetember 2008) at: http://www.bourseinvestor.com/bi4/pdfnews/default.asp?d=00867240&f=20080806.

Whether this particular demand milestone is reached in

2010 or 2012, China does not have the production capacity (nor the apparent political intention) to meet it.

[24.] Treadgold, T. (2008, September 15). Rare Opportunity. *Forbes*. Available (September 2008) from: http://www.forbes.com/global/2008/0915/030.html.

About Rare Earths | Demand. Retrieved October 2008, from Arafura Resources Limited Web site: http://www.arafuraresources.com.au/market.html.

From 2005-2006 alone, China reduced its REE export quota by 10%. From 2006-2007, REE exports dropped by 15% — yet export *value* rose over 50%.

(See ResearchInChina. (2007). *China Rare Earth Industry Report, 2006*; and ResearchInChina. (2008). *China Rare Earth Industry Report, 2007-2008*. Beijing, China. Summaries available online (October 2008) at: http://www.researchandmarkets.com/reports/c53085 and http://www.researchandmarkets.com/reports/c90226 respectively.)

Also see Roskill Information Services. (2007). *The Economics of Rare Earths and Yttrium* (13th ed.), op. cit., et al.

[25.] See Campbell, P (2008/08). *Cost Benefit of Additives for NdFeB*. op. cit.

> *"But China has also been implementing a strategy to support the development of downstream rare earth industries, such as Neo magnets, and to conserve its natural rare earth resources. It is doing this by tightening control over the rare earth oxides and metals that it exports, through the imposition of higher export duties and stricter export quotas.*
>
> *For 2008, the new tariffs on exported neodymium and dysprosium are 15% and 25% respectively, and the quota for all rare earth oxides and metals is 22,780mT, about half the amount it exported the previous year; only 23 Chinese companies are now approved exporters, down from 41 in 2007. By taking these and other measures, the Chinese government has demonstrated its desire and ability to stabilize rare earth prices, albeit at relatively high levels."*

Also see Yuanta Core Pacific Securities. (May 2006). *China Rare Earth* [Company Report]. Hong Kong: Edward Fung. Available (September 2008) at: http://www.creh.com.hk/download/eng/doc_client/ResearchReport/39/ChinaRareEarth_060525_CR.pdf.

> *"We see the major risk to CRE's [China Rare Earths'] rare earth business lying on the supply side. With [the] Chinese Government stepping in to control the quantity of rare earth products, procurement of raw material will be vital. Currently, all the rare earth mines are state-owned."*

There is no prospect of that arrangement changing. Supply restrictions have become more pronounced since the report's publication.

See *supra* note 24; also below, note 31, *Richardson* op. cit.

[26.] Chinese demand, combined with rising demand from non-Chinese consumers, is setting the stage for increasingly serious supply shortfalls. See Lifton, J. (2008). *Ninja Neodymium Investors*, op. cit.

> *"There will therefore be a global shortage of rare earth metals in general, and perhaps a shortage of as much of 15,000 tonnes per annum just of neodymium in a world that may demand, on present trends, a total of 185,000 tonnes per annum of rare earths in 2014."*

[27.] Sinton, C. W. (2007). Study of the Rare Earth Resources and Markets for the Mt. Weld Complex. Retrieved September 2008, from Lynas Corporation Web site: http://www.lynascorp.com/content/upload/files/press_releases/BCC_FINAL_REPORT.pdf

[28.] *Supra* note 23.

[29.] This is clear from basic arithmetic and is the main driver of renewed investor interest in developing non-Chinese neodymium and REE sources. For one example of insider perspectives on this fact see: Treadgold, T., *Rare Opportunity*, op. cit;

Also see Khoury, A. Beware: gap in the road ahead. *Business Asia* (April 2008). Available (September 2008) from: http://findarticles.com/p/articles/mi_m0BJT/is_1_16/ai_n27946738.

For perspectives on possible Chinese responses, see notes 33 and 34 below.

