Rare Earth Elements in Transportation

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Arnold Magnetic Technologies Corporation
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CONFERENCE OF METALLURGISTS
MetSoc
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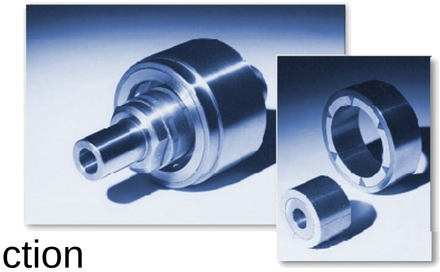
- Let’s start with a brief introduction into our company.
- Arnold was established in northern Illinois in 1895, becoming a chartered manufacturer in 1905 in Marengo, Illinois.
- We serve over 2000 customers spread across 10 market segments.

ARNOLD MAGNETIC TECHNOLOGIES

Arnold Focus

- Magnet Production
  - SmCo RECOMA® - (Lupfig, Switzerland; Rochester, NY; Ganzhou, China)
  - Alnico, cast and sintered - (Marengo, IL)
  - Ferrite (Bonded) - (Marietta, OH; Norfolk, NE)
  - Injection Molded - (Shenzhen, China)
  - Electrical Steels - ARNON ® (Marengo, IL)
  - Electromagnets - (Ogallala, NE)



- Fabricated Magnets
  - Slice, grind, EDM
- Assemblies / Value Added Production
  - Precision machining centers for magnets and non-magnetic components
  - Precision assembly
    - Complex magnet and assembled shapes
    - Magnetized / un-magnetized assembly
    - High temperature and specialized adhesives
  - Encapsulation / sleeving
  - Rotor Balancing

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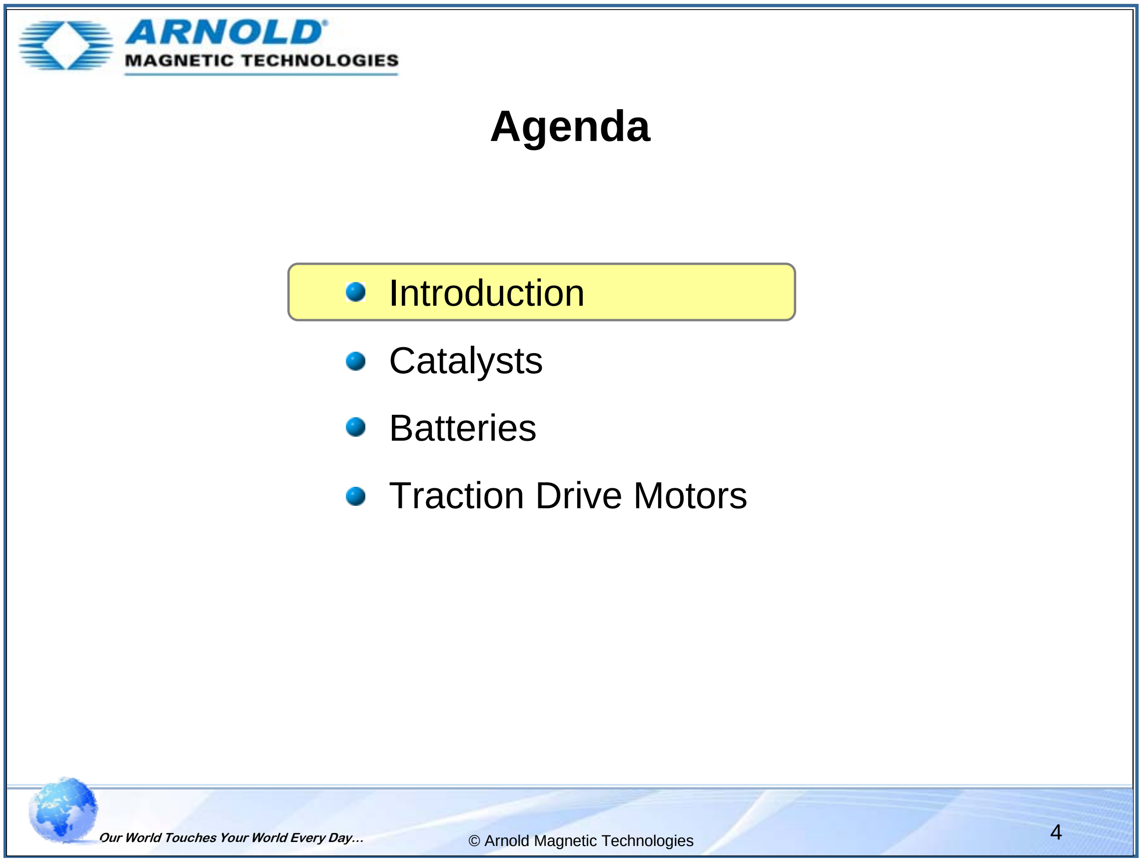
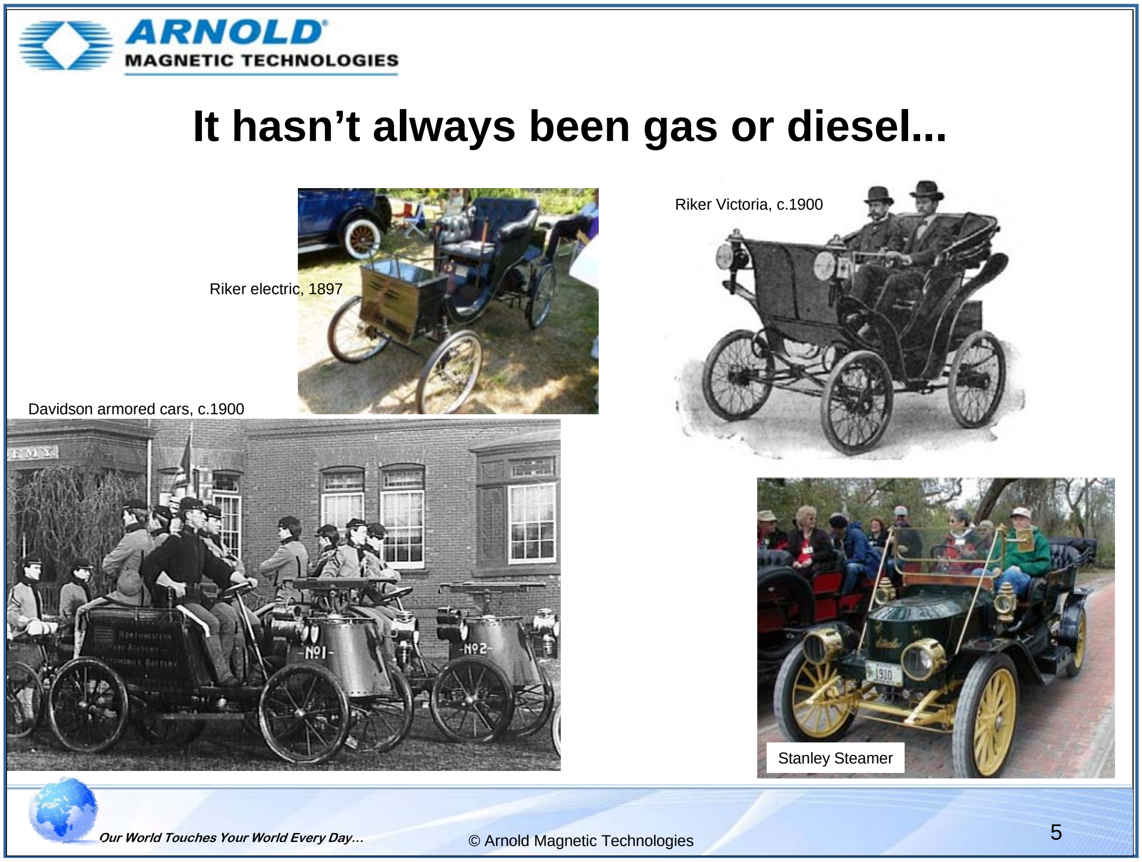
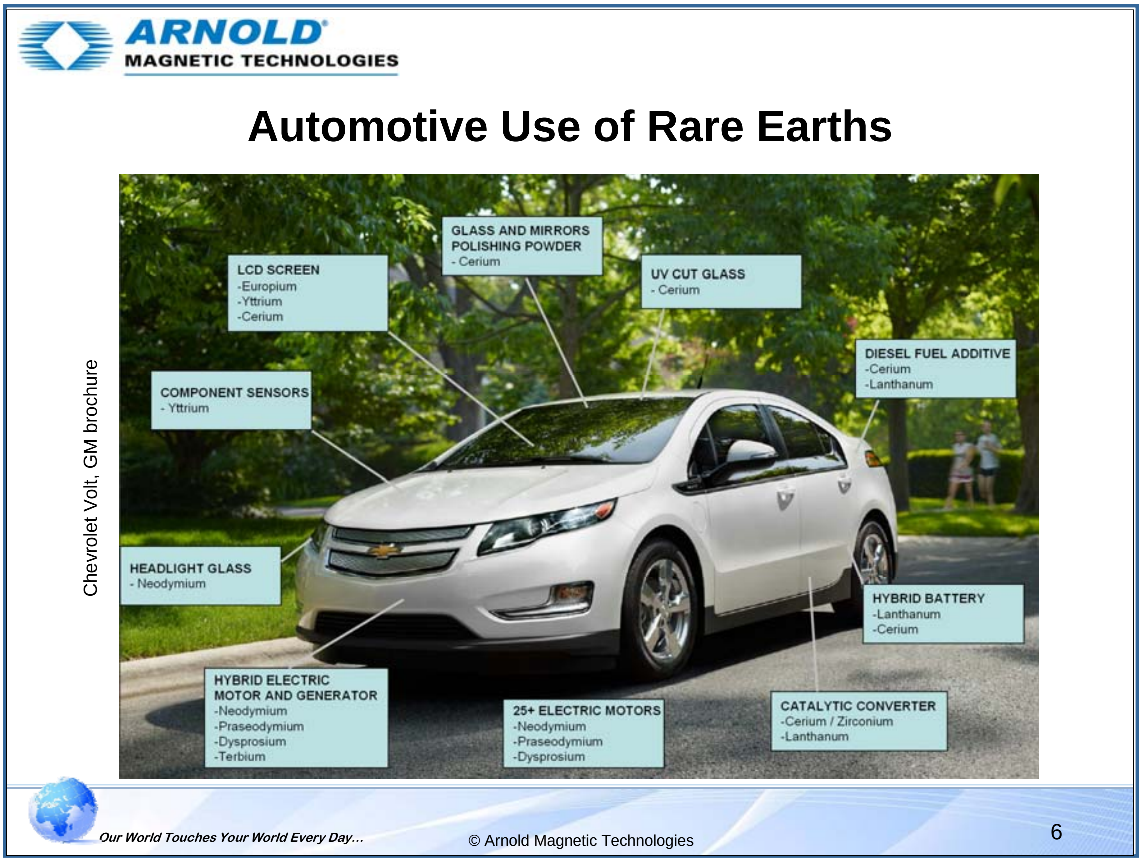
- This is the business focus of Arnold today and is a summary of the manufacturing conducted at Arnold's 10 factories.
- It includes vertically integrated manufacture of a number of magnetic materials with an emphasis on higher technology projects and precision machined components.



