

RARE EARTHS

Jane Spooner, Micon International Limited

China holds the leading position among producers of the rare-earth elements, or lanthanide elements. Rare earths are also produced in India, Russia, Kazakhstan, Kyrgyzstan, Thailand and Malaysia. Further processing of concentrates, and partially processed or intermediate products, is carried out in a number of locations in Europe, the US and Japan, as well as in China.

The rare earths, or lanthanides, comprise the 15 elements in the periodic table with atomic numbers 57 to 71. Often included with the lanthanides are scandium (atomic number 21) and yttrium (atomic number 39). Because of their similar physical and chemical characteristics, the lanthanide elements and yttrium often occur together in nature. While scandium may occur with the rare earth elements, it is also found in a range of other minerals.

World production of rare earths is around 100,000 t/y rare earth oxide (REO). Output of yttrium is significantly less, of the order of 2,500 t/y yttrium oxide (Y_2O_3). Global production data for scandium are not publicly available.

The principal commercial sources of the rare-earth elements are: bastnaesite, a fluorocarbonate which occurs in carbonatites and related igneous rocks; xenotime, a yttrium phosphate commonly found in mineral sand deposits; and loparite, a titanate related to perovskite and which occurs in alkaline igneous rocks. In China, rare-earth elements and yttrium are found in ion-adsorption clays that formed as a result of lateritic weathering of igneous rocks. Monazite is no longer a significant commercial source of rare-earth elements because it commonly contains thorium, of which the intermediate daughter elements are radioactive. Limited amounts are mined in China and India.

Although they tend to occur together, the 15 lanthanide elements are divided into two groups. The 'light' elements are those with atomic numbers 57 through 63 (lanthanum to europium) and the 'heavy' elements from 64 to 71 (gadolinium to lutetium). The term 'middle rare earth' comprises those with atomic numbers 62 through 64 (samarium, europium and gadolinium, also referred to as SEG). Generally, the light rare-earth elements are more common and more easily extracted than the 'heavies'. Yttrium has properties more similar to the heavy group, in spite of its low atomic weight, and is included within the heavy rare-earth elements (see Table 1). The term, didymium, refers to a mixture of neodymium and praseodymium, and mischmetal refers to alloys of the unseparated rare-earth elements in naturally occurring proportions. (Promethium, atomic number 61, does not occur in nature).

Scandium is relatively widely distributed in nature and occurs in a variety of silicates, phosphates and oxides but not at sufficient concentration to support its

recovery as a primary product. Thortveitite (a scandium-yttrium silicate) in tailings has provided a source of scandium in the US but it is otherwise recovered from wastes arising from the processing of uranium, tungsten, titanium, tantalum, copper and iron ores. The USGS reports that world production of scandium is located principally in China, Russia and Ukraine.

Processing of rare-earth concentrates generally involves an initial cracking or leaching step to bring the elements into solution. This is followed by a number of separation stages, first to separate groups of elements (the lights from the heavies) and then to separate individual elements from each other. Solvent extraction is the principal method used. Marketable products include rare-earth oxides, carbonates, acetates and other compounds, as well as metals and alloys. The rare earth content is generally expressed in terms of rare-earth oxide, REO, or total rare-earth oxide (TREO). For some applications, the purity of products may be quoted as four nines, or five nines, ie, 99.99% or 99.999%, of the specified element in the total rare-earth content (or REO in TREO).

Estimated primary, mine production of rare earths is shown in Table 2.

China

The rare-earth industry in China was restructured to comprise two groups of producers in 2003: the Northern group, based principally in Inner Mongolia, Gansu and Sichuan; and the Southern group comprising units in Guangdong, Hunan, Jianxi and Jiangsu provinces. In October, 2004, however, AMR Technologies Inc noted that the reorganisation into the Northern and Southern groups had not been fully accepted by the participants, and it has subsequently been confirmed that this restructuring has been abandoned.

Production by the group of ten producers in northern China, led by Baotou Steel and including Baotou Rare Earth (Group) Co, Gansu Rare Earth Co. and the Sichuan Rare Earth Group, is based principally on bastnaesite. Near Baotou, Inner Mongolia, bastnaesite is a by-product of iron mining. In Gansu and Sichuan, bastnaesite is the primary mineral. The hardrock deposits in northern China (in common with rare-earth deposits in other countries) are dominated by the light rare earths, cerium, lanthanum and neodymium, which together account for over 90% of the total REO content. Output in Inner Mongolia and Sichuan accounts for some 70% of total rare-earth production in China (in terms of REO). Production of bastnaesite in Inner Mongolia in 2004 is reported at 58,000 t REO.

