RARE EARTHS IN SELECTED U.S. DEFENSE APPLICATIONS

James B. Hedrick
U.S. Geological Survey
983 National Center
Reston, VA 20192

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email: jhedrick@usgs.gov

The rare-earth elements (REE) have a wide variety of defense applications, some of which are critical to the national security of the United States. As essential materials in the manufacture and operation of defense and weapons systems, the REE are used in many forms from low-purity concentrates and natural mixtures of metal (mischmetal) to ultrahigh-purity compounds and metals. Although they are common in the Earth's crust, they rarely occur in sufficient concentrations to be economically extractable. The principal sources of the REE are the four minerals, bastnäsite, loparite, monazite, and xenotime and the rare-earth ion adsorption clays. Production of REE has been primarily from Australia, China, India, Malaysia, Russia, and Thailand, with China being the dominant world producer.

Rare-Earths Defined The rare earths are not rare nor are they earths (the historical term for an oxide/nonmetal). The rare earths are a moderately abundant group of 17 metallic elements that includes the 15 lanthanides, yttrium, and scandium. The elements range in crustal abundance from cerium, the 25th most abundant element of the 78 common elements in the Earth's crust at 60 parts per million (ppm), to thulium and lutetium, the least abundant rare-earth elements at about 0.5 ppm (Mason and Moore, 1982, p. 46). In rock-forming minerals, REE typically occur in compounds as trivalent cations in carbonates, oxides, phosphates, and silicates.

Based largely on ionic radius, the REE are classified into two groups; the light-group rare-earth elements from lanthanum to europium, abbreviated LREE, and the heavy-group rare-earth elements from gadolinium to lutetium, including yttrium, abbreviated HREE. REE minerals and deposits generally are classified as either a LREE or HREE type although minerals of both types may occur in a single deposit. Minerals and deposits with LREE are more abundant than those with HREE.

RE Ores The REE have multiple ores. The principal rare-earth ores are bastnäsite, monazite, xenotime, loparite, and lateritic ion-adsorption clays. The majority of the economic REE are derived from LREE ores. Bastnäsite, the principal source of most of the world's REE, is dominated by LREE. It has been mined from several igneous carbonate-rich deposits called carbonatites (Mountain Pass, CA, USA; Mainning, Sichuan Province, China; Weishan, Shandong Province, China, etc.) and from the Bayan Obo, China, iron-niobium-REE deposit, with geologic affinities to both carbonatite and hydrothermal iron-oxide (-Cu-Au-REE) deposits, such as Olympic Dam, Australia, and Kiruna, Sweden (Haxel and others, 2002).

Monazite, a rare earth-thorium phosphate mineral, is quite similar to bastnäsite as a LREE ore, however, it contains slightly more of the HREE, especially, yttrium, dysprosium, and gadolinium. The negative aspect of mining and processing monazite is its typically high content of thorium, a naturally occurring radioactive element (4.5%-10% ThO_2 equivalent). The radioactive content has virtually eliminated monazite production except in small quantities from southeast Asia and India. It is typically mined as a heavy-mineral sand from fluvial or aeolian beach or dunal deposits. It is recovered as a byproduct during processing for ilmenite, rutile, and zircon or cassiterite.

Loparite, a lesser known LREE ore mined from Russia's Kola Peninsula, is an oxide mineral. It has a small HREE content that is similar to monazite's, but with a more balanced REE mix. Loparite is recovered by hard-rock mining methods from the alkali massif's porphyritic rocks with concentrations in the urtites and their feldspar equivalents, juvite and malignite (Hedrick and others, 1997).

Xenotime, a HREE ore, is mined as a byproduct of tin mining and to a lesser extent, as a byproduct of heavy-mineral sands mining. Like monazite, it is a phosphate mineral and was the major ore of yttrium until the mining of the ion adsorption lateritic clays became dominant as a result of lower mining costs and higher abundance.

The ion adsorption lateritic clays are HREE ores. The ore mined in Longnan, Jiangxi Province, China, is enriched in yttrium and is the world's main source of REE. The REE distribution of the Longnan ore is analogous to xenotime and was obviously derived from the intense weathering of this mineral.

The lateritic ion adsorption clay from Xunwu, Jingxi Province, China, is LREE-enriched, however it still has a much higher HREE content compared to the other LREE ores, bastnäsite, monazite, and loparite. This ore also is a significant source of the world's yttrium supply.

World REE Supply The world's REE supply is provided primarily from China. In 2002, the latest available production data, China produced 97,000 short tons (88,000 metric tons) equivalent REO. This represents 90% of the world's total production of 108,000 short tons (98,200 metric tons) REO (Hedrick, 2004). Principal uses were in glass polishing and ceramics, petroleum refining catalysts, metallurgical additives and alloys, automotive catalytic converters, rare-earth phosphors, permanent magnets, and miscellaneous applications. U.S. REE import sources in 2002 were China with 62% and France with 12%. Intermediate REE compounds processed in France, however, were primarily sourced from China (Hedrick, 2004).

The REE ores are processed by various methods to make intermediate REE concentrates and are further purified using solvent extraction and selective precipitation. These REE are used in hundreds of products, including several that are critical to defense applications.

Precision Guided Munitions REE are used in both missiles and "smart" bombs which are broadly classified as precision guided munitions (PGM). Missiles are classified into eight categories; air-to-air, air-to-surface, air-launched bombs, cruise, anti-ship, surface-to air, surface-to-surface, and strategic nuclear missiles. Although most of the missiles covered in these eight categories incorporate rare earths, only a select few are discussed in this paper (Missile data were provided by the U.S. Government and its contractors, including the U.S. Army, Navy, Air Force, Marines, National Guard, The Boeing Company, Lockheed Martin Corporation, and Raytheon Company). Each missile uses samarium-cobalt permanent magnet motors to direct the moving flight control surfaces (fins) (Hedrick and Templeton, 1991).

Air-to-air Three types of missiles are classified as air-to-air, the AIM-9 "Sidewinder," the AIM-54 "Phoenix," and the AIM-120 AMRAAM. The AIM-9 "Sidewinder," which uses infrared heat-seeking targeting, has four fins mounted on the forward section of its fuselage that control its flight trajectory with rare-earth magnet motors. The AIM-54 "Phoenix" is a long-range missile that uses semiactive and active radar guidance. It is directed by samarium-cobalt motors positioning the fins at the rear of the missile.

The advanced longer-range AIM-120 AMRAAM (Advanced Medium-Range Air-to-Air Missile) is replacing the AIM-7 air-to-air missile. Movable flight surfaces of the AIM-120 are mounted mid-fuselage and are directed by samarium-cobalt actuators.

Air-to-surface The AGM-84E SLAM (Standoff Land Attack Missile) missile was designed to attack ships and land-based targets. The SLAM is directed by rare-earth-controlled fin actuators that are mounted mid-fuselage and has a range of over 70 miles (113 km). The AGM-88 HARM (High speed Anti-Radiation Missile) is an anti-radar missile. Designed to seek and destroy radar-emitting sources, it can be fired at an active radar source or launched in loiter mode, where it will cruise and delay targeting until a radar source is activated. Fins are controlled by rare-earth magnets that direct the missile based on guidance data from rare-earth microwave-sensing devices.

Stinger handheld missiles Small, lightweight, and portable, the stinger missile can be easily hidden inside a car or a van. The missile has heat sensors in the tip and a computer that guides it straight to an aircraft's engines using rare-earth magnet motors to control the fins. They can shoot down an aircraft as high as 11,500 feet (3,505 meters) and can attain a velocity of Mach 2.0.

Cruise missiles The only production cruise missile in this category is the BGM-109 Tomahawk. The BGM-109 Tomahawk missile deploys its flight control surfaces after launch. The guidance system of the Tomahawk is connected to tail control fins that use direct drive rare-earth magnet actuators.