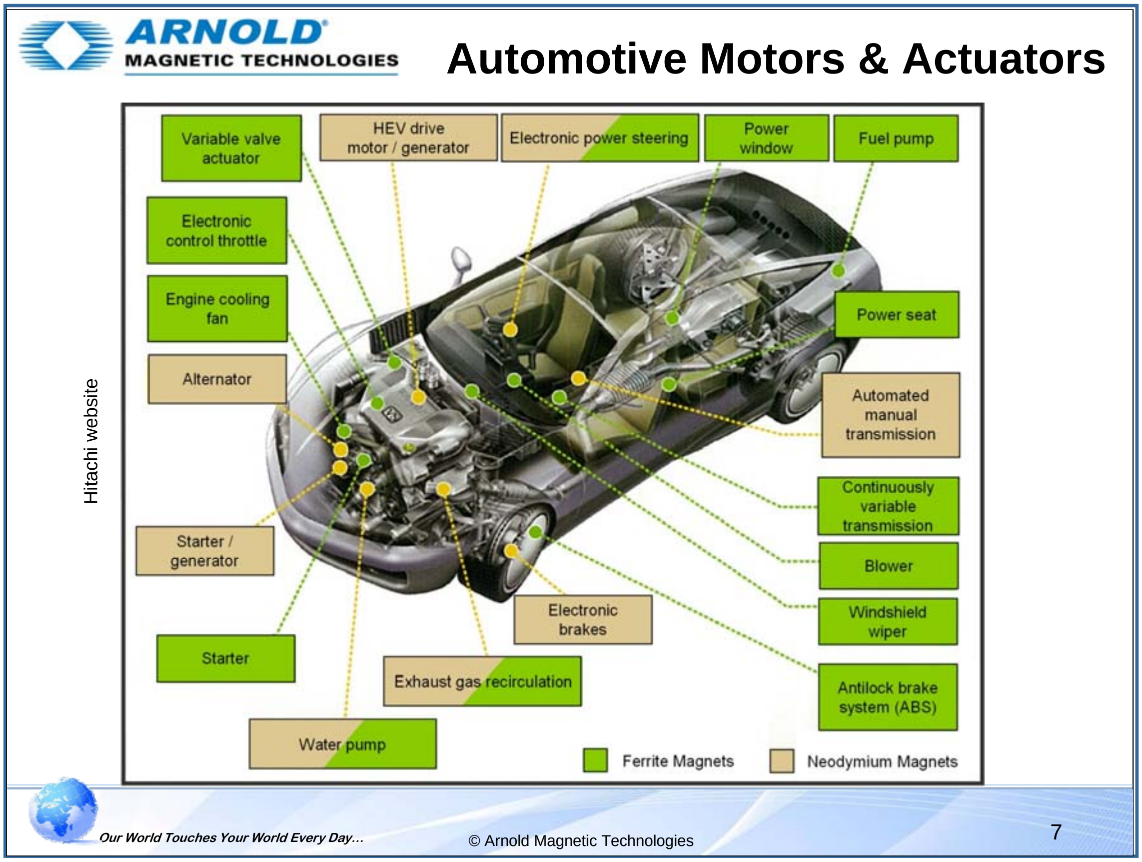
- Rare earth oxides, metals and alloys are contained in automotive equipment but are also used in the manufacturing process for components for the transportation industry.
- Due to time constraints, we will focus today on these three applications for rare earths: catalysts, batteries and drive motors.



- Many of us might believe that electrically driven vehicles are rather new or that the auto industry has always been dependent upon gasoline.
- However, some of the earliest vehicles were driven by steam.
- Furthermore, electric cars were found in Europe and North America in the 1800s.
- The discovery of oil in the USA in 1859 and subsequent development of the oil and gas industry "fueled" the North American industrial revolution and permitted growth of the internal combustion engine as a drive system of choice on cars and trucks.
- "The 19th century was a period of great change and rapid industrialization. The iron and steel industry spawned new construction materials, the railroads connected the country and the discovery of oil provided a new source of fuel. The discovery of the Spindletop geyser in 1901 drove huge growth in the oil industry. Within a year, more than 1,500 oil companies had been chartered, and oil became the dominant fuel of the 20th century and an integral part of the American economy." History.com
- The energy content and convenience of liquid fuel caused the ICE (internal combustion engine) to substantially replace alternative drive systems, including steam and electric, examples of which are shown in these early photographs.



- In this illustration of the Chevy Volt, GM shows us the diversity of rare earth content in vehicles and also many requirements for rare earths during processing of components.
- We see, for example, that rare earths are used not only to polish glass but to modify the light transmission characteristics (neodymium) of glass.
- Rare earths are used in the catalytic converter and also in refining the gasoline used to fuel the ICE (internal combustion engine).
- There has been a transition from mechanical linkages to “drive-by-wire” technology. This requires sensors (many use rare earth magnets including SmCo magnets), wires to transmit the signals, a computer to analyze input and provide output, and motors and actuators to act on the signal from the computer.
- Where a traction drive motor is utilized, a second, higher voltage battery is utilized. Hybrid vehicles have used NiMH batteries containing lanthanum and cerium (e.g., the Prius). There is a conversion to lithium-ion battery technology taking place but some vehicles still use the proven NiMH battery technology. Furthermore, end-of-battery-life replacement will require the same battery type. With over one million batteries in commercial use, the replacement market should be sizable.



- This illustration from Hitachi provides applications and likely magnet type(s) with green representing ferrite and tan representing rare earth magnets, most of which are neodymium iron boron, though some SmCo magnets are used, especially in sensors.
- When a motor is mentioned, most of us will immediately think of a device that drives a spinning shaft, but there are linear motors as well, such as door lock actuators and entertainment system speakers.
- However, many of the vehicular systems still rely on ferrite magnets as they are less expensive and naturally corrosion resistant, for example to road salt.
- Newer grades of ferrite magnets include minor amounts of lanthanum and cobalt to improve magnet performance by about 25%.