The southern China, the industry comprises seven processors in Guangdong, Hunan, Jianxi and Jiangsu provinces. Production is based on ion adsorption clays that are relatively depleted in cerium (as a result of the lateritic weathering process) and generally also contain significant yttrium. Reported output of ion adsorption clays is reported at 25,000 t REO in 2004.

Table 3 shows the relative abundance of the individual rare-earth elements in selected feedstock material in China.

Downstream separation activities are carried out in a large number of facilities which are integrated with, or purchase, concentrates or partially separated rare earth feedstocks. The origin of the feedstock material (hard rock bastnaesite and the ion absorption clays) largely dictates the product range (light, middle and heavy rare-earth elements) of each plant. The largest producers operate separation plants although they may also sell partially processed concentrates to independent operators.

The rare-earth sector, in common with other industrial sectors, has suffered the effects of power shortages and is having to conform to tighter environmental controls. In July, 2004, 18 rare-earth processing plants were closed as a result of their failure to meet environmental standards, although a number were permitted to reopen at the end of the year, and in the first half of 2005 serious floods affected output in southern China. A new value-added tax (VAT) of 12% on Chinese rare-earth exports was imposed in 2004.

The ion absorption clays of southern China are the source of by far the greater proportion of world yttrium production.

United States

The US Geological Survey reported that rare-earth concentrates, intermediate products and separated oxides were available from stocks of previously mined bastnaesite at the Mountain Pass operation of Molycorp Inc. In July 2004, Molycorp received approval of its environmental impact report and permit to enlarge the Mountain Pass mine by mining a further 250 feet below surface and to construct a new tailings storage facility and evaporation pond. The Mountain Pass operation has been on care and maintenance since 1998 when it closed due to a spill from a broken pipeline.

India

Indian Rare Earth Ltd processes monazite extracted from heavy mineral sands in Kerala, Tamil Nadu and Orissa. Approximately 3,000 t/y of monazite are recovered in the plant near Kochi. Rare-earth chlorides, fluorides and carbonates, cerium products, neodymium oxide and didymium carbonate are produced at the Rare Earths Division plant at Aluva. Thorium is a co-product. Kerala Minerals and Metals Ltd extracts monazite from mineral sands in Kerala. A joint venture between Cochin Minerals and Rutilites Ltd, Indian Rare Earths and the Kerala State Industrial Development Corp is seeking to develop a new mining area on the Alappuzha coast.

India is the second-largest source of yttrium, which is derived from its monazite production. Indian Rare Earth Ltd produces yttrium oxide at its Rare Earths Division plant

Russia and Central Asia

The Russian rare-earth industry is based on loparite, a titanium-tantalum niobate mined from the Lovozero massif in the Murmansk region. The mined concentrate, produced by JSC Sevredmet, is processed by Solikamsk Magnesium Works at its facilities at Solikamsk where the plant has recently been upgraded to produce rare earth carbonates and partly separated products. Rare-earth chlorides from Solikamsk had previously been shipped to Estonia and Kazakhstan for processing. The costs of handling these chlorides, which are naturally radioactive, prompted the development of capacity to remove the radioactive elements on-site.

Irtysk Rare Earths Co Ltd produces a range of separated rare-earth oxides, metals and other products at up to four nines purity at Irtysk in eastern Kazakhstan.

The Kyrgyzsky mining and metallurgical combine is reported to produce rare-earth metals at Orlovka, Kyrgyzstan.

Separated rare earths and processed products

The production of separated rare-earth products from purchased concentrates or partially processed material is carried out by a relatively small number of companies, worldwide, few of which are integrated upstream to rare-earth mining operations. Generally, the natural occurrence of the light rare-earth elements (lanthanum, cerium and neodymium) is ten, or more, times the occurrence of the medium and heavy elements (see Table 3). It is important to note, also, that producers of separated rare earths have to recover, and then market, a range of some 15 co-products while attempting to maximise the margins on each. As a result, market balance has been difficult to achieve and periods of excess supply or shortage of individual elements has been a characteristic of the industry.