[30.] Japanese companies are not sanguine about the current situation. "If the market of electric-powered vehicles is expected to grow, development of motors that use a minimum amount of neodymium and dysprosium is a must." See Kariatsumari, K (2008/08/19). Future of Electric Vehicles Lies in Parts Development. *Tech On | Nikkei Business Publications*, available (September 2008) from http://techon.nikkeibp.co.jp/english/NEWS_EN/20080819/156573/.

Also see *Benecki*, *supra* note 13.

[31.] See below, note 34.

Also: Richardson, E. Buying Magnets Overseas: A Strategic Decision. *Magnetics Business and Technology* (April/May 2008), p. 22-24. Available (October 2008) at:

http://www.magneticsmagazine.com/images/PDFs/Online%20Issues/Magnetics_AprilMay08_lowres.pdf.

Excerpt:

> *"China is the world's dominant supplier of magnets and they know it. They control the neo magnet market through the supply of the rare earth metals.... [T]he reality is that every country that supplies rare earth oxides other than China has major problems. The Australian oxides come with radioactive thorium, the Canadian source is undeveloped, and the US source has been closed for more than 10 years... Knowing this, the Chinese have raised prices of the rare earth metals sky-high and show no signs of relinquishing control of this market.*
>
> *"The evidence of China's intentions to dominate the global magnet industry is not just limited to rare earth materials either. The Chinese would very much like to control other magnet materials as well.... On Feb. 20, the Commerce Department preliminarily found that Chinese producers/exporters of flexible raw magnets have received net countervailable subsidies of more than 70 percent....*
>
> *"Clearly, the Chinese want to dominate the magnet industry, and they are willing to put enormous resources in place to do just that."*

[32.] See Kawamoto, H. (April 2008). Japan's Policies to be adopted on Rare Metal Resources. *Science & Technology Trends - Quarterly Review*. (*27*), p. 57-76, published by Japan's Ministry of Education, Culture, Sport, Science and Technology. Available online (September 2008) from the website of the Japanese government's National Institute of Science and Technology Policy: http://www.nistep.go.jp/achiev/ftx/eng/stfc/stt027e/qr27pdf/STTqr2704.pdf.

Also; *Japan, South Africa join in search for rare metals*. (2007, November 17). Kyodo News. Available (September 2008) from website of *The Japan Times* at: http://search.japantimes.co.jp/cgi-bin/nb20071117a3.html;

Nishiyama, G (2008, November 7). *Interview - Japan urges China to ease rare metals supply*. Available (September 2008) from Reuters AlertNet Web site: http://www.alertnet.org/thenews/newsdesk/L08815827.htm;

Masaki, H (2007, June 21). Japan goes prospecting for rare metals. *Asia Times (Online)*. Available (September 2008) from: http://www.atimes.com/atimes/Japan/IF21Dh01.html.

[33.] See, for example, *Baotou Rare Earth plans 300,000 tonne stockpile*. Reuters, (2008, August 26). Accessible (September 2008) at Reuters Web site: http://www.reuters.com/article/rbssIndustryMaterialsUtilitiesNews/idUSSHA478920080826.

The new Baotou stockpile is clearly sized for strategic impact. See "Rare Earths Eyed". (2008, September 1). *The Australian*, p. 30:

> *"China now controls world supply, and the [Baotou] company noted above produces most of that.*
>
> *"Some commentators are saying that to build such an inventory over five years would mean either lifting production by anything between 20 per cent and 50 per cent, or stopping all exports and perhaps even limiting supplies even to domestic producers.*
>
> *"Whatever the thinking at Baotou, it looks very much like a market power play and it will be giving rare earths customers (especially in the US military) some new frown lines."*

(See also Lifton, J (2008, September 18). Is There A Rare Earths' Renaissance? *Resource Investor*, Retrieved September 2008 from: http://www.resourceinvestor.com/pebble.asp?relid=46285.)

Analysis of China's motives for establishing a reserve of this size leads to varying conclusions. See, for example, Lifton, J (2008, August 28). China's Inner Mongolia Baotou Steel Rare-Earth Hi-Tech Co. Ltd. , *Resource Investor*, Retrieved September 2008 from: http://www.resourceinvestor.com/pebble.asp?relid=45750.

