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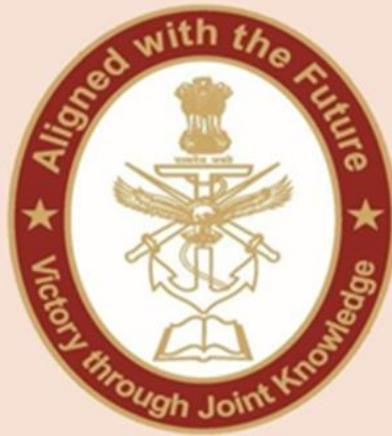
RARE EARTH ELEMENTS: THE HIDDEN ENGINES FUELLING THE FUTURE

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CENTRE FOR JOINT WARFARE STUDIES



CENJOWS

**RARE EARTH ELEMENTS:
THE HIDDEN ENGINES
FUELLING THE FUTURE**



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Introduction

The rare earth elements perplex us in our researches, baffle us in our speculations, and haunt us in our very dreams. They stretch like an unknown sea before us mocking, mystifying and murmuring strange revelations and possibilities.¹

- William Crookes

Imagine substances that are scarce, unevenly distributed and having an extraction process so complex that they create a competition among even the so called biggest of the biggest economies in the world. There is a possibility that few things comes to our minds. But what if someone were to tell you that one such substance has an application ranging so wide that they are found in wind turbines, semi conductors, missile guidance systems, electric vehicles, nuclear reactors, night vision devices, X-rays, high temperature fuel cells making them a critical for applications in defence, aerospace, clean energy, electronics, and healthcare thus making them substances of strategic importance. These truly justify their name, **The Rare Earth Elements**

(hence referred to as REEs). This article explores their application focusing particularly in the domain of aerospace and defence, their global reserves and supply chain and an Indian perspective in terms of challenges and opportunities that they offer in this era of intense competition and of asserting global dominance.

The 17 Keys of the Cosmic Vault

(Fig. REEs highlighted in a Periodic Table)

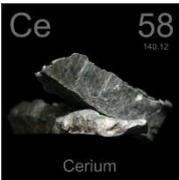
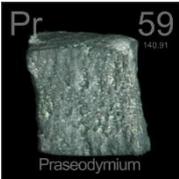
(Source - od6metals.com)

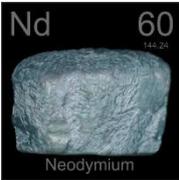
There is a total of 17 REEs which includes 15 lanthanide series elements¹, lanthanum (La) through lutetium (Lu) along with scandium (Sc) and yttrium (Y). Each of these has their respective applications in various fields as mentioned earlier. The table below provides comprehensive details about their Chemical properties, Physical properties and their major applications.

Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
scandium (Sc)	21	44.956	1541	2836	<ul style="list-style-type: none"> Used in making Light weight High strength Aerospace alloys,

¹ Elements on the periodic table from atomic number 57 through 71.
² The number of Protons (positively charged sub atomic particles) in an element.
³ Temperature at which the element starts to melt.
⁴ Temperature at which the element starts to Boil.

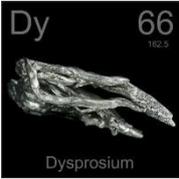
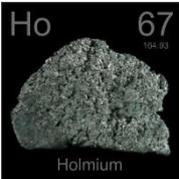
Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
 <p>Scandium</p>					<ul style="list-style-type: none"> • Jet engine parts and Turbine blades, • Munitions and precision and Explosives • Coatings for military instruments etc • Thermal barrier coatings
<p>yttrium (Y)</p>  <p>Yttrium</p>	39	88.906	1526	2930	<ul style="list-style-type: none"> • Phosphors in display • YIG filters in Radar and Sonar • Missile casings • Heat resistant ceramics etc
<p>lanthanum (La)</p>  <p>Lanthanum</p>	57	138.905	918	3464	<ul style="list-style-type: none"> • Used as alloy additive for structural materials • High quality lenses, sensors, infrared absorbing pilot vision systems • In making carbon arc lamps • Used in advanced radar and sonar devices • NiMH batteries • Scintillator materials

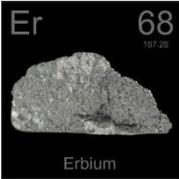
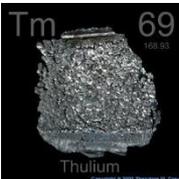
Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
<p>cerium (Ce)</p> 	58	140.116	795	3443	<ul style="list-style-type: none"> • Used as a polishing compound for aircraft components • Protective coating in Aircraft engines • Used in catalytic operations to control emissions • Manufacturing of Optical lenses
<p>praseodymium (Pr)</p> 	59	140.908	935	3130	<ul style="list-style-type: none"> • Manufacturing of precision optical glasses • Used in epoxy primer coatings on military aircraft • Used as a dopant in laser materials and fibre optics • Used to enhance NdFeB magnets • Used for films and coatings on semiconductors

Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
neodymium (Nd) 	60	144.242	1024	3074	<ul style="list-style-type: none"> • Used in Actuators and Control mechanisms • Used in sensors for measuring various parameters in aircrafts • Neodymium magnets are used in EM Propulsion • NdFeB magnets are used for fin control mechanisms • Used to power high frequency devices
promethium (Pm) 	61	145	1042	3000	<ul style="list-style-type: none"> • Used in long life atomic batteries for maintenance free power in space crafts • Used in non-destructive testing and medical imaging • Use as prototype radiation source • Used to minimise thermal signatures in stealth operations
samarium (Sm)	62	150.36	1072	1794	

Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
 <p>Samarium</p>					<ul style="list-style-type: none"> • Used in Satellite attitude control devices. • Used in Navigation and Gyroscopes • Used to reduce radar signatures as coatings • SmCo magnets are used in turbo machinaries • Used in sonar transducers and destroyers
<p>europium (Eu)</p>  <p>Europium</p>	63	151.964	822	1597	<ul style="list-style-type: none"> • Used in cockpit and Heads up displays (HUDs) • Used to provide UV fluorescence feature to prevent counterfeiting • Acts as neutron absorbers hence enhancing nuclear safety • Used to enhance clarity and precision of optical sensors

Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
gadolinium (Gd) 	64	157.25	1313	3273	<ul style="list-style-type: none"> • Used in supporting advanced sonar systems for their magnetic properties • Used for neutron shielding in Nuclear powered submarines • Used in advanced ISR systems because of their Paramagnetic nature and thermal stability • Used in production of sensors • Used in sonar systems, acoustic devices and precision actuators. • Used to enhance image quality, brightness and colour quality in military and aerospace defence technologies • Used to improve thermal stability and magnetic properties of NdFeB magnets
terbium (Tb) 	65	158.925	1356	3230	

Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
<p>dysprosium (Dy)</p> 	66	162.5	1407	2567	<ul style="list-style-type: none"> • Used as a stabiliser in high temperature fuel cells. • Used to enhance magnets used in advanced air radar precision guided munitions. • Used to dope crystals that are used in target, guidance and defence applications • For Nuclear safety in military propulsions • Holmium doped lasers are used in military targeting and guidance systems and directed energy weapons.
<p>holmium (Ho)</p> 	67	164.93	1474	2700	<ul style="list-style-type: none"> • Used as radar absorbing materials to enhance stealth abilities. • Holmium lasers are used to secure military laser communications systems

Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
erbium (Er) 	68	167.259	1529	2868	<ul style="list-style-type: none"> • Used in sonar suppression systems. • Used to amplify optical signals in fibre optic cables. • Used in solid state lasers • Used to produce IR absorbing lights used in military eye wear • Used in IR Sensors and detectors • Used in geological surveying and battle field awareness • Used in Portable X-ray machines, • Used as a dopant in Fibre lasers • Used for lidar sensing, IR countermeasures, atmospheric sensing technologies. • Used in high-temperature superconductors
thulium (Tm) 	69	168.934	1545	1950	
ytterbium (Yb)	70	173.045	824	1196	

Element	Atomic Number ²	Atomic Mass (AMU)	Melting Point (°C) ³	Boiling Point (°C) ⁴	Applications in Aerospace and Defence
 <p>Ytterbium</p>					<ul style="list-style-type: none"> Used in stress gauges that are used to monitor ground deformations from nuclear explosions Used in coating materials for turbine blades and engine parts
<p>Lutetium (Lu)</p>  <p>Lutetium</p>	71	174.967	1663	3402	<ul style="list-style-type: none"> Used as catalysts in petroleum refining, Used to manufacture high refractive index glasses

(Table – REEs with their Chemical and Physical Properties and their Application)

(Source - Compiled by the Author)

(Source for Images - <https://periodictable.com>)