Toronto-based AMR Technologies Inc is the majority owner and the operator of two joint venture rare-earth production facilities in China. The product range at Jiangyin Jia Hua AMR in Jiangsu principally comprises the middle and heavy rare-earth elements while at Zibo Jia Hua AMR in Shandong, the focus is on light elements. AMR's principal products are cerium, lanthanum, neodymium, yttrium and yttrium-europium co-precipitates for which the major markets are in the automotive, catalyst, electronics and glass sectors. The company has downstream manufacturing facilities in its neodymium-iron-boron magnet powders ('Neo' powders) plant in Thailand, in the production of mixed rare-earth/zirconium oxides and in the application of nanotechnology in rare earths and zirconium.

China is now the largest producer of both nickel-metal hydride battery alloys and neodymium-iron-boron magnetic alloys.

Inner Mongolia HEFA Rare Earth Science & Technology Development Co operates five rare-earth processing factories near Baotou, with a capacity of around 10,000 t/y REO. It produces a range of separated products, metals and alloys. The company announced plans to construct a central concentrate roasting plant, with capacity of 40,000 t/y, early in 2003.

Among other important rare-earth processors in China are Gansu Rare Earth Corp, Xinwei group (China Rare Earth Holdings) and Yue Long Non-ferrous Metal. Primet llc operates a light rare-earth manufacturing plant at Leshan in Sichuan where it partners a local miner of rare earths.

Rhodia Electronics and Catalysts, based in France, undertakes the rare-earth business of Rhodia, producing a full range of separated and value-added products. Notable are its proprietary automotive catalysts and a range of rare-earth products for the electronics industry. Rhodia's principal facility is at La Rochelle, and the company has interests in China (Baotou Rhodia Rare Earths Co, which operates rare earth separation and processing facilities near Baotou, and Liyang Rhodia, located at Liyang), as noted above, in the US and in Japan. In the US, Rhodia processes previously-separated rare earth products, which it imports from its plant in France, to high-purity finished products. It produces a range of oxides, salts, metals and alloys. Rhodia's US operations at Freeport, Texas, manufacture advanced ceramic and catalyst materials.

Other manufacturers of rare-earth products in the US are Grace Davison, a subsidiary of W R Grace & Co, and Santoku America Inc. Grace Davison produces cerium and lanthanum compounds for fluid-cracking catalysts used in the petroleum industry, and cerium and zirconium products used in automotive catalysts. Santoku America specialises in magnet alloys (neodymium-iron-boron and samarium-cobalt) and nickel metal hydride alloys for rechargeable batteries.

In Japan, Shin-Etsu reports that it operates the largest rare-earth separation and refining facilities where it produces a range of products, including nano-size materials. Shin-Etsu also produces rare-earth magnets. Santoku and Rhodia operate a joint venture, Anan Kasei, for the production and marketing of rare earths for catalysts, phosphors, glass polishing, pigments and glasses. High purity rare-earth metals, yttrium and scandium, are also produced by Santoku.

The rare-earths and chemicals business unit of Treibacher Industrie AG, of Austria, produces separated rare-earth metals, hydrogen storage alloys, a variety of mischmetal compositions and lighter flints, and a range of rare-earth oxides and chemicals for specialty glasses, catalysts, electronics, and ceramics. Rare-earth oxides are produced in a number of forms, including spray powder materials, as ingots used in the vapour deposition of coatings, coatings for precision castings, sintering aids and high performance grinding beads. The company has an interest of 25% in AS Silmet in Estonia. AS Silmet produces separated lanthanum, cerium, neodymium, praseodymium carbonates, oxides,

chlorides, nitrate solutions and metals, and a range of mixed products and polishing powders at its plant at Sillamae. Production is reported in the range of 3,000 t/y of rare-earth products and 700 t/y of metals.

Magnequench Inc manufactures rare earth-iron-boron magnetic powders (Neo powders) for bonded magnets and powder products at Tianjin, China. Magnequench is the leading producer of rare earth-iron-boron powders, with an estimated market share of 85%. Through its patents, Magnequench is the only company legally permitted to supply Neo powder for bonded rare earth-iron-boron magnets manufactured or sold in the US.