The fundamental goal driving the project may be nothing more than strategic *independence* – the capability to direct neodymium and REE market conditions, in either direction, at will.

[34.] "There is oil in the Middle East; there is rare earth in China." This declaration by Chinese Premier Deng Xiaoping in 1992 encapsulated China's awareness of the power afforded it by its REE resources.

Later Chinese Premier Jiang Zemin, in a 1999 visit to China's REE-producing Baotou region, was more explicit: "Improve the development and applications of rare earth, and change the resource advantage into economic superiority."

(See *Rare Earth: An Introduction*. Retrieved October 2008, from Baotou National Rare Earth Hi-Tech Industrial Development Zone: Web site: http://www.rev.cn/en/int.htm; and Cox, C (2006, October 10). *Rare Earth May Be China's Checkmate*. Available (September 2008) from The Anchor House, Inc. Web site: http://theanchorhouse.com/2006/10/10/rare-earth-may-be-chinas-checkmate/.)

In 1995, Magnequench, the U.S.-based division of General Motors that invented the neodymium-iron-boron magnet in 1983, was purchased by two Chinese companies (San Huan New Material and China National Nonferrous Metals Import and Export Company (CNNMIEC)), each led by a different son-in-law of Premier Deng. By 2003 Magnequench had closed all of its North American manufacturing and research facilities and moved them to China.

In summer of 2005, the now Chinese-owned Magnequench acquired Canada's AMR Technologies, one of the last North American producers of neodymium magnets and REE products. At the same time, China's state-owned CNOOC Corporation announced an all-cash bid for American-based Unocal; not only a major oil-producer but also the owner of the United States' only REE mine, Mountain Pass, California—site of the highest-grade known REE ores in the world. (Mountain Pass had been shuttered since 1998 (and remains so at publication time) by environmental regulators.) These transactions raised concerns among some U.S. politicians and regulators, and the proposed CNOOC-Unocal acquisition was eventually blocked. In the words of Carolyn Bartholomew, chairman of the U.S.-China Economic and Security Review Commission:

> *"Unocal is also the owner of the last U.S. source of rare earth minerals… We first saw China's interest in acquiring rare earth materials and bonded magnet technology when a Chinese state-owned company purchased Magnequench in 1995. Just six weeks ago, Magnequench, now a Chinese company, announced its intention to acquire AMR Technologies in Canada. With this acquisition and the acquisition of Unocal, the Chinese government will have cornered the supply of rare earth materials…"*
>
> (See *Statement of Carolyn Bartholomew* at the U.S. China Relations Seminar, (2005, July 14) hosted by the Carnegie Endowment for International Peace. Text available (September 2008) at: http://www.uscc.gov/testimonies_speeches/speeches/2005/05_07_14_carolyn_batholomew.htm.)

According to a more recent report, China is now looking to capture a stake in a prospective Canadian rare-earth producer. (Doll, C. (2007, May 7) Rare Earth in Saskatchewan: China is unlikely to welcome a made-in-Canada solution to its monopoly on rare earth metals. *Western Standard*. Available (October 2008) from: http://www.westernstandard.ca/website/article.php?id=2480.)

In each of the above two examples, China focused its sights on projects that have the *potential to become* future producers—as opposed to *being* current producers—of neodymium and other REEs; an indication of China's long-term vision of REE markets and strategic influence.

(See Lague, D. China corners market in a high-tech necessity. (2006, January 22). *International Herald Tribune*, available (September 2008) from: http://www.iht.com/articles/2006/01/22/business/rare.php; U.S.-China Economic and Security Review Commission . (2005). *2005 Annual Report* (Chapter 2, Sec. 2, p. 101). Washington D.C. Available (September 2008) at: http://www.uscc.gov/annual_report/05_annual_report.php; and Tkacik, J. J. (2008, May 2). *Magnequench: CFIUS and China's Thirst for U.S. Defense Technology*. Available (October 2008) from: http://www.heritage.org/Research/Asiaandthepacific/wm1913.cfm)

35. The temperature fragility of neodymium PMs has become a critical impediment to realizing the high fuel efficiency that hybrid vehicles are supposed to be capable of.

The Toyota Prius, for example, is required to regularly (at least every few minutes) shut down its electric motor to allow it to cool. (If the automatic cooling function fails, a hard-wired safety trip deactivates the motor when the windings reach 174°C.) The vehicle's combustion engine then provides sole power until the electric motor returns to a safe temperature, repeating in a continuous on-off cycle. These procedures are necessary to prevent severe heat-induced damage to the motor's neodymium PMs, which occurs as their Curie Temperature (T_C) is neared.

This leads to even greater operational challenges in hot weather conditions or when the electric motor is already warm. Magnetic field strength and torque output both decline as the PMs' temperature rises—another reason why the combustion engine must be frequently employed—and if the electric motor is already hot from driving, peak torque can only be applied (such as when accelerating, passing another vehicle or driving up an incline) for several seconds before the automatic temperature-limiting systems activate.

As a result of these restrictions the burden of locomotion is frequently shared with or shifted over to the Prius's combustion engine, greatly reducing vehicle fuel efficiency. The electric motor's heat sensitivity also necessitates a second, dedicated liquid cooling system in addition to the standard radiator loop which cools the internal combustion engine. Additional costly elements of modern hybrid vehicles, such as the torque-split device, can be traced back to neodymium PM-based motors' temperature fragility and resulting inability to serve as a vehicle's sole prime mover.

(See Oak Ridge National Laboratory. (2005). *Report on Toyota Prius Thermal Management* (ORNL/TM-2005/33 | 122586). Oak Ridge, TN: ORNL. Available online (September 2008) at: http://www.ornl.gov/~webworks/cppr/y2001/rpt/122586.pdf; also see U.S. Department of Energy | FreedomCAR Partnership (2006) *Electrical and Electronics Team Technical Roadmap*. Available online (October 2008) at: http://www1.eere.energy.gov/vehiclesandfuels/pdfs/program/eett_roadmap.pdf).

Significant degradation of PMs' field strength—and therefore operating capability—begins well before irreversible heat damage. "[N]eodymium magnets can lose magnetic energy at fairly modest temperatures and are operating at much less than half of their power by the time they reach 100° C to 125° C." Research programs are underway to discover some method of raising neodymium PMs' temperature resilience. (See *Hitachi Metals Develops Neodymium Magnet Material Resistant to Higher Temperatures*. (2008, June 26). The Nikkei Weekly. Available (October 2008) from Green Car Congress Web site: http://www.greencarcongress.com/2008/06/hitachi-metals.html; Also see *supra* notes 20 and 32.)

The best known proposals rely on the addition of other REEs like dysprosium to raise the PMs' safe operating temperature — meaning that even if successful, they will not resolve the underlying resource shortages that define the neodymium and REE markets.

In sum, the use of a PM-based motor as a vehicle's prime mover is fraught with performance, reliability, engineering and cost challenges, in addition to the underlying issue of supply security.

An AC induction machine (such as a Chorus Motor), however, has no such limitations aside from respecting the temperature rating of the phase insulation, which is considerably higher than the temperatures at which neodymium PMs' field strength begins to degrade. If the induction motor can generate sufficient peak torque, be economically cooled, and power electronics and manufacturing costs kept low, the above problems are largely resolved.

36. See, for example, Ogando, J (2007, November 19). Electric WheelTug System to Move Planes on the Ground. *Design News*. Available (September 2008) from: http://www.designnews.com/article/14474-Electric_WheelTug_System_to_Move_Planes_on_the_Ground.php.

The Chorus Motors at the heart of WheelTug have already moved a Boeing 767 loaded to 90% of maximum take-off weight at taxi speeds. WheelTug will be built *inside* the nosewheels of Boeing 737NG and other full-size aircraft. Video and information available (October 2008) at: http://www.wheeltug.com.