Global scenario

As their name suggests, they are Rare i.e., are found in a limited geographical region thus creating a very competitive scenario making them extremely important. Countries around the world with abundant REEs reserves have a tactical as well as a strategic advantage and an edge given their wide range applications. Countries like China, having the world's largest reserves is a global front runner and a major producer where REEs contribute a large portion to it's economy. Global Rare Earth Elements Market Size is expected to grow from **USD 3.88 billion** in 2024 to **USD 10.42 billion** by 2035, at a CAGR of **9.40%**² while its demand is projected to grow from 91kt in 2024 to 150kt by 2040.³ It is estimated that the top 3 mining countries will contribute about 3/4th of

the total and top 3 refining ones will contribute about 92% of the total by 2030.⁴ The top 10 countries by REE reserves are as follows,⁵

China	44 MT ⁵
Vietnam	22 MT
Brazil	21MT
Russia	10MT
India	6.9MT
Australia	5.7MT
United States	1.8MT
Greenland	1.5MT
Tanzania	890KT ⁶
Canada	830KT
South Africa	790KT
Thailand	4.5KT

A country’s ability to “extract” also is an important factor considering the complexities involved in the same. Possession of technologies that aids and smoothens the process is what makes it able to utilise the reserves to the full extent. Each REE has its own procedure that needs to be followed in order to get the maximum products out of the ore and then apply the refining process to obtain the finished product in order to be used in various domains mentioned earlier.

REEs: the hidden heroes in Defence applications

Rare Earth Elements (REEs) are critical to modern defence technologies due to their unique magnetic, optical, and catalytic properties.⁶ They are indispensable in a wide range of military applications, from precision-guided munitions to advanced communication systems, radar technologies, and in next generation advanced weapon systems.⁷ Their limited availability, along with their strategic importance, has made REEs a point of contestation in geopolitical and military strategies, as nations try their best to secure reliable supply chains to maintain technological dominance.

⁵ Million Tonnes

⁶ Kilo / Thousand Tonnes

One of the most prominent uses of REEs in defence is in the production of high performance magnets, particularly those made from neodymium,⁸ dysprosium, and samarium.

Neodymium – iron - boron (NdFeB) magnets, in addition to dysprosium that are used to enhance thermal stability,⁹ are among the strongest permanent magnets available. These magnets are critical components in electric motors and actuators used in military platforms such as fighter jets, drones, and missile guidance systems.

For example, the precision-guided Joint Direct Attack Munition (JDAM) depends on these magnets for its control systems, making them an able contenders for accurate targeting.¹⁰ Similarly, samarium - cobalt magnets, that have extreme temperature resistance, are used in radar systems and missile propulsion units, such as those in the Aegis Missile Defence System (AMDS).¹¹ These magnets provide the reliability and performance required in extreme operational environments, where achieving targets is uncompromisable.

REEs also play a vital role in advanced electronics and communication systems, which are the crucial for modern warfare. Elements like yttrium, europium, and terbium are essential in the production of phosphors used in displays, lasers, and night - vision equipment.¹² Yttrium, for instance, is a key component in yttrium – aluminium - garnet (YAG) lasers,¹³ which are employed in range-finding and target designation for precision strikes. These lasers are integral to systems like the Hellfire missile, used extensively in anti-tank and anti-personnel operations. Europium and terbium, on the other hand, are critical for creating the vivid displays in cockpit screens and heads-up displays (HUDs) in aircrafts.¹⁴ These displays allow pilots to process critical information in real time, enhancing situational awareness and mission success rates. Furthermore, REEs like lanthanum are used in the production of high-refractive-index glass for optical lenses in reconnaissance satellites and unmanned aerial vehicles (UAVs), enabling high-resolution imaging for intelligence, surveillance, and reconnaissance (ISR) missions.¹⁵

Another critical application of REEs lies in the domain of energy systems, particularly in batteries and propulsion technologies. Dysprosium and praseodymium are used in high-capacity nickel-metal-hydride (NiMH) batteries, which power movable military

equipment such as radios, GPS devices, and field sensors.¹⁶ These batteries offer high energy density and reliability, crucial for operations in remote or sensitive environments where opportunity to recharge are limited. Additionally REEs are integral in the development of advanced propulsion systems. Cerium, for example, is used as a catalyst in the production of jet fuel additives, improving combustion efficiency in engines like those of the F-22 Raptor.¹⁷ Similarly, scandium is increasingly combined with lightweight aluminum alloys for airframes and missile casings, reducing weight while maintaining structural integrity, which enhances fuel efficiency and payload capacity in military aircraft and missiles.¹⁸

Radar and electronic warfare systems also heavily depend on REEs. Gallium, often obtained as a by product of REE processing, is used in gallium arsenide semiconductors¹⁹ for radar and communication systems. These semiconductors are found in phased array radars, such as those used in the Patriot missile defence system,²⁰ which require high-speed, high-frequency performance to detect and track incoming threats. Additionally, REEs like erbium are used in fiber-optic communication systems, enabling secure, high-bandwidth data transmission for military networks.²¹ These systems are critical for coordinating operations across dispersed units, ensuring real-time communication in complex battlefields. The integration of REEs in these technologies underscores their role in maintaining a technological edge in electronic warfare, where speed and reliability are paramount.