Projects and Industry Developments

In March, 2005, Lynas Corp Ltd announced the completion of the feasibility study for development of its Mt Weld project in Western Australia. Mined and crushed ore will be transported via the port of Esperance to Shandong in China where a plant will be constructed for the flotation and treatment of the concentrate to produce intermediate rare-earth chlorides. Iron oxide will be recovered as a co-product. Initial production will be at a rate of 10,500 t/y REO, increasing to 15,000 t/y REO after five years. Lynas reports that proved and probable reserves of 2.08 Mt at 15.5% REO, estimated in compliance with the JORC Code, will support the first 14 years of the operation. The total capital cost is estimated at A\$49.2 million. Environmental approvals are in hand in both Australia and China and the company plans initial production in 2006. In addition to the Mt Weld rare-earth project, Lynas has identified a niobium resource within the Crown and Coors sectors at Mt Weld that also carries rare earth and yttrium values. A pre-feasibility study for the niobium resource is planned for 2005. As with the rare-earth project, processing of the mined material would be undertaken in China.

Great Western Minerals continued exploration at its Hoidas Lake project in Saskatchewan, Canada. A bulk sample was taken in 2004 for metallurgical testing at the Center for Advanced Mineral and Metallurgical Processing in Montana and the winter exploration programme resulted in the delineation of a new zone of mineralisation. Rare-earth elements occur in apatite and allanite. Rare Earth Metals continued work on the Eden Lake carbonatite deposit in Manitoba, Canada. Rare Element Resources worked on the Bear Lodge alkaline igneous intrusion located in northeastern Wyoming, US, where rare-earth mineralisation occurs in carbonatite veins. The company plans to undertake metallurgical testwork on sampled material.

Other deposits remain undeveloped for reasons that include complex mineralogy, association with radioactive elements and the availability of low-cost supply from China.

The restructuring and development of integrated downstream processing in the rare-earth industry also has reduced the market for rare-earth concentrates

outside China so that any new project must consider further processing, at least to partially-separated products.

Rare-earth minerals have been recovered as by-products from titanium-bearing heavy sands, particularly in Australia, and from tin dredging in Malaysia; however, the thorium content of monazite from these operations has precluded its use as a rare-earth feedstock since the mid-1990s.

In January 2004, Lynas Corp acquired just under 20% of the shares of AMR. Lynas noted that “we have commenced execution of our strategy for establishing our Downstream Project through the acquisition of a majority [sic] interest of 19.9% in AMR Technologies”. In mid-2005, AMR and Lynas negotiated a settlement in respect of AMR’s allegation that Lynas had acted to make a take-over bid for AMR without complying with the take-over bid requirements of securities regulations in Ontario. Lynas sold its holding in AMR in July, 2005. Also in July, 2005, the shareholders of AMR approved the combination of AMR with Magnequench Inc. The combination of AMR, the second-largest producer of specialty rare-earth and zirconium products, and Magnequench, the largest producer of neodymium magnetic powders, offers vertical integration, improved market position in the neodymium magnet sector and the opportunity for increased product research and development. Integrated demand for neodymium will allow AMR greater flexibility in the production and costing of its co-product rare-earth elements.

Sumitomo Special Metals Co and Magnequench Inc, between which a cross-licensing agreement legally restricts the sale of rare earth-iron-boron magnets in the US to only these companies, hold the patents on a number of basic rare earth-iron-boron bonded magnet compositions with expiry dates in 2003 or 2004 in Europe and Japan, and 2005-2007 in the US. Sumitomo holds the rights to sintered rare earth-iron-boron magnets.

Demand

The lanthanide elements, as a group, have magnetic, chemical and spectroscopic properties that have led to their application in a wide range of end-uses. Within the group, there are gross differences in the physical and chemical properties that result in the light and heavy rare-earth elements being utilised differently. The subtle differences between the properties of individual elements allow them to be used in particular applications and for which the technical specifications are very precise.

AMR reported the following breakdown of demand for individual rare-earth elements in 2004 in a presentation, “Meeting the Needs of a Growing Market: Will There Be Enough Rare Earths?”, by Constantine E. Karayannopoulos:

Neodymium oxide	11,000 t
Praseodymium oxide	5,000 t

Dysprosium oxide	800 t
Terbium oxide	175 t
Europium oxide	210 t
Yttrium oxide	5,000 t

Generally, a balance is maintained between supply and demand for neodymium, based on the requirements of the magnetics industry. Although both cerium and lanthanum have relatively high-volume applications, they tend to be in oversupply as a result of demand for neodymium which is less readily available.