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Distribution of Rare Earth Oxide consumption by market in 2008

Rare Earth Oxide	Catalysts FCCs	Catalytic Converters (auto)	Ceramics	Glass industry	Metallurgy except batteries	Neodymium magnets	Battery alloys	Phosphors	Other	Total
	Catalysts					*Motors*	*Batteries*			
Cerium	1,980	6,840	840	18,620	5,980	-	4,040	990	2,930	42,220
Dysprosium	-	-	-	-	-	1,310	-	-	-	1,310
Europium	-	-	-	-	-	-	-	441	-	441
Gadolinium	-	-	-	-	-	525	-	162	75	762
Lanthanum	17,800	380	1,190	8,050	2,990	-	6,050	765	1,430	38,700
Neodymium	-	228	840	360	1,900	18,200	1,210	-	1,130	23,900
Praseodymium	-	152	420	694	633	6,140	399	-	300	8,740
Samarium	-	-	-	-	-	-	399	-	150	549
Terbium	-	-	-	-	-	53	-	414	-	467
Yttrium	-	-	3,710	240	-	-	-	6,230	1,430	11,600
Other oxides	-	-	-	480	-	-	-	-	75	555
Total	19,800	7,600	7,000	28,400	11,500	26,300	12,100	9,000	7,500	129,000
	21%					*20%*	*9%*			

Values are rounded

Rare Earths Elements - End Use and Recyclability - USGS, Table 2, Page 5, USGS

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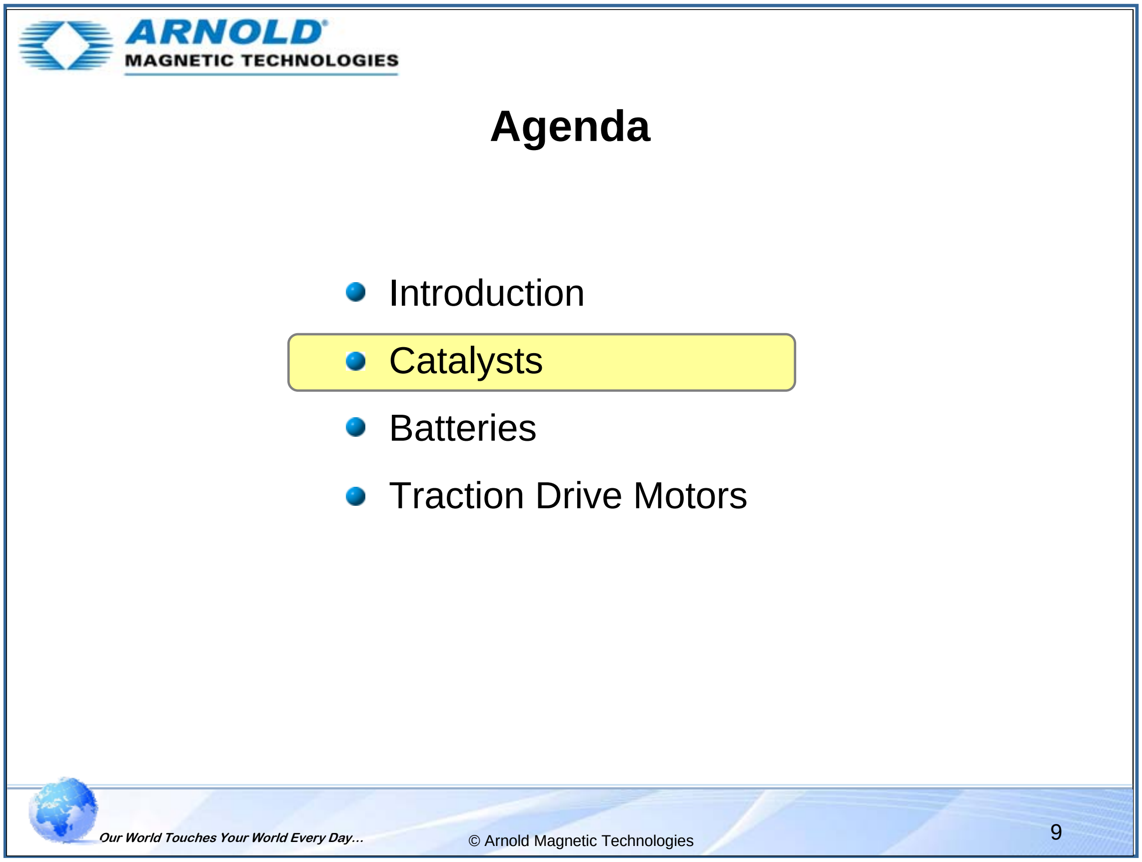
- The USGS published figures on use of rare earths in various market segments.
- Highlighted here are the three segments we'll be exploring further today and their approximate share of the total rare earth materials market.
- Together they represent approximately one half of the market.



- So, as time is critical, we’d better “get cracking”.

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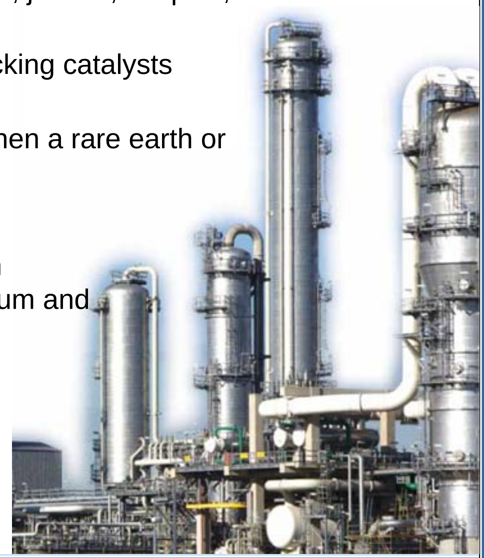
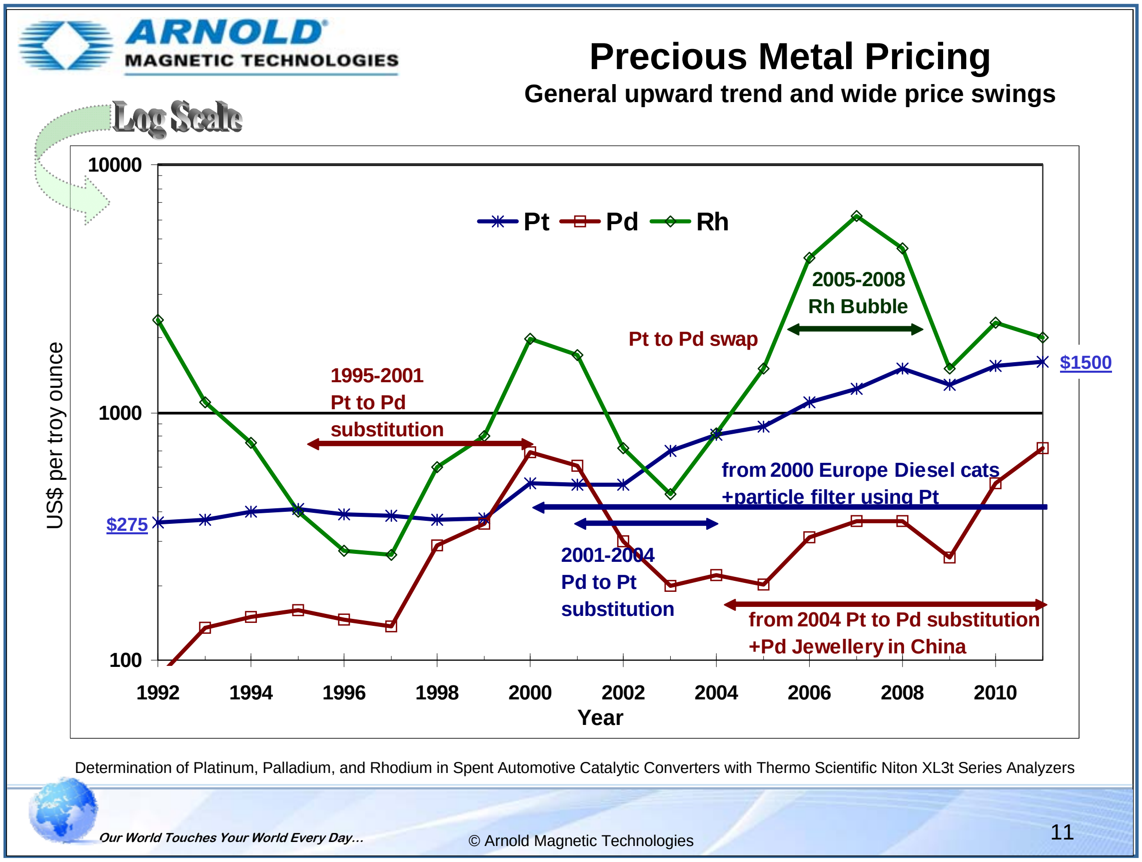
Catalysts

- Fluid Cracking Catalysts
  - Used in the petroleum-refining industry to convert heavy crude oil into gasoline, diesel fuel, kerosene, jet fuel, lamp oil, chemicals, etc.
  - Rare earth oxides are added to zeolite cracking catalysts through ion exchange
  - Refiner-specific requirements determine when a rare earth or non-rare earth catalyst is used
- Vehicle Exhaust Catalytic Converters
  - CeO_2, La_2O_3 and Nd_2O_3 in conjunction with platinum-group elements (platinum, palladium and rhodium)
  - Convert hydrocarbons, aldehydes, carbon monoxide into carbon dioxide, water vapor, nitrogen, and oxygen



References:
http://apps-stage.catalysts.basf.com/Main/precious_base_metal_services/refining.be
http://www.catalysts.basf.com/p02/USWeb-Internet/catalysts/en/content/microsites/catalysts/prods-inds/mobile-emissions/gas-engines

- There are two main catalyst applications for transportation: 1) fluid cracking catalysts (FCCs) for producing fuels from crude oil and 2) catalysts used in catalytic converters (CATCONs) to reduce exhaust pollution.
- Each application has traditionally used three precious metals: platinum, palladium and rhodium.
- Due to these materials' costs (and rarity), rare earths were introduced into the formulations.



- Each of the precious metals has experienced both overall increase in cost and noticeable rapid, sizable changes in pricing.
- The combination of cost increases and volatility drove the substitution of rare earths into the catalyst formulations.

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Fluid Catalytic Cracking (FCC) Catalyst Optimization to Cope with High Rare Earth Oxide Price Environment

Introduction

"The use of rare earths in FCC catalysts was driven by the need for more active and hydrothermally stable products with better yield performance. Rare earth oxides (REO) achieved these goals by enhancing catalytic activity and preventing loss of acid sites during normal unit operation. To address the specific needs of each FCC unit, catalyst manufacturers formulate catalysts with various rare earth levels that allow for optimal unit performance. The level of REO in a specific catalyst formulation is determined by operational severity and product objectives. As the need for increased amounts of gasoline grew over time, refiners tended to increase the level of rare earths in their catalyst formulation to meet their profitability targets. Rare earth gradually increased over the years and at the end of 2010, the average was 3%, with several refineries running in excess of the average."

How Rare Earth Affects FCC Catalyst Performance

"When considering a move to reduce REO component in the catalyst, it is critical to grasp the performance shifts and economic impact of such a change. The economic impact comprises two aspects. It is a function of total catalyst cost and the value created from a given catalyst formulation. Reducing the rare earth level will have an immediate cost saving, but this calculation alone will not give the true profit generation picture if the margin benefits from the yield slate are not included."

Better Performance

Better cost-benefit

http://www.catalysts.basf.com/p02/USWeb-Internet/catalysts/en/function/conversions:/publish/content/microsites/catalysts/prods-inds/process-catalysts/**BF-9626_US_REAL_Technical_Note.pdf**

- Now that we have also experienced a dramatic short term swing in rare earth material pricing, a re-examination has taken place regarding rare earth use in catalysts.
- Bottom line is that while catalysts can function without rare earths, they offer performance enhancement that will make their elimination difficult.

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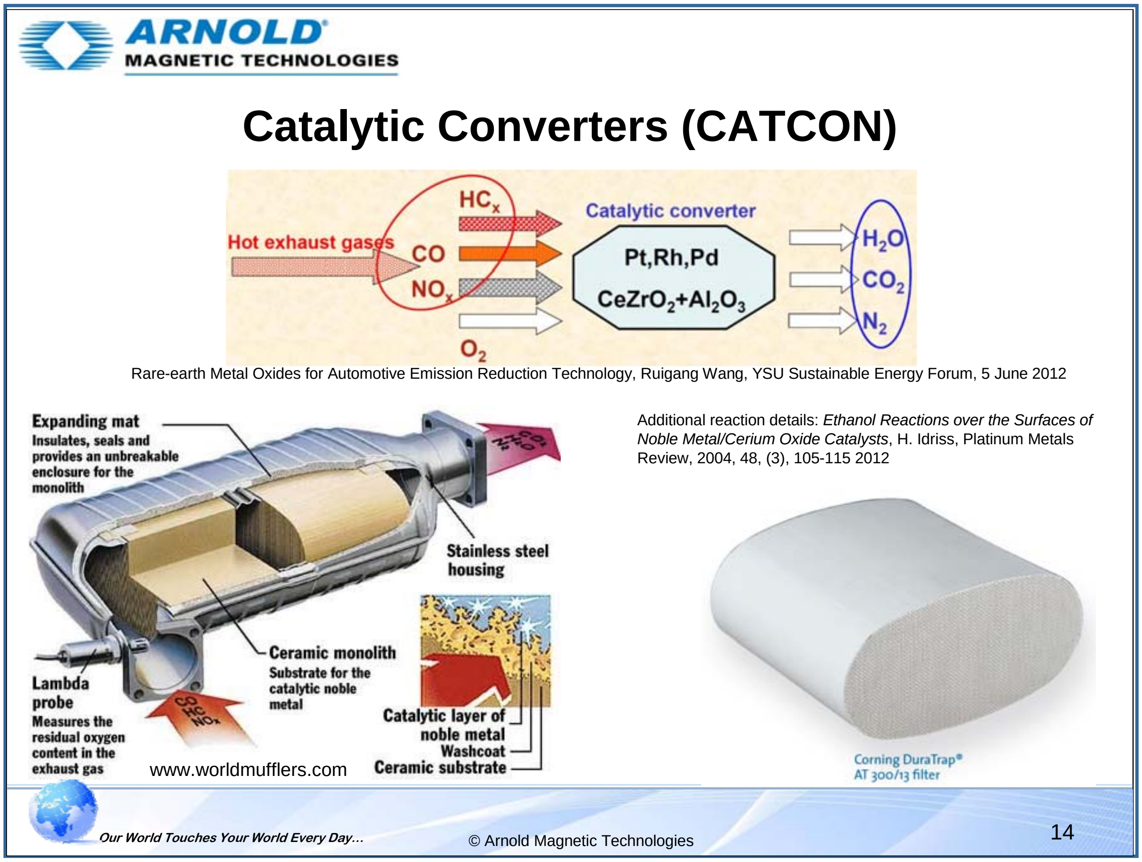
REEs in FCCs

Rare earth elements (REEs) play an important role in petroleum refining. Lanthanum and cerium are used as additives for fluid catalytic cracking (FCC), a key process in gasoline production. These REEs increase gasoline yield and reduce air emissions from the oil refining process. A modest reduction of rare earth supply would not likely have a large impact on gasoline supplies or prices. The unprecedented increases in rare earth oxide (REO) costs during the past year have likely added less than a penny to the price of gasoline. However, current high REO prices are providing incentives for catalyst manufacturers to develop catalysts with low or near-zero rare earth content. Under more extreme conditions, with a sudden loss of significant rare earth supply, gasoline production per barrel of oil would decline, but with weak gasoline demand in the Atlantic Basin expected for several years, overall refinery capacity should still be adequate to meet demand.

Higher rare earth cost has little effect on gas prices and alternatives do exist should there be a total curtailment

DOE Critical Materials Strategy, 2011, http://energy.gov/sites/prod/files/DOE_CMS2011_FINAL_Full.pdf, page 14-15

- And, as Diana Bauer of the US DOE points out, the higher rare earth cost has had negligible affect on fuel pricing.



- What exactly is the function of the CATCON?
- As shown in this graphic, the variable valence state of cerium facilitates completion of the reaction of partially combusted output gases.
- Other CATCON structures are used, but the honeycomb structure is most common.
- Corning, Inc, a manufacturer of CATCON substrates has announced the construction of a new factory for the production of CATCONs targeted at the diesel engine market for North America.

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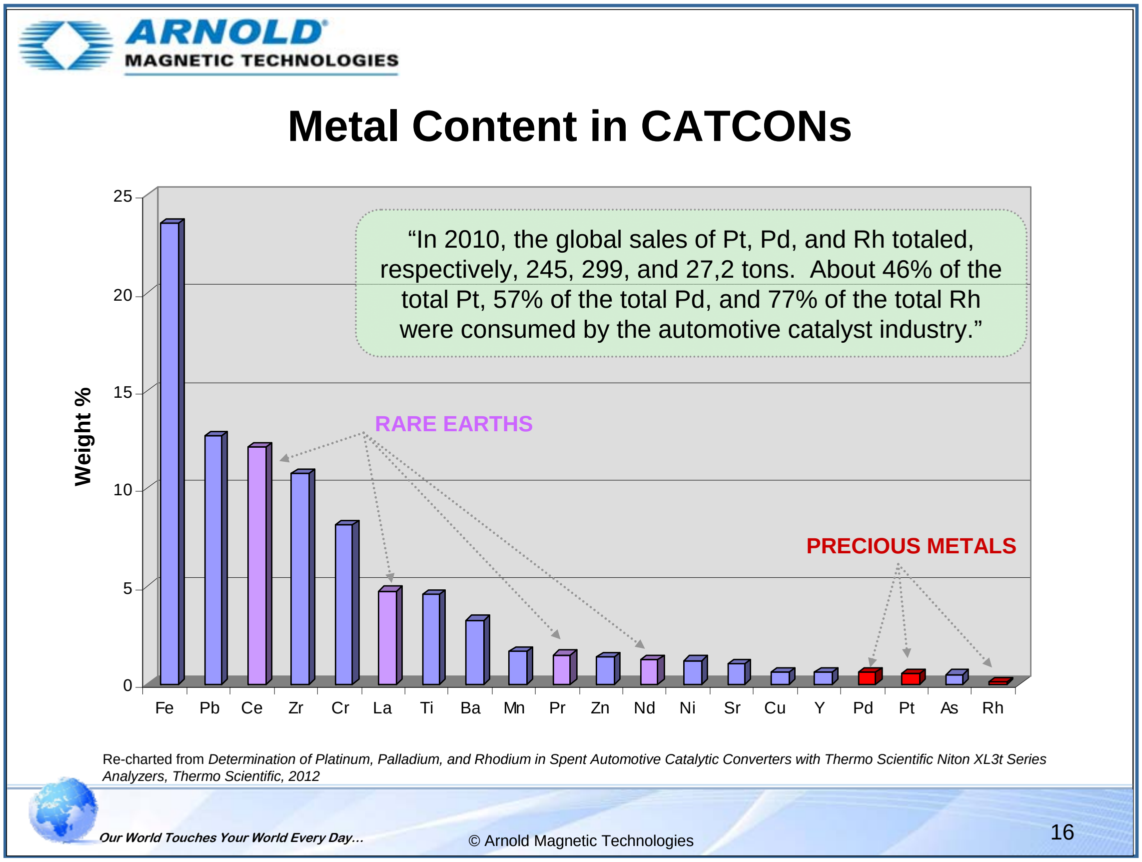
"Rare Metal" usage in catalytic converters

> "There is simply not enough platinum and rhodium going round on this planet to satisfy the collective demand of automotive emission-control systems and all of these other areas."