Smart bombs U.S. Joint Direct Attack Munitions (JDAM) are a group of air-to-surface "smart bombs" that use neodymium-iron-boron magnets to control the drop direction when dropped from an aircraft. The JDAM program retrofitted existing munitions by adding directional control for improved accuracy; reclassifying them as PGMs. JDAM's include the GBU-29 (350-lb), GBU-30 (500-lb), GBU-31 (2,000-lb), GBU-32 (1,000-lb), GBU-35 (1,000-lb), and the GBU-38 (500-lb). Other bombs retrofitted with tailkits using rare-earth magnets are the Global Positioning System Aided Munitions (GAM) encompassing the GBU-36/B (2,000-lb) and the GBU-37/B (4,500-lb) penetrator known as the "bunker buster" (Kopp, 1996).

Lasers U.S. defense forces employ neodymium:yttrium-aluminum-garnet (Nd:YAG) lasers as rangefinders, target designators, and target interrogators. Onboard U.S. tanks and other vehicle-mounted weapon systems, rare-earth lasers are used to determine the range of enemy targets at distances of over 22 miles (35 kilometers). Portable rangefinders, carried by ground troops, have a range of at least 9 miles (14 kilometers).

Portable target designators, which illuminate a target with a precisely coded beam of laser light, operate at ranges up to 30 miles (48 kilometers), while airborne laser target designators are operable to distances of 80 miles (129 kilometers). The laser-equipped computer gun sight on the Abrams M1A1/2 tank combines a Raytheon rangefinder and integrated designator targeting system for a high-probability first hit.

Rare-earth laser interrogators are used for enemy detection and countermeasures. A short laser pulse, often in the ultraviolet (UV) range, is emitted that illuminates the object and allows a receiver to analyze and determine if the object is friend or foe. Object information determined includes object type, speed, direction of movement, analysis of its weapons system, and appropriate response. A second type of laser interrogator scans for enemy optics, and upon detection, employs countermeasures to evade detection and/or destroy the enemy system. A third type of interrogator, typically attached to a missile weapons system, emits a predetermined wavelength and pattern to visually interrogate multiple objects in the battlefield. Within milliseconds, it elicits a predetermined signal or response from all friendly objects in the battlefield and launches missiles to destroy all unidentified (unfriendly) objects.

The principal system used to detect underwater mines uses a rare-earth laser system. The airborne countermeasure system known as “Magic Lantern” uses a blue-green frequency-doubled Nd:YAG laser to scan below the water surface (Military & Aerospace, 1997).

Communications Traveling wave tubes (TWT) and klystrons that generate and amplify microwaves use rare-earth magnets in their waveguides. In defense applications, TWT's and klystrons are used in satellite communications, troposcatter communications, pulsed or continuous wave radar amplifiers, and communication links. To focus the electron beam, periodic permanent magnets of rare earths are used in wide bandwidth helix TWT, while nonperiodic permanent magnets are applied in higher-energy, narrow bandwidth klystrons.

Rare-earth lasers are used in line-of-sight communication links in satellite- and ground-based systems. Communication lasers have had limited application in satellites that are in geosynchronous or geostationary orbit (GEOs), but expanded use is planned in low Earth-orbit (LEOs) satellites. Laser light’s higher frequencies allows a greater bandwidth and faster data throughput than conventional microwave transfer.

Erbium-doped fiber and fiber amplifiers are applied in high-capacity fiber optic systems. In field scenarios, distribution of a fiber optic communications grid can be quickly accomplished by ground troops, vehicles, or fast line distribution from helicopters. Advantages of the erbium-doped fiber are its capacity to carry large amounts of digital data, its ability to cover large distances without a repeater or signal amplifier, a wide range of temperature stability, immunity to interchannel crosstalk, and security from outside interference and electronic interception.

Rare-earth speakers Neodymium-iron-boron permanent magnets are used in speakers and other sound system components (tape, hard disk, and CD/DVD drives) used in psychological warfare. For example, in Ethiopia, a decoy invasion was staged in darkness using the sounds of ships, tanks, helicopters, and voices created by speakers on rafts. Meanwhile the landing force quietly came ashore miles away. Samarium-cobalt or neodymium-iron-boron rare-earth permanent magnets, and terbium-iron-nickel alloy with dysprosium (Terfenol-D) are used in stealth technology in helicopters to create white noise to cancel or hide the sound of the rotor blades. Terfenol-D, a magnetostrictive alloy, was originally developed by U.S. Navy scientists for use as a transducer for sonar applications (Clark, 1980). Sensors monitor noise or vibration levels, then computers drive Terfenol-D actuators to provide equal force at the same frequency, but 180° out of phase, effectively eliminating the noise or vibration.