The principal geographical centres of consumption of rare earths are in the US, Europe, Japan, Korea and China, where components such as automotive catalyst systems, fluorescent lighting tubes or display panels are manufactured. In the US, the following consumption data for 2004 are reported by the US Geological Survey:

Automotive catalysts	46%
Glass polishing and ceramics	14%
Metallurgical additives and alloys	13%
Petroleum refining catalysts	7%
Phosphors	5%
Permanent magnets	3%
Other	12%

Global trends that strongly influence the demand for rare earths are miniaturisation, particularly of consumer electronic devices, automotive emissions control and energy efficiency. The general shift of manufacturing away from the US, Europe and Japan to China, Korea and elsewhere, is also affecting the pattern of primary demand for rare-earth products.

Rare-earth elements and yttrium used in the principal end-use sectors are summarised in Table 4. It is estimated that catalysts (including both petroleum cracking and automotive catalysts) make up the single largest demand sector in terms of volume, followed in decreasing order, by glass, metal alloys, glass polishing, magnets, phosphors and ceramics. High-value market sectors include phosphors, optical glass (lenses), dopants for optical fibres, lasers, advanced ceramics and capacitors. In terms of value, phosphors make up by far the most important group at approximately 30% of the total market, followed by magnets, catalysts and alloys at 12-15% each. Relatively low-value applications, such as lighter flints, steel and foundry additives, petroleum refining catalysts and some glass polishing compounds, do not require separated rare-earth elements at high purity. Automobile catalyst, battery and magnetic alloy products are very widely used and are based on the light rare earths but have fairly stringent quality criteria that take them out of the commodity category.

Components using rare earths, such as batteries, magnets, display screens or phosphors, are then incorporated in the manufacture of finished consumer or industrial products, although the final manufacturing step may take place in a different region of the world.

In 2004, demand was strong for rare-earth products in each of the display, magnetics and electronics industries. Demand for lanthanum and cerium can be met relatively easily (since they are relatively abundant compared to the other rare-earth elements). The focus is on the rare-earth elements used for magnets (neodymium, praseodymium, terbium, dysprosium and samarium) and phosphors (terbium, europium and yttrium), for which prices increased sharply in 2004 reflecting strong demand during the year and into 2005. Overall demand growth for the rare-earth elements has been projected at just over 3%/y but, over the next five years, magnet applications are expected to grow much faster, at annual rates in the region of 20%.

Cerium and/or lanthanum are required in most automotive catalyst systems for both petrol and diesel engines. The use of cerium and lanthanum can also be adjusted to optimise consumption of more costly platinum and palladium. As a result, automotive catalysts are one of the most important demand sectors for rare earths.

Rare earth permanent magnets have high magnetic intensity and are used in a very wide range of applications in small electric motors and in audio and video equipment. The principal types are neodymium-iron-boron magnets, to which dysprosium, praseodymium and/or terbium may be added and which are manufactured from magnetic (Neo) powders by either sintering or bonding with resin. Neodymium-iron-boron magnets offer high intensity at very low volume. They have replaced traditional ferrite magnets in electronic equipment and motors, and have allowed the progressive miniaturisation of a wide range of consumer electronic items including mobile telephones, digital and conventional cameras, computers and MP3 players. Because of their high magnetic intensity neodymium-iron-boron magnets are widely applied in magnetic-separation equipment in the minerals and recycling industries. Neodymium-iron-boron permanent magnets are also used in motors for hybrid cars. The replacement of ferrite magnets is expected to continue in a range of industrial applications.

Samarium-cobalt magnets offer higher thermal stability and corrosion resistance than the neodymium types and are used where these properties are required in sensors and pump couplings, for example. Samarium-iron-nitride magnets, a relatively new development, are more resistant to demagnetisation than the other rare-earth types, but are currently more complex to manufacture.

Roskill's 'Letter from Japan' reported that demand for the principal rare-earth oxides used in magnetic materials (neodymium, praseodymium, terbium,

dysprosium and samarium) together amounted to some 15,500 t in 2004. Neodymium oxide accounted for nearly 70% of the total.

The traditional and relatively high-volume end-use sector for rare earths in cerium oxide polishing powders, remains strong since virtually all optical glass lenses (including those in many digital cameras) and glass display panels for computer monitors and television screens are polished to high specifications. The trend to larger screen formats also has a significant impact on demand for polishing compounds since the relationship is to the area of the screen, not the linear dimension used to describe screen size.

The principal applications for rare-earth phosphors are in display screens (cathode ray, liquid crystal and plasma) and in low-energy fluorescent lighting tubes. Each of the different display technologies requires somewhat different types and compositions of phosphors, as do fluorescent tubes in which the phosphors reduce energy consumption and provide specific colours.

Lanthanum-nickel-hydride batteries, which were rapidly replacing nickel-cadmium batteries in the late 1990s, are now being overtaken, in turn, by lithium ion batteries in electronic equipment and cameras. For hybrid vehicles, however, nickel-metal-hydride batteries remain the primary choice, although the lithium ion battery is challenging for the lead in this sector.

Neodymium and lanthanum, and to a lesser extent cerium, are used in the ceramic insulating layers between the conductive metallic electrode layers of multilayer ceramic capacitors (MLCC). These are found in cell phones, laptop computers, cameras and automobile electronic controls (braking, suspension, navigation aids) which also depend on high-intensity rare-earth magnets.

Magnetic refrigeration, based on the magnetocaloric properties of gadolinium in arc-welded alloys composed of gadolinium, silicon and germanium, is a relatively new development that may provide relatively high energy efficiency compared with conventional refrigeration systems and, also, the elimination of environmental effects associated with the use of chlorofluorocarbons or ammonia as heat-transfer fluids.

Small quantities of yttrium are used as dopants for synthetic crystalline materials, eg, yttrium aluminium garnets (YAG) and yttrium aluminium perovskites for lasers and scintillators. Rare-earth oxides are also used in synthetic gemstones to provide specific colours and quality (cubic zirconia is stabilised with yttrium).

Trains based on magnetic levitation ('maglev') technology using neodymium magnets, have been opened in Shanghai to link the international airport and with the city's financial district, and are planned in Los Angeles. Two other maglev trains operate in Germany and Japan.

Solid oxide fuel cells utilise lanthanum manganite doped with rare earths for the cathode, and yttria-stabilised zirconia as the electrolyte. Fuel cell research efforts in the US and the EU will be pooled under a co-operative programme.

The application of nanotechnology in rare-earths products is advancing in the areas of coatings and fillers where nano-sized materials are already used to enhance performance, and in automotive catalysts where mixed zirconium-cerium oxides have greater thermal stability and the oxygen storage capacity is greater at higher temperatures. Potential applications include yttria-stabilised zirconia as an electrolyte film for fuel cells, and battery electrodes composed of nano-sized crystalline materials. AMR is active in the development of nanotechnology for its rare earths products. An example is its project with Rothman's Benson and Hedges Inc to apply nano-cerium products to control the emission of smoke from cigarettes and cigarette papers. On the nano-scale (1-100 nanometres where $1 \text{ nm} = 10^{-9} \text{ m}$), materials have similar, but superior, properties because the extremely small particle size results in very large surface area.

Scandium is used principally in aluminium alloys for sporting goods such as baseball bats and bicycle frames. Scandium alloys are not only stronger and more resistant to corrosion, but welds are also stronger and less liable to cracking. Minor amounts are used in semiconductors, lasers, specialty lighting (including halogen bulbs) and in welding wire.

Prices

Prices for rare earths reflect relative abundance and specific markets for individual rare earth elements, as well as the product (oxide, metal or compound) and purity.

The USGS published an estimate of US\$4.08/kg REO for bastnaesite concentrate in the US in 2004, unchanged since 2000. Mineral Price Watch, published by Metal Bulletin plc, reported bastnaesite concentrates at US\$2.25/lb of contained REO in January 2005, unchanged since January 2004, and yttria (99.99% Y_2O_3) in bulk at US\$9-12/kg (down from US\$13-16/kg in January 2004). Prices for readily available grades of material are available on the website of suppliers such as Stanford Materials which, in mid-2005, listed the following: cerium oxide polishing powder for cathode ray tubes, optical lenses etc, at US\$6.00-6.85/kg in 1 t lots; praseodymium oxide at US\$28.50-30.00/kg in 100-kg lots for 99-99.9% REO/TREO; US\$185/kg for 99.99% REO/TREO; and europium oxide at US\$388-432/kg for 99.9-99.99% REO/TREO in 20-kg lots. Stanford Materials quotes scandium metal (99.99%) at US\$5.42/g in 1,000 g lots, and scandium oxide (99.999% Sc_2O_3 /TREO) at US\$1.15/g in 5,000 g lots. (It should be noted that publicly-quoted prices may not accurately reflect current market conditions.)