Johannes Schwank, 2007, a chemical engineer at the University of Michigan in Ann Arbor

- However, as we produce more and more cars and trucks, it is becoming evident that… (see quote).
- Therefore, rare earths will play an increasingly important role in catalysis.



- Recycling of CATCONs is necessary to re-capture precious metals and rare earths.
- This is accomplished by crushing the CATCON, separating the precious and rare earth metal content (to the extent economically and technically possible) adding additional fresh catalyst content and applying the mix to new CATCONs.
- The chart shows the chemical analysis of crushed CATCONs for recycling and includes at least some of the matrix material.
- What we see is the large percentage of rare earth use relative to the precious metals.

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CATCON Recycling

Table 1. Estimated amount of cerium oxide contained in catalytic converters in the United States in 2010 and potentially recoverable cerium oxide equivalents.

[Estimates are based on one catalytic converter per vehicle. Calculated estimates for cerium oxide and cerium oxide equivalents are rounded to two significant figures. CATCON, catalytic converter]

Source category	Number of vehicles[1] (millions)	Amount of cerium oxide per catalytic converter (grams)	Total amount of contained cerium oxide (metric tons)	Amount of potentially recoverable cerium oxide equivalents[2] (metric tons)
Vehicles in use in 2010:[3]				
Cars and light-duty trucks	230.4	80	18,000	8,800
Heavy-duty vehicles	11.62	100	1,200	590
On-highway motorcycles	8.212	23	190	93
Total	250.2		19,000	9,500
New vehicles and CATCONs sold in 2010:				
New cars and light-duty trucks[4]	11.39	80	910	450
New heavy-duty trucks[5]	0.379	100	40	20
New on-highway motorcycles[6]	0.307	23	7.1	3.5
New aftermarket CATCONs[7]	2.5	80	20	9.8
Total	14.58		980	480
From scrap and other sources in 2010:				
Cars and light-duty trucks scrapped[8]	10.63	80	850	420
CATCONs from replacement and other sources[7]	2.5	80	200	98
Total	13.13		1,100	520

Potential for Recovery of Cerium Contained Automotive Catalytic Converters, Donald Bleiwas, U.S. Geological Society, 1-1-2013
http://digitalcommons.unl.edu/usgspubs/114

- In Don Bleiwas' report (reference is at bottom of slide), he calculates the potential for recycled cerium oxide for 1) all vehicles in-use, 2) for only 2010 vehicles and 3) from scrapped equipment.
- Note that these figures apply only to the USA and represent total available "Ce-oxide equivalent" rare earth.
- Annual recycling will be a fraction of the total vehicles in use.
- Amount potentially recoverable derives from a 70% recycle rate and 70% recycle yield.

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Notes for Table 1

[1]Rounded to the nearest thousand, except for new aftermarket CATCONs, which was rounded to two significant figures.

[2]Estimate based on 70-percent capture of CATCONs recovered from vehicles classified as scrappage and 70-percent metallurgical recovery. Scrapped vehicles were defined by the National Automobile Dealers Association as those vehicles no longer registered from a previous year. Vehicles may be re-registered at a later time, exported, or delivered to parts and scrap dealers.

[3]Source: U.S. Department of Transportation, Research and Innovative Technology Administration, 2011.

[4]Source: WardsAuto.com, 2012.

[5]Source: Davis, Diegel, and Boundy, 2011.

[6]Source: Chung, 2012.

[7]National statistics on the aftermarket sales and recycling of CATCONs were not available; however, it was reported that 880,000 new aftermarket CATCONs were sold in California during 2007 (Ozone Transport Commission, 2011). Based on the sales data in California, it can be grossly estimated that 2.5 million new aftermarket CATCONs containing 80 grams of cerium oxide in each converter were installed in vehicles in 2010 and that an equal number became potentially available for recycling.

[8]Scrappage is defined as the number of registered vehicles with major damage—from an accident or flood, for example—and vehicles that have not been registered within 1 year. If a vehicle is re-registered, it is added back to the approximation of the number of vehicles in use (National Automobile Dealers Association, 2011). Some of these vehicles, and the CATCONs installed in them, may not be immediately available for recycling if they are exported out of the country, remain idle, or are placed back into service. The estimate does not represent the actual number of vehicles that enter the recycling stream by being dismantled for parts or shredded; that information was not available. Statistical data related to scrappage of heavy-duty vehicles and motorcycles were also not available.

Catalyst Summary

- Rare earth additions to FCCs and CATCONs reduce the demand for precious metals
- In addition to substituting for precious metals, RE additions in FCCs improve cracking and separation for obtaining select output materials
- Recycling is currently done for the precious metals, not for the relatively abundant Cerium and Lanthanum

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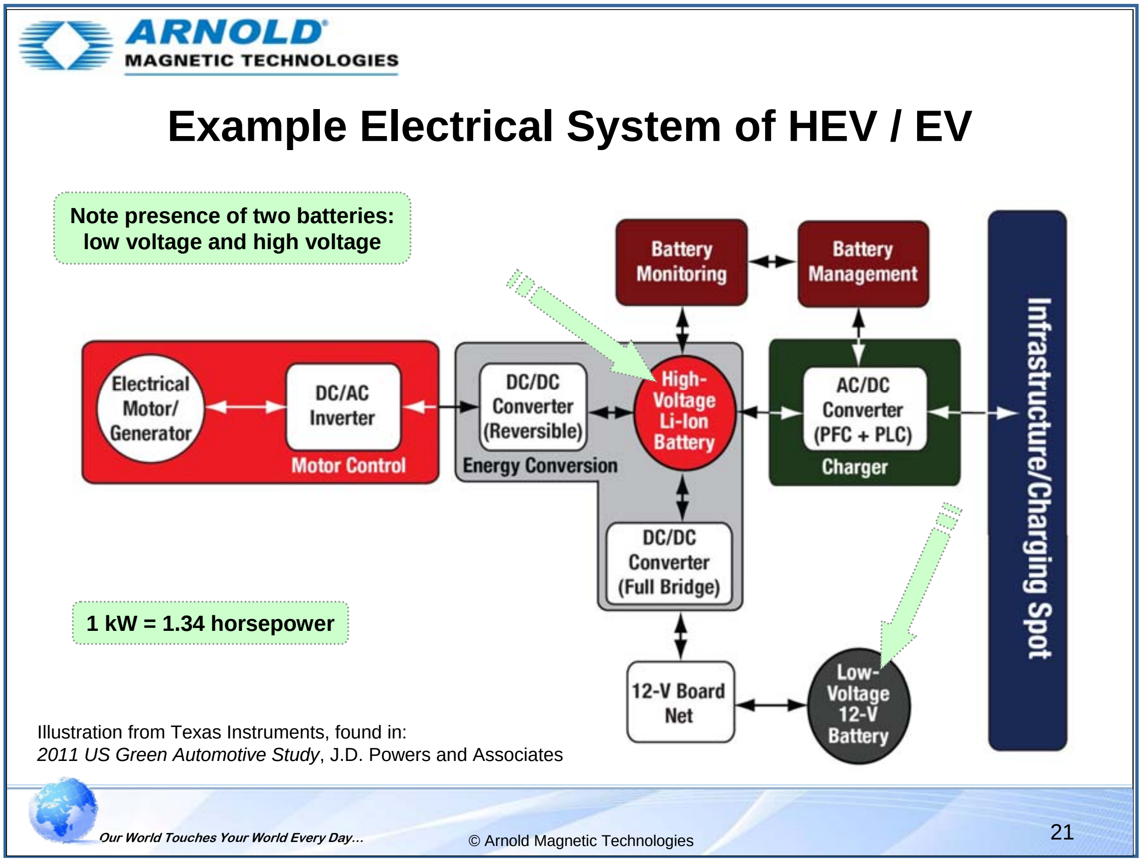
Agenda