Aircraft Samarium-cobalt permanent magnets are used in generators that produce electricity for aircraft electrical systems. In addition, small high-powered rare-earth magnet actuators are employed in moving the flight control surfaces of aircraft, including flaps, rudder, and ailerons.

Yttria-stabilized zirconia, a high-temperature resistant ceramic coating, is used as a thermal barrier in the "hot" sections of jet engines to protect the metal alloys. Yttria keeps the zirconia from changing from a tetragonal to monoclinic structure, which would degrade the ceramic's high-temperature stability and strength. The ceramic coating is used in the Pratt & Whitney

F100-PW-229 turbofan engine for the McDonnell Douglas Corp. F15 Eagle and the Lockheed Martin F16 Fighting Falcon fighter jets (Hedrick, 1990).

Displays Color televisions and computer monitors are essential components in many defense system control panels to display and quickly communicate data, especially in avionic displays and vision enhancement screens. Rare earths have been used in color cathode ray tube (CRT) phosphors since the early 1960s. Europium-yttrium compounds have long been used as a red phosphor in CRT screens because of its sharp excitation color peak at 611 nanometers (nm). Color super video graphics array (SVGA) monitors typically use medium-to-short persistence phosphors. This enables faster SVGA image changes and eliminates ghosts.

Cerium oxide is an additive in CRT glass to reduce “browning” from electron emissions and as a glass polishing compound for CRT faceplates. Recent technology uses liquid crystal digital (LCD) displays in flat panel displays (FPD) for computers, avionics, and weapon system monitors. FPDs typically use either twisted nematic/super-twisted nematic (TN/STN), thin film transistor (TFT) LCD technology, or plasma display panels (PDP) (Asahi Glass Co. Ltd., 2003). All of these FPDs have glass panels or substrates that are polished with cerium oxide.

Avionic displays use terbium-doped gadolinium oxysulfide and lanthanum oxysulfide phosphors for high-luminescence. The rare-earth avionic phosphors emit yellow-green light at 542 nm and 545 nm wavelengths, respectively (Teckotsky, 1981).

Installed on the Abrahms M1A1/2 tank is a Raytheon AN/VSS-5 Drivers Vision Enhancer that allows the driver to view the horizon using a microwave (7.5- to 13-micron) multielement detector array.

Radar Systems Rare earths are used in several applications in radar systems. Rare-earth permanent magnets, typically samarium-cobalt, are used in the radar’s TWT to focus the microwave energy. Yttrium-iron garnets (YIG) and yttrium-gadolinium garnets (YGG) are used in phase shifters, tuners, and filters. These systems are used in the PATRIOT (Phased Array Tracking to Intercept of Target) air defense missile system's guidance and radar control group (Hamant, 1977). Samarium-cobalt magnets are used in both the missile's and radar system's TWT (oral communications, Robert F. Hatem, Manager, Customer Relations, and Howard L. Graves, Patriot Program, Raytheon Co., Bedford, MA, June 25, 1993). YGG's are used in the toroids in the PATRIOT's phased array elements and in the radio frequency (RF) circulators in the radar and missile. RF circulators magnetically control the flow of electronic signals.

Samarium-cobalt permanent magnets are used to focus the electron beam of radar magnetron tubes. Magnetron tubes are used in ground-based systems for air traffic control and surveillance radar, search radar, and weapon fire-control radar. Defense radar also is used for anticollision and avoidance, weather detection, and as a navigational aid in aircraft and naval applications.