Table 1: Atomic numbers and symbols

Group	Element	Atomic Number	Symbol
Light	Lanthanum	57	La
	Cerium	58	Ce
	Praseodymium	59	Pr
	Neodymium	60	Nd
Medium	Samarium	62	Sm
	Europium	63	Eu
	Gadolinium	64	Gd
Heavy	Terbium	65	Tb
	Dysprosium	66	Dy
	Holmium	67	Ho
	Erbium	68	Er
	Thulium	69	Tm
	Ytterbium	70	Yb
	Lutetium	71	Lu
Others	Yttrium	39	Y
	Scandium	21	Sc

**Table 2: World production of mined rare-earth elements
(tonnes rare-earth oxide equivalent)**

	2001	2002	2003	2004
China	78,000	88,000	92,000	95,000
Commonwealth of Independent States	2,000	2,000	2,000	2,000
India	2,700	2,700	2,700	2,700
Malaysia	350	240	250	250
Total	83,050	92,940	96,950	99,950

Sources: USGS, AMR Technologies Inc

Table 3: Commercial rare-earth minerals in China

Oxide	Baotou Basnaesite Concentrate	Sichuan Basnaesite Concentrate	High-Eu clay, Guangdong	High-Y clay, Longnan, Jiangxi
TREO	50%	50%	92%	92%
La	23.0	29.2	27.1	2.4
Ce	50.1	50.3	1.4	0.6
Pr	5.0	4.6	7.03	1.1
Nd	18.0	13.0	22.03	5.4
Sm	1.6	1.5	4.95	3.5
Eu	0.2	0.2	0.8	0.0
Gd	0.8	0.5	6.03	6.1
Tb	0.3	0.0	0.57	1.2
Dy	0.0	0.2	3.6	7.5
Er	0.0	0.0	2.48	4.0
Y	0.2	0.5	22.0	62.0
Ho-Tm-Yb-Lu	0.8	0.0	2.1	5.9

Source: AMR Technologies Inc

Table 4: Rare-earth products and applications

Application	Product(s)	Rare-earth element(s)
Glass polishing	Lenses, display screens (CRT, LCD, PDP)	Cerium
Glass additives	Optical lenses, display screens	Cerium, lanthanum, neodymium
Lighter flints		Mischmetal alloy
Catalysts, fluid cracking	Petroleum refining	Mixed rare earth products
Catalysts, auto	Automobiles	Cerium, lanthanum, neodymium
High intensity magnets	Electronic and electric motors, audio equipment	Neodymium, samarium, dysprosium, praseodymium, terbium
Batteries and hydrogen storage systems	Electronics, tools, hybrid cars	Mischmetal, lanthanum alloys
Phosphors, display	Computer, TV and other display screens	Yttrium, europium, terbium
Phosphors, lamp	Fluorescent and halogen lamps	Yttrium, lanthanum, cerium, europium, gadolinium, terbium
Phosphors, X-ray	X-ray film	Lanthanum
Fibre optics/lasers	Rare earth dopants	Lanthanum, erbium, ytterbium
Advanced ceramics	Nitrides, Y-stabilised	Yttrium

	ceramics etc	
Capacitors	Multilayer ceramic	Lanthanum, neodymium, cerium
Fuel additives	Gasoline, diesel fuels	Cerium
Fuel cells	Solid oxide fuel cells	Lanthanum, yttrium
Pigments	Replacement for cadmium in red pigments	Lanthanum, cerium
Magnetic refrigeration	Magnet alloy	Gadolinium
Steel and foundry	Desulphurisation	Mischmetal
Alloys	Magnesium, aluminium and hydrogen storage alloys	Cerium, neodymium, lanthanum, yttrium