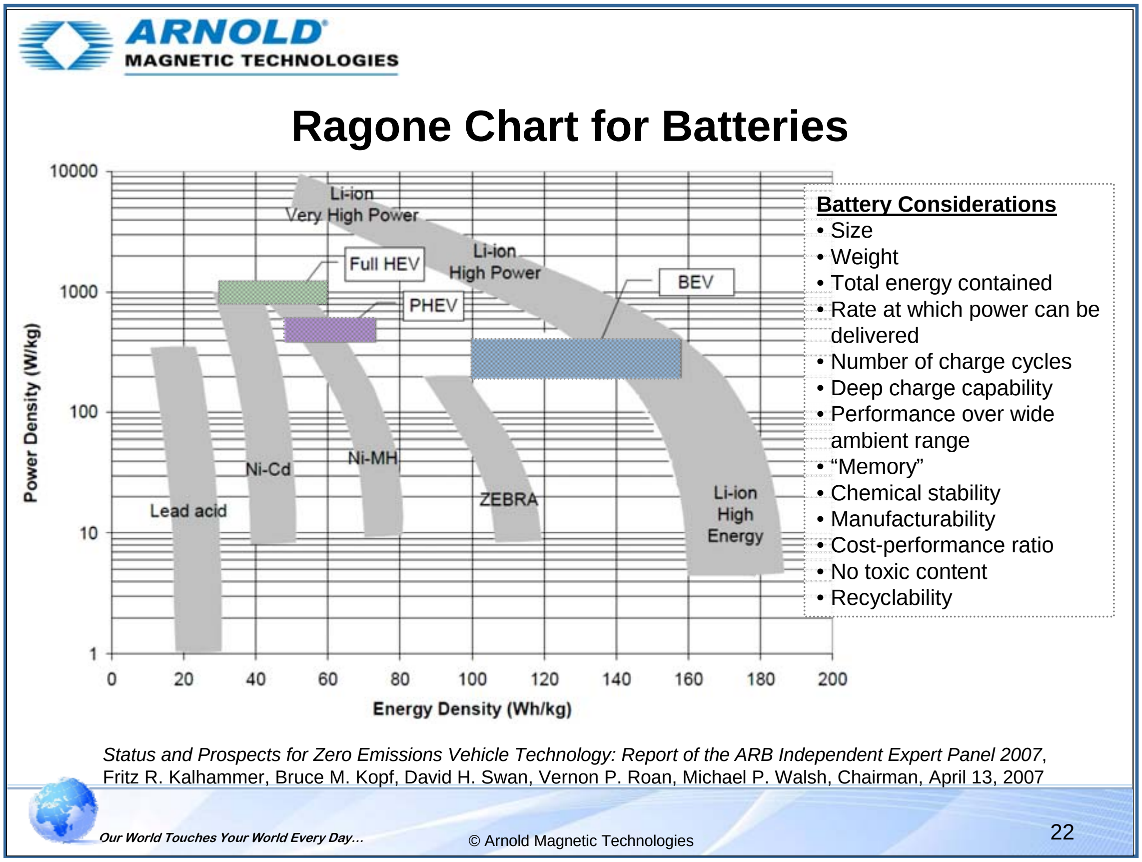
- Introduction
- Catalysts
- Batteries
- Traction Drive Motors



- Hybrid drive systems are complex with dual voltage systems, charging circuits, and battery management.
- High voltage systems (100 to 350 volts or more) present safety problems and repair worker training requirements.
- Vehicle accident and rescue personnel require training in driver extraction from damaged vehicles to avoid electrocution.

For comparison…

- Home electric power usage is 3 to 10 kW versus traction drive motors of 20 to over 100 kW.



- The Ragone chart, named after David Ragone, is a chart used for performance comparison of various energy storing devices.
- On such a chart the values of energy density (in Wh/kg) are plotted versus power density (in W/kg).
- One or both axes are logarithmic, which allows comparing performance of very different devices (for example extremely high, and extremely low power).
- Battery requirements for three electric vehicle types are indicated on this plot by dark colored rectangles.
- Full electric (battery electric) vehicles are dependent upon the higher energy storage of Li-ion batteries while PHEV and HEV vehicles can use NiMH batteries.

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Batteries in Hybrid Vehicles

Attribute (Year / Mfg / Model)	2004 Toyota Prius	2006 Lexus RX 400h	2006 Honda Civic	2007 Toyota Camry	2007 Nissan Altima	2008 Chevrolet Tahoe	2010 Toyota Prius	2010 Honda Insight	2010 Ford Fusion	2010 Mercedes-I S400	2011 Hyundai Sonata	2011 Honda CRZ
Battery Type	NiMH	NiMH	NiMH	NiMH	NiMH	NiMH	NiMH	NiMH	NiMH	Li-Ion	Li-polymer	NiMH
Number of Modules	28	30	22	34	34	240	168	84	204	32	72	84
Battery Weight	29.4	-	-	160	160	145	64.7	65	-	-	96	65
Rare Earth Weight**, kg	8.8	-	-	48.0	48.0	43.5	19.4	19.5	-	-	-	19.5
System Voltage	201.6	288	158.4	244.8	244.8	288	201.6	100.8	275	126	270	100.8
Peak Capacity, Ah	6.5	6.5	5.5	6.5	6.5	5.76	6.5	5.75	5.5	6.5	5.3	5.75
Motor Size, kW	50	123 + 50	15	105	105	120	60	10	60	15	30	10
Fuel tank, gal	11.9	17.2	12.4	17.2	20	24.5	11.9	10.6	17.5	23.8	17.2	10.6
Driving Range*, miles	628	558	690.7	779.2	860	596	774	585	837	643	-	471
Fuel efficiency*, mpg	53	32	56	45	43	24	65	55	48	27	-	44

*Driving range and fuel efficiency w/o using accessories
** Estimated rare earth metal weight from approximate battery composition percent of total battery weight

- This table showing several vehicles from many manufacturers and over seven years presents the dominance of NiMH batteries through 2010.
- Several vehicle models are now using Li-ion batteries and new vehicles are expected to depend increasingly on Li-ion.
- Each battery "pack" is comprised of numerous modules.

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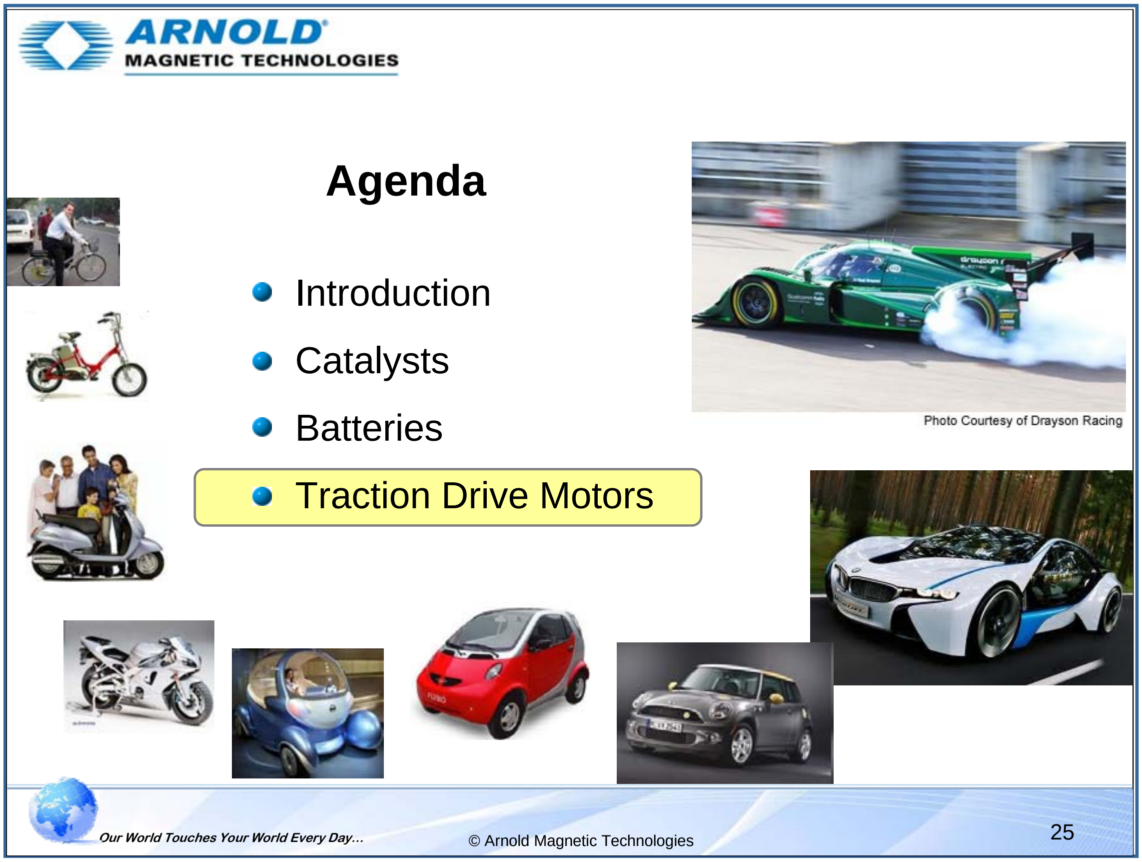
Battery Summary

- Li-ion is starting to replace NiMH on new applications
- Large number of existing NiMH batteries provides a sizable replacement market
- Additional battery development is required for wide acceptance of BEV technology
  - Reduced battery cost/unit of power output
  - Larger battery for extended range capability
  - Elimination of “range anxiety”



- Drive motors in transportation range from pedal-assist motors on bicycles to high performance motors in dragsters.
- Electric vehicle size ranges from under 100 pounds to over several tons.

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Comparison of Traction Drive Motor Technologies

	Permanent Magnet Motor	Induction Motor	Reluctance Motor
Cost ($/kW)	$$$	$$	**$**
Power density (kW/L)	**Highest**	Moderate	Moderate
Specific power (kW/kg)	**Highest**	Moderate	Moderate
Efficiency (%)	**Best**	Good	Better
Noise and vibration	Good	Good	Unacceptable
Manufacturability	Difficult	Mature	**Easy**
Potential for technical improvement for automotive applications	Significant	Minimal	Significant

Comparison of traction drive motor topologies – L. Marlino, ORNL

4-cylinder ICE

Electric traction drive motor

Wikipedia:
English Toyota 1NZ-FXE 1.5L Straight-4 Engine and Electric-Drive Motor
Date 22 August 2008
Source Own work
Author Hatsukari715

- Although other motor topologies are used, permanent magnet motors offer the optimal combination of performance (efficiency) versus cost.