The strategic importance of REEs in defence is compounded by their scarcity in supply and the challenges associated with their extraction and processing. REEs while may not be exactly "rare" in terms of geological abundance, but their deposits are often low-grade and difficult to mine economically. China has dominated the global REE market, controlling approximately 60-70% of production and over 80% of refining capacity as of recent estimates.²² This dominance raises significant concerns for nations like the United States, which relies heavily on REEs for its defence industrial base. REE supply chain vulnerabilities are widely acknowledged as a critical national security issue, as disruptions could impair the production of key defence systems. For instance, a 2010 incident where China temporarily halted REE exports to Japan highlighted the risks of over-reliance on a single supplier, prompting efforts to diversify sources and invest in domestic production.²³

Looking ahead, the role of REEs in defence is likely to expand as emerging technologies, such as quantum computing and hypersonic missiles, demand even more specialized materials. For instance, REEs like holmium and thulium are being explored for their potential in quantum sensors, which could revolutionize navigation and detection systems for submarines and satellites.²⁴ The development of these technologies highlights the need for robust supply chains and innovative extraction methods to meet future demand.

Geological Potential and Reserves

In India, the deposits of REEs are found in various geological formations such as carbonatites, alkaline complexes, pegmatites, and beach placer sands.²⁵ Some prominent regions where these deposits are found include

1.Odisha and Andhra Pradesh: Eastern coast rich in Monazite sands yield light REEs (LREEs) like lanthanum, cerium, praseodymium, and neodymium.²⁶

2.Rajasthan: The Amba Dongar Carbonatite complex and new deposits in Balotra, Jalore, and Barmer has deposits of bastnasite, britholite, and xenotime, rich in both LREEs and heavy REEs (HREEs) like dysprosium and terbium.²⁷

3.Kerala and Tamil Nadu: Coastal placer deposits contain monazite, but due to the prevalence of thorium as well, there's an extraction challenge due to presence of radioactivity.²⁸

4.Other Regions: Deposits in Mysore (Karnataka), Ranchi (Jharkhand), Bastar (Chhattisgarh), and Amarkantak (Madhya Pradesh) are linked to carbonatites and pegmatites, with potential for HREEs.²⁹

Recent Discoveries

Recent exploration efforts have boosted India's REE potential

1.Anantapur, Andhra Pradesh (2023): The CSIR-National Geophysical Research Institute (NGRI) identified LREEs (lanthanum, cerium, neodymium) in carbonatite-syenite complexes under the SHORE project.³⁰ Minerals like allanite, ceriate, thorite, and monazite were found, with deep drilling on going to confirm economic viability.

2.Singrauli Coalfields, Madhya Pradesh (2025): A ground breaking discovery of REEs (neodymium, yttrium, europium) in fly ash from coal fields offers a sustainable alternative source.³¹ The Central Mine Planning and Design Institute Limited (CMPDIL) plans a pilot extraction plant by FY26, using ion-exchange and solvent extraction (SX).

3.Purulia, West Bengal (2025): The Geological Survey of India (GSI) confirmed 0.67 million tonnes of REEs in hard rock deposits, including bastnasite and monazite.³²

4.Balotra and Jalore, Rajasthan (2025): GSI and Department of Atomic Energy (DAE) efforts identified high-grade bastnasite, britholite, and xenotime deposits, offering higher REE concentrations for efficient refining.³³

In 2024, India produced 2,900 metric tonnes of REEs,³⁴ compared to the global 390,000 metric tonnes³⁵ (a mere 0.74%), while China alone contributed about 270,000 Metric tonnes (about 69%).³⁶ IREL exports high-purity lanthanum, cerium, neodymium-praseodymium, samarium, gadolinium, and yttrium, but recent policies prioritize domestic needs for aerospace and defence.

Aerospace and Défense Applications

REEs are critical to India's aerospace and defence sectors, underpinning strategic programs:

1.Missile Systems: Neodymium and dysprosium are used in NdFeB magnets for precision-guided munitions,³⁷ ensuring accurate targeting and navigation. HREEs like terbium enhance magnet performance in extreme conditions.³⁸

2.Fighter Jets: Fighter jets use samarