



Critical Materials: Rare Earth & Related Elements

Mark Johnson

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Critical Materials in Clean Energy



Coordinated Critical Materials Effort

- Policy and International Affairs (PI) led Department-wide Critical Materials Strategy Study
 [David Sandalow, Assistant Secretary, PI]
- US-Japan Roundtable (LLNL) on Rare Earths (Nov 2010)
- US-EU Workshop on Rare Earths Research (Dec 2010)
- ARPA-E Workshop on Critical Materials Technology (Dec 2010)







Shifting Economics Of Rare Earth Materials



Within 5 Years: World's Dominant Supplier of Rare Earth Materials May Switch From a Net Exporter to a Net Importer





Rare Earth Criticality by Element



US DOE: Critical Materials Strategy (Dec 2010)





Possible Approach: Eliminate Need for Material

1																	2
н																	He
Hydrogen 1.00794												100,000					Helium 4.003
3	4											5		7	8	9	10
Li	Be											В	C	N	0	F	Ne
6.941	Beryllium 9.012182											Boron	- Cath -12.0 /07-	Nitrogen 14.00674	Oxygen 15.9994	Fluorine 18.9984032	Neon 20.1797
11	12										8	13	4	15	16	17	18
Na	Mg											Al	Si /	P	S	Cl	Ar
Sodium 22.989770	Magnesium 24.3050				200							Alumium 26:9815-8	18.0855	Phosphasus 30:973761:	Sulfur 32.066	Chlorine 35.4527	Argon 39.948
19	20	21	22	23	24	25	26	27	28	29	30		32	33	34	35	36
К	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	lia .	Ge	As	Se	Br	Kr
Potassium 39.0983	Calcium 40.078	Scandium 44.955910	Titanium 47.867	Vanadium 50.9415	Chromium 51.9961	Manganese 54,9380490	luin 55.845	SN 933200	Nickel 58,6934	Cooper	65.39	ensisten in	erman m 72, 1	Arsenic 74,92160	Selenium 78.96	Bromine 79.904	Krypton 83.80
37	38	39	40	41	42	43	4 44	45	46	47	48	49	0	51	52	53	54
Rb	Sr	Y	Zr	Nb	Mo	Тс	Ru	Rh	Pd	Ag	C.	to /	Sn	Sb	Те	Ι	Xe
Rubidium 85.4678	Strontium 87.62	Vitrium 88.90585	Zirconium 91.224	Niobium 92.90638	Molybdenum 95.94	Technetium (98)	Ruthenium 101.07	Rhodium 102.90550	Parodium 106 2	Silver 107.8682	Cymani - 12.411 -		Tin 118.710	Antimony 121.760	Tellurium 127.60	Iodine 126.90447	Xenon 131.29
55	56	57	72	73	74	75	76	77	/8	79	74	1	82	83	84	85	86
Cs	Ba	La	Hf	Та	W	Re	Os	Ir	Pt	Au	Hg	///	Pb	Bi	Ро	At	Rn
Cesium 132.90545	. Bariam . .137.327	AND ADDRESS.	Hafnium 175-10	Tantalum 180.9479	Tungsten 183.84	Rhenium 186.207	Osmium 190.23	Iridum 192.217	Platinum 195.078	Gð 196.5 50 5	Mercur 200.5	7 alliur 2 4.38 3	Lead 207.2	Bomath 208,98038	Polonium (209)	Astatine (210)	Radon (222)
87	88	89	104	105	106	107	108	109	110	.)1	111	11	114				
Fr	Ra	Ac	\mathbf{Pf}	Db	Sg	Bn		Mt									
(223)	(226)	(227)	(261)	(262)	Seaborgium (263)	Bohrium (267)	(265)	(266)	(200	(272)	(2)						
												V/					
				58	59	60	61	62	63	64	65	66	67	68	69	70	71
				Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Но	Er	Tm	Yb	Lu
				140.116	Praseodymium 140.90765	144.24	Promethium (145)	Samarium 150.36	151.964	Gadolinium 157.25	158,92534	16.2.50	Holmium 164.93032	Erbium 167.26	Thulium 168.93421	Ytterbium 173.04	Lutetium 174.967
				90	91	92	93	94	95	96	97	98	99	100	101	102	103
				Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr
				Thorium 232.0381	Protactinium 231.03588	Uranium 238.0289	Neptunium (237)	Plutonium (244)	Americium (243)	Curium (247)	Berkelium (247)	(251)	Einsteinium (252)	Fermium (257)	Mendelevium (258)	Nobelium (259)	(262)







Batteries for Electrical Energy Storage in Transportation (BEEST) Program



Possible Approach: Get Most From Available Supply

1																	2
H																	He
Hydrogen																	Helium
3	4	1										5	6	7	8	9	10
Ti	Be											R	Ċ	Ň	Õ	F	Ne
Lathainni	Beryllium											Boron	Carbon	Nitrogen	Oxygen	Fluorine	Neon
6.941	9.012182											10.811	12.0107	14.00674	15.9994	18.9984032	20.1797
11	12											13	14	15	16	17	18
Na	Mg											Al	Si	P	S	CI	Ar
22.989770	24.3050											26.981538	28.0855	30.973761	32.066	35.4527	39.948
19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
K	Ca_	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Potassium 39.0983	Calcium 40.078	Scandium 44.955910	Titanium 47.867	Vanadium 50.9415	Chromium 51.9961	Manganese 54 938049	Iron 55.845	Cobalt 58/0332700	Nickel 58 6934	Copper 63 546	Zinc 65.39	Gallium 69.723	Germanium 72.61	Arsenic 74 92160	Selenium 78.96	Bromine 79 904	Krypton 83.80
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
Rh	Sr	v	Zr	Nb	Mo	Тс	Ru	Rh	Pd	Δσ	Cd	In	Sn	Sb	Te	I	Xe
Rubidium	Strontium	Yttrium	Zirconium	Niobium	Molybdenum	Technetium	Ruthenium	Rhodium	Palladium	Silver	Cadmium	Indium	Tin	Antimony	Tellurium	Iodine	Xenon
85.4678	87.62		91.224	92.90638	95.94	(98)	101.07	102.90550	106.42	107.8682	112.411	114.818	118.710	121.760	127.60	126.90447	131.29
55 C	50 D	51		73	74	75 D	/0	1/	/8 D4	/9	80	81	82 DL	83	84 D	85	80 D
CS	ва	La	HI	1 a	W	Re	US	Ir	Pt	Au	Hg	II Thallium	PD	Bl	PO	At	Radan
132.90545	137.327		178.49	180.9479	183.84	186.207	190.23	192.217	195.078	196.96655	200.59	204.3833	207.2	208.98038	(209)	(210)	(222)
87	88	89	104	105	106	107	108	109	110	111	112	113	114				
Fr	Ra	Ac	Rf	Db	Sg	Bh	Hs	Mt									
Francium (223)	Radium (226)	Actinium (227)	Rutherfordium (261)	Dubnium (262)	Seaborgium (263)	Bohrium (262)	Hassium (265)	Meitnerium (266)	(269)	(272)	(277)						
(/	()	()	()		. ()	(===)	()										
				58	59	60	61	62	63	64	6.5	66	67	68	69	70	71
				Се	Pr	Nd	Pm	Sm	H an	Gd	Th	Dv	Ho	Er	Tm	Vb	
			7	Cerium	Praseodymium		Promethium	Samarium	Laux piunte	Gadolinium	Temiun		Holmium	Erbium	Thulium	Ytterbium	Lutetium
				140.116	140.90765	02	03	0.4	05	06	07	08	164.93032	167.26	168.93421	173.04	174.967
			_	Th	D	92 TI	N	D.		C		Cr.	E.	100 E	MJ	102	105
				Thorium	Protactinium	Uranium	1NP Neptunium	Plutonium	Am Americium	Curium	Berkeniu	Californium	E S Einsteinium	F m	IVI C Mendelevium	1NO Nobelium	Lawrencium
				232.0381	231.03588	238.0289	(237)	(244)	(243)	(247)	(247)	(251)	(252)	(257)	(258)	(259)	(262)

Light Rare Earth Elements

Heavy Rare Earth Elements





Rare Earth Elements Are Not That Rare







Developing Technology Alternatives Across Supply Chain









Critical Materials in Clean Energy from DOE-Wide Study

														[2 He				
	Hydrogen 1.00794 3 4 Li Be]								5 B	6 C	7 N	8 0	9 F	4.003 10 Ne			1	
	Software Beryllium 6.941 9.012182 11 12	-								Boron 10.811 13	Carbon 12.0107 14	Nitrogen 14.00674 15	^{Oxygen} 15.9994 16	^{Fluorine} 18.9984032 17	^{Neon} 20.1797 18			$\langle \rangle$	
	Na Mg Sodium 22.989770 24.3050 10 20			24 25		07	28	20	20	Aluminum 26.981538	Si 28.0855	Phosphorus 30.973761	S Sulfur 32.066	Cl Chlorine 35.4527	Ar Argon 39.948				
	19 20 K Ca Potassium Calcium Calcium 0.078	Scandium Titar	2 23 `i V ium Vanadium	Cr Mr Chromium Mangane	se liron	Co	28 Ni Nickel		Zn Zinc (5.20	Gallium	Germanium	33 As Arsenic	Selenium	Bromine	S6 Kr Krypton		-		-
	39.0983 40.078 37 38 Rb Sr	³⁹ 4 Y Z	0 41 r Nb	42 43 Mo Tc	49 55.845 44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe				
	Rubidium Strontium 85.4678 87.62 55 56	Vitrum Zirco 88.90585 91.3	nium Niobium 224 92.90638	Molybdenum 95.94 (98) 74 75	m Ruthenium 101.07 76	Rhodium 102.90550 77	Palladium 106.42 78	^{Silver} 107.8682 79	Cadmium 112.411 80	114.818 81	^{Tin} 118.710 82	Antimony 121.760 83	Tellurium 127.60 84	Iodine 126.90447 85	xenon 131.29 86			1	
-	Cs Ba Cesium 132 90545 137 327	La H	If Ta Tantalum 49 180 9479	W Re Tungsten 183 84 186 20	n Osmium	Ir Iridium	Platinum	Au Gold	Hg Mercury 200 59	TI Thallium 204 3833	Pb Lead	Bi Bismuth 208 98038	Polonium (209)	At Astatine (210)	Rn Radon		2		
	87 88 Fr Ra	89 10 Ac R	04 105 (f Db	106 107 Sg Bh	108 Hs	109 Mt	110	111	112	113	114	200.70050	(20)	(210)	(222)	100	P State State		
	Francium Radium (223) (226)	Actinium Rutherf (227) (20	ordium Dubnium (262)	Seaborgium Bohriu (263) (262)	Hassium (265)	Meitnerium (266)	(269)	(272)	(277)										
	all		-58 Ce	59 60 Pr Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 1 1				
. See	THE	HTT	140.116 90	140.90765 144. 91 92	(145) 93	150.36 94	151.964 95	157.25 96	158.92534 97	98	164.93032 99	167.26 100	168.93421 101	173.04 102	1				
and the			Th Thorium 232.0381	Protactinium 231.03588 UU Uraniuu 238.02	n Np Neptunium 89 (237)	Pu Plutonium (244)	Am Americium (243)	Cm Curium (247)	Bk Berkelium (247)	Cf Californium (251)	Es Einsteinium (252)	Fm Fermium (257)	Md Mendelevium (258)	No Nobelium (259)		F	- 6	1	
Jul and	H4401	M LEF													-				
(L)	4.776	HL.				١	Veh	icle	5										
	M						VCII												
							Ligh	tine	7								_		
							0.	C.											
							Sola	r P∖	/										
							Wi	nd											





Key Elements in Energy-Wide Supply Chain



Technology Opportunity Areas for Study



Opportunities For New, Disruptive Approaches to Technology Needs

> Metrics to Drive New Learning Curves and Approaches







45% of Global Rare-Earth Production Bayan Obo, China



Primary Ore: Bastnasite: RE-(CO₃)F 800 million metric tons; 6% REO

> <u>Secondary Ore</u>: Monazite: RE-PO₄

Photos: Google Maps



US Rare-Earth Production Capability Mountain Pass, CA (re-opened by Molycorp)