Cross field amplifiers (CFA) generate moderate bandwidth, moderate gain, and output signals in a smaller and lighter weight unit than traditional microwave tubes. CFA are used in ground-based, airborne, and phased array radar applications. Output is typically focused with samarium-cobalt magnets. CFA are used in the phased array system of the AN/SPY-1 radar in the Navy's AEGIS system. The AEGIS radar and missile array is the most advanced shipboard system deployed for antiaircraft and antimissile defense. Yttria also is used in some electron-emitting cathodes in TWT, magnetrons, and other devices.

Coatings Gadolinium metal, applied as a paint or coating, was used as a defensive measure against neutron radiation. Gadolinium, which has the highest neutron capture cross section of all the elements, is the material of choice for absorbing high-energy neutrons.

Optical Equipment Cerium-based compounds are used as polishing media for many types of optical lenses encountered in the battlefield. Many of these lenses also contain the additive lanthanum oxide, to increase light refraction and decrease dispersion. Precision polished optical lenses are used for ranging, targeting, observation, detection systems, countermeasures, photography, and protection from harmful laser wavelengths, flashblindness, UV and reflected light. Rare earth-containing optics are used in binoculars, rifle scopes, laser targeters and designators, telescopes, microscopes, protective eyewear, rangefinders, night-vision equipment, camera lenses, filters, and protective lenses.

Sonar Terfenol-D rare-earth alloy is replacing piezoceramic materials in several devices including high-power sonar on ships and submarines. Terfenol's response to a magnetic field is 200 times faster than a mechanical device. It also has recently been designed for use as a diesel fuel injector, adjusting its size almost instantaneously to dispense the proper amount of fuel.

Terfenol also is used in actuators to quickly, forcefully, and precisely adjust, aim, balance, and control all types of equipment, such as lasers, reflectors, and lenses.

Ultrasonic transducers REE ultrasonics, defined as the oscillations in a frequency range between 16 kHz and 1 GHz that cannot be heard by humans, are used in sonochemistry, ultrasonic welding, food processing, waste material conversion, ultrasonic machining, medical tools, hand tools, and to kill bacteria.

Sonic transducers Terfenol's acoustic energy is developed through the expansion and contraction of a highly tuned acoustic element, driving high-pressure waves. The oil industry uses this property in a downhole instrument to increase the strategic supply of oil. This acoustic energy, or sound energy, results from a change in pressure. The introduction of acoustic or vibratory energy into an oil-bearing formation affects oil recovery in several ways. Vibration reduces surface tension between the oil and the rock wall, freeing the oil to leave the pores and flow to the well bore. This same vibrational energy also results in the elimination of surface films that prevent oil from flowing out of the pores.

Computers Computers having neodymium-iron-boron permanent magnets are used in many defense systems. Designed to withstand vibration, impact, and g-forces, rare-earth disk drive motors and actuators are installed in aircraft, tanks, missile systems, and command and control centers.

Electronic Counter Measures Electronic counter measures (ECM) cover a wide array of applications. ECM systems comprise equipment to detect a variety of electronic signals and transmissions in the battlefield. Interactive ECM equipment acts to jam, absorb, redirect, or return false data. Jammers act to interfere with an enemy's original signal so it becomes scrambled or useless. ECM can also capture radar transmissions and cancel the returning signals by matching or shifting wavelengths. Radar data also may be intercepted, analyzed, and returned as a false reflected signal that redirects missiles off-target. Interactive ECM systems are used to intercept voice and wavelength transmissions, analyze the message, alter the message, and retransmit a false or conflicting voice or signal that will confuse, divert, or even cancel an enemy's mission. Rare earths, including gadolinium, yttrium, and samarium are used in several types of ECM equipment such as the Tail Warning Function (TWF). The TWF is a defensive system that uses a pulsed Doppler radar to detect missiles approaching the aircraft from behind and dispenses defensive countermeasures to defeat the attack by jamming them with ECM.

Future Supply Future REE supplies are expected to be primarily from the Bayan Obo and Mianning deposits in China. Lesser amounts of REE are expected to be sourced from Australia's Mt. Weld carbonatite, India's heavy-mineral sands deposits in the States of Kerala, Orrisa, and Tamil Nadu, and the United States' Sulphide Queen carbonatite at Mountain Pass, CA.

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