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Material Usage in Motor Applications

Temperature and general applicability

Motor Application	Temperature, °C Min	Max	Primary Mat'l Applicability Alnico	Ferrite	NdFeB	SmCo
Transducers/Loudspeakers	0	80	x	x	x	
Motors – Consumer and electronics	0	100		x	x	
Motors – HVAC	0	110		x	x	
Motors – Industrial	-40	150		x	x	x
Motors – Electric bicycles	0	150		x	x	
Motors – Traction drives	-40	180			x	
Motors – Traction drives, PM assisted	-40	180		x	x	
Motors – Specialty (Superchargers)	-40	220				x
Motors/generators – Aerospace	-60	220				x

Transportation related

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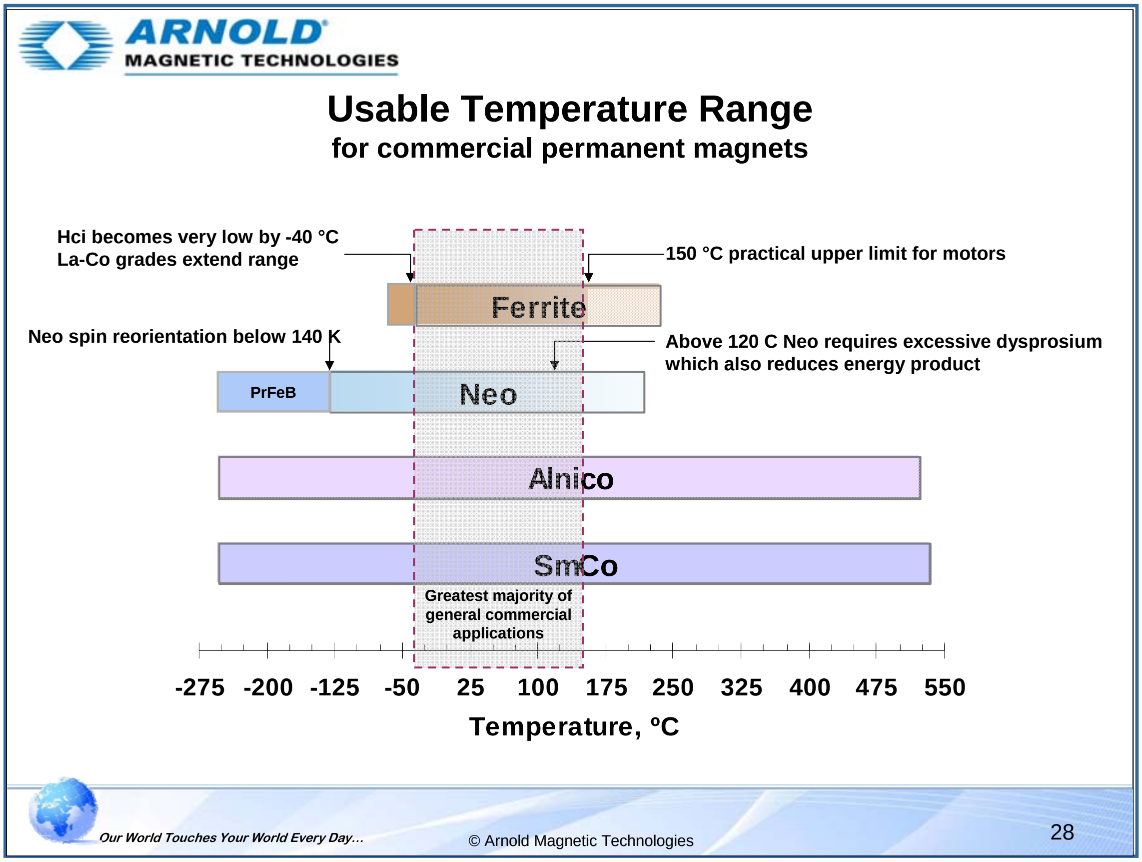
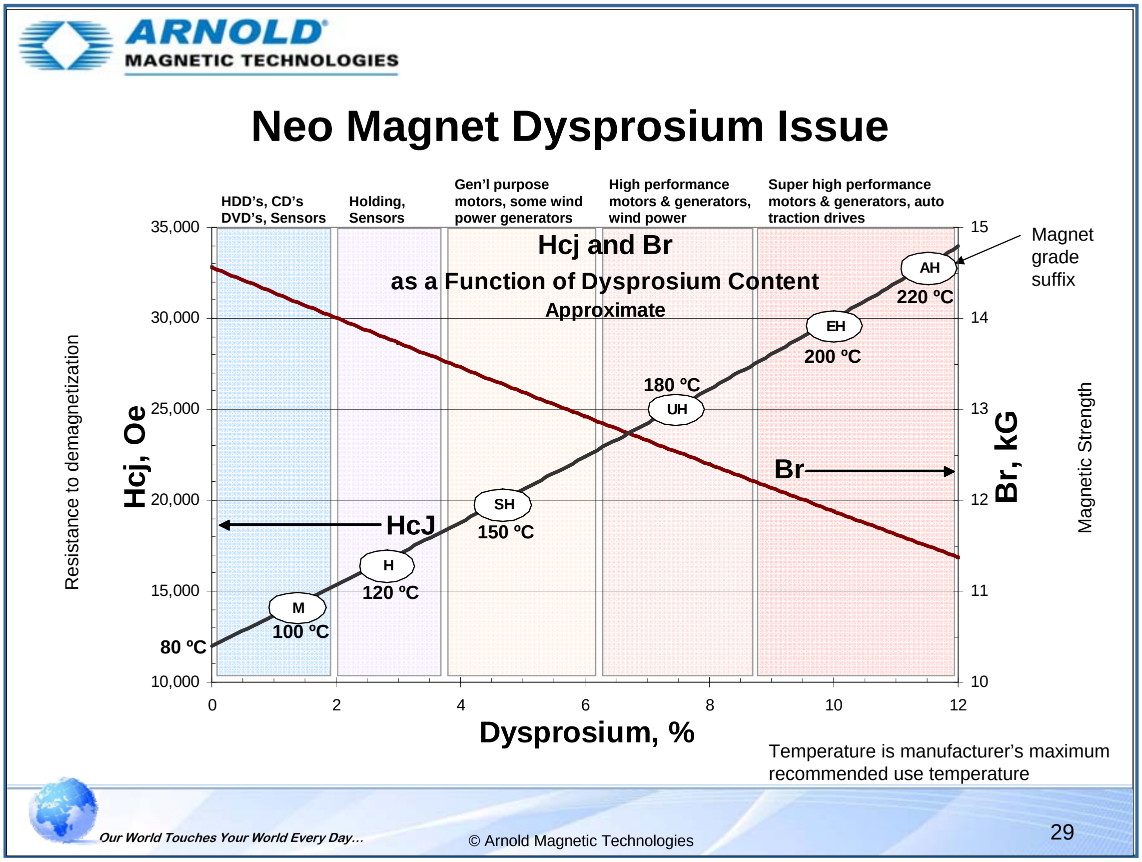
- Motors are the single largest application for both ferrite and rare earth permanent magnets.
- This chart presents the more commonly used permanent magnets for each application with vehicular transportation highlighted.



- A key characteristic in selecting the best magnet is the temperature range of the application.
- We note here that both Neo and ferrite magnets have a more limited useful temperature range than SmCo and alnico.
- Ferrite can be theoretically used to over 250 ºC. However, even by 150 ºC, it loses 25% of its flux output and that is the practical upper temperature limit for ferrite magnet applications.
- Neo is not naturally a high temperature magnet material - we try to make it work at high temperatures by substituting dysprosium for some of the neodymium.



- In order to get a Neo magnet to resist demagnetization, it has been necessary to add HREs, heavy rare earths (dysprosium and/or terbium), to the composition.
- Dysprosium is preferred as it is more available and lower cost than terbium.
- While permitting use of Neo magnets at higher temperatures, use of HREs results in a reduction in Br and maximum energy product (BHmax).
- Some typical applications are shown for each range of material grades.