Primary Ore: Bastnasite: RE-(CO₃)F 3.3 million metric tons: 7-9% REO

Photos: Google Maps





Different Types of Rare Earths

Heavy and Light Rare Earths are from different Ores

Light Rare Earths

Neodymium – Magnets

Heavy Rare Earths

Dysprosium - High Temp Magnets

Yttrium – SOFCs and Phosphors Terbium – Phosphors Europium - Phosphors

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		LIG	нт		D	IEDIU	м		(H	AVY			/ \	
ТҮРЕ	LOCATION (S)	Lanthanum (La)	Cerium (Ce)	Praseodymium (Pr)	Neodymium (Nd)	Samarium (Sm)	Europium (Eu)	Gadolinium (Gd)	Terbium (Tb)	Dysprosium (Dy)	Holmium (Ho)	Erbium (Er)	Thulium (Tm)	Ytterbium (Yb)	Lutetium(Lu)	Yttrium(Y)
Currently ac	tive:															
Bastnäsite	Bayan Obo, Inner Mongolia	23.0	50.0	6.2	<u></u>	0.8	0.7	0.7	9.1	0.1	0.0	0.0	0.0	0.0	0.0	
Xenotime	Lahat, Perak, Malaysia	1.2	3.1	0.5	1.6	1.1	0.0	3.5	0.9	8.3	2.0	6.4	1.1	6.8	1.0	61.0
Rare earth laterite	Xunwu, Jiangxi Province, China	43.4	2.4	9.0	31.7	3.9	0.5	3.0	0.0	0.0	0.0	0.0	0.0	0.3	0.1	8.0
lon adsorption clays	Longnan, Jiangxi Province, China	1.8	0.4	0.7	3.0	2.8	0.1	6.9	1.3	6.7	1.6	4.9	0.7	2.5	0.4	65.0
Loparite	Lovozerskaya, Russia	28	57.5	3.8	8.8	0.0	0.1	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Various	India	23	46	5	20	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Various	Brazil	N.A.														
Possible to a	come online in	the ne	ext 5 y	ears:												
Bastnäsite ²²	Mountain Pass, California, United States	33.2	49.1	4.3	12.0	0.8	0.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Monazite	Mount Weld, Australia	26.0	51.0	4.0	15.0	1.8	0.4	1.0	0.1	0.2	0.1	0.2	0.0	0.1	0.0	0.0
Wionazite	Eastern coast ²³ , Brazil	24.0	47.0	4.5	18.5	3.0	0.1	1.0	0.1	0.4	0.0	0.1	0.0	0.0	0.0	1.4
Apatite	Nolans bore, Australia	20.0	48.2	5.9	21.5	2.4	0.4	1.0	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0
Fergusonite ²⁴	Nechalaco, Canada	16.9	41.4	4.8	18.7	3.5	0.4	2.9	1.8	0.7	0.0	0.0	0.0	0.0	0.0	7.4
Bastnäsite & Parisite	Dong Pao, Vietnam	32.4	50.4	4.0	10.7	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.007
Alanite & apatite	Hoidas Lake, Canada	19.8	45.6	5.8	21.9	2.9	0.6	1.3	0.1	0.4	0.0	0.0	0.0	0.0	0.0	1.3
Trachyte	Dubbo Zirconia, Australia	19.5	36.7	4.0	14.1	2.5	0.1	2.1	0.3	2.0	0.0	0.0	0.0	0.0	0.0	15.8





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Rare Earth Oxide and Metal Extraction Process







Supply and Demand Scenarios Neodymium (Permanent Magnets)

Neodymium Oxide Future Supply and Demand









Magnetic Systems: Motors for Electric Vehicle (EV) 2020 Roadmap Goals with Low Rare Earth Content



Advanced Electric Motor Concepts



Example: Parallel Path Magnetic Motor Technology





Needed Enabling Magnetic Materials







Soft Magnetic Nanocomposite

High Permeability (Fe, Fe-Si, Fe-Co) Low Eddy Current Loss Isotropic Permeability (ideal) Manufacture-able / Moldable Enables Novel Structures

Hard Magnetic Nanocomposite

Spring Exchange Coupling Coercivity of Hard Phase (SmCo, NdFeB) Remnance of Soft Phase (Fe, Fe-Co) High Energy Density Reduced Rare Earth Content Current: U Del. & GE







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Nanocomposite Permanent Magnets



Nanocomposite exchange spring coupled permanent magnets with high energy product and less rare earths





Large Scale Wind Generator (>10MW) Systems



ARPA-E Workshop: Critical Materials Technology



Catalysts: Fluid Catalytic Cracking







Figure 3-6. Effects of rare earth on gasoline octane and yield.

1-2% catalysts replaced per day. All catalyst replaced every 2 months due to loss of aluminum. Old catalyst is landfilled.

Recover Rare-earth content from spent FCC catalyst could potentially have Impact.

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Application: Rare Earth Phosphors for CFLs



			Emission		
Phosphor	Code	Color	Wavelength	Nature	Rare Earth(s)
BaMgAl ₁₀ O ₁₉ :Eu ²⁺	BAM	Blue	450 nm	Broad band	Eu
$LaPO_4:Ce^{3+}, Tb^{3+}$	LAP	Green	545 nm	Sharp line	La,Ce,Tb
Y ₂ O ₃ :Eu ³⁺	YEO	Red	610 nm	Sharp line	Y, Eu

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Cost of Lighting (CoL) vs. First Lumen Cost (Bulb)







First Purchase Price for Lighting



Technical Pathway to Low First Cost LEDs: Eliminate Droop Losses Through Innovation



Physical Origins of Droop Auger Recombination Non-Radiative Defects Carrier Overflow from MQWs Crystal Polarity

Rare Earth Free Phosphors Luminscent Nanoparticles without Cadmium







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Summary: Critical Materials Technology



Questions