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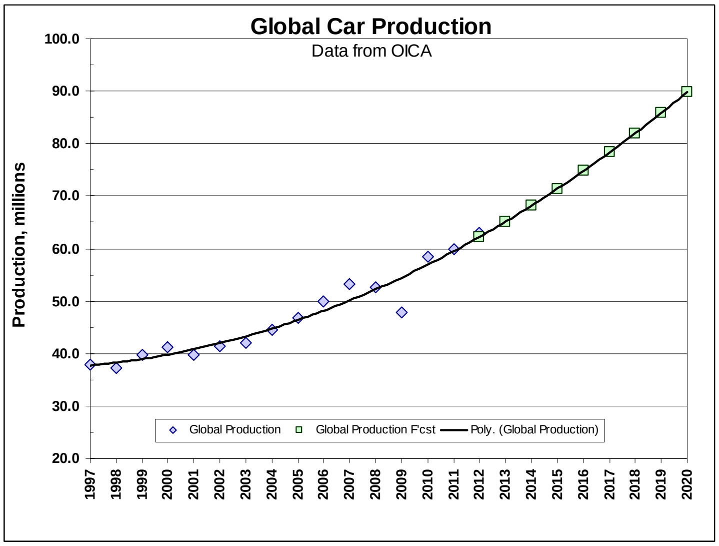
Rare Earth Requirements



http://www.oica.net/category/production-statistics/

Traction Drive Motor Only

Year 2020 Forecast Quantities

90,000,000		cars produced in 2020
10%		percentage Hybrid and EV
9,000,000		hybrid and EV
1	kg	Magnet weight per car, average
9,000,000	kg	total magnet weight
9000	tonnes	total magnet weight
32%		Total RE Content, metal
26%		Nd + Pr content
6%		Dysprosium content
2340	tonnes	weight Nd + Pr
540	tonnes	weight Dy
97%		melt yield
82%		oxide to metal yield
85%		magnet mateiral yield
68%		net yield
3,461	tonnes	weight Nd + Pr oxide
799	tonnes	weight tonnes oxide

% of 2010 reported production
Nd + Pr = 13.4%
Dy = 49.9%

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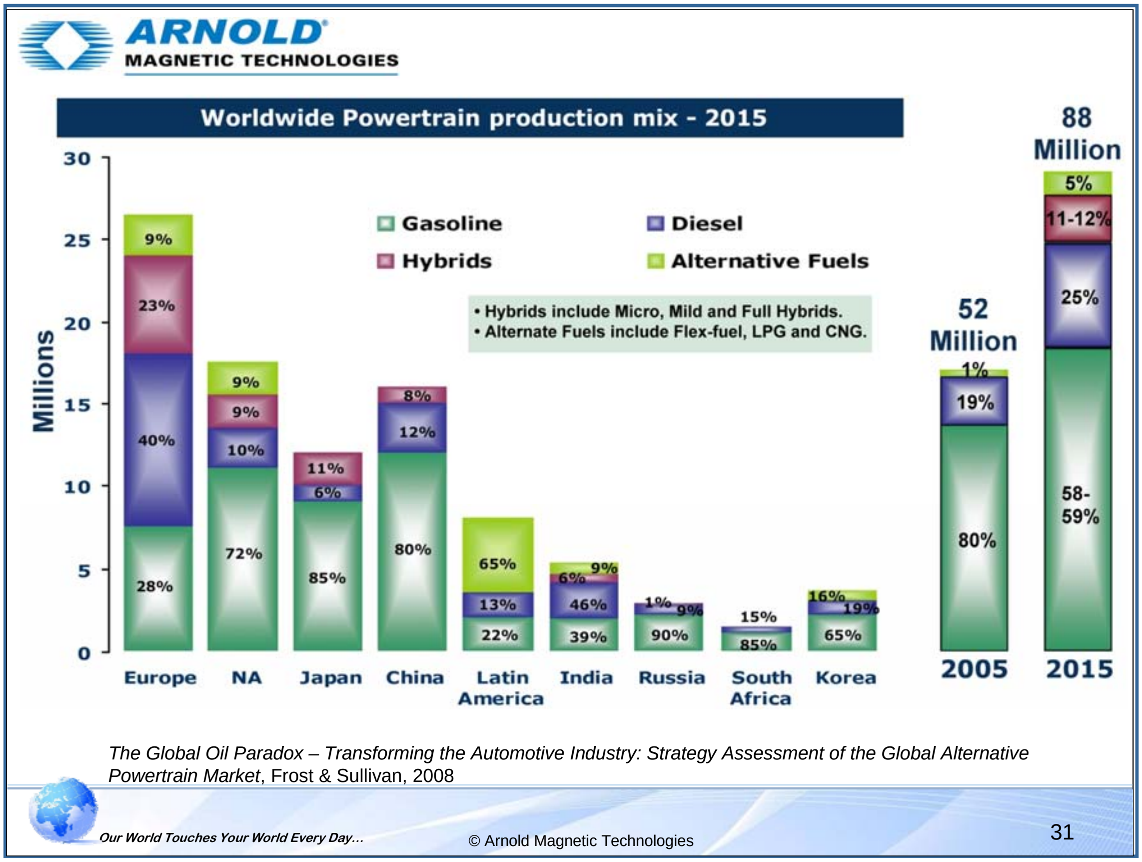
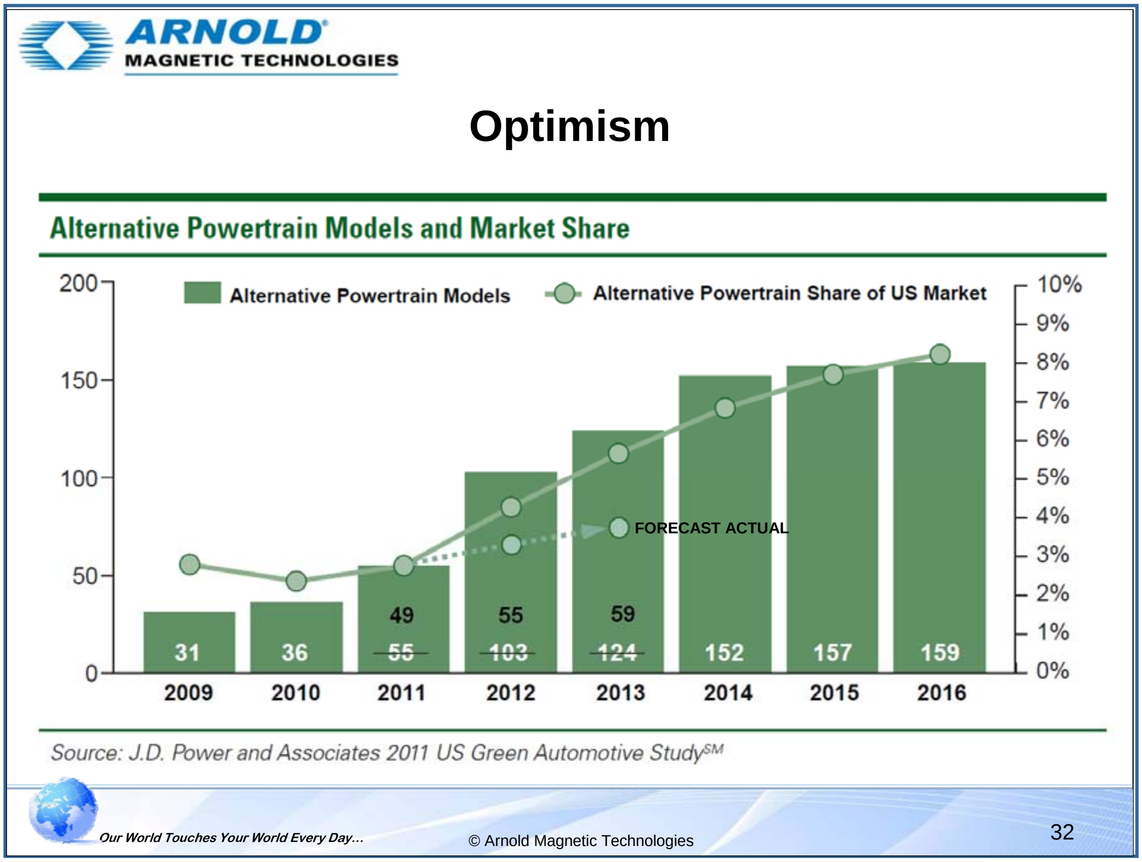
- Global car production has been tracked by OICA and is charted here from 1997 through 2012.
- A second order regression fit allows us to extrapolate to year 2020 when it’s possible that 90 million automobiles might be manufactured and sold.
- If 10% of those are to be hybrid vehicles they might use 3,461 metric tons of neodymium and praseodymium oxide which represents ~13.4% of forecast global supply.
- However, dysprosium usage would require approximately half of global supply.
- The calculations include a reduction in dysprosium content by 25% permitted by the dysprosium diffusion technology. As the diffusion technology develops still lower dysprosium content may be possible.



- In 2005, gasoline and diesel represent 99% of fuel input.
- This declines to 83% in 2015 with the greatest alternative drive system growth being hybrid drive systems.
- An important issue with this slide is the recognition that even with the growth in use of alternative power sources, that conventional fuel vehicles will continue to increase in number.



- Forecasts for implementation of alternative drives and fuels have been consistently over-optimistic.
- For example, in this JD Power's forecast from 2011, we see the number of vehicle models is about half the previously forecast number and market penetration is about 2/3 of forecast.
- Nevertheless, the number of hybrid and electric vehicles is increasing significantly. (See data below for year 2011 and 2012)..

	2011		2012	
	Units	%	Units	%
Total Sales (units)	12,734,356		14,439,684	
Hybrid	268,807	2.11%	434,498	3.01%
PEV	17,813	0.14%	53,172	0.37%
Total Hybrid, EV, PEV	286,620	2.25%	487,670	3.38%

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MAGNETIC TECHNOLOGIES

Final wrap up…
Traction Drive Motor Summary

- Adoption of HEV and BEV is lagging earlier forecasts but likely to continue growing
  - Dependent on alternate fuel cost
  - Development of battery technology
  - Competitive cost of the technology
- Permanent magnet drive motors are dependent upon
  - Availability of dysprosium
  - Other device demand for Neo magnets
- Permanent magnet drives offer best efficiency
- All motors are dependent upon price stability of copper and steel, not just on magnet materials

Mercedes-Benz SLS AMG Electric Drive:
740-hp super-sports car with one electric motor per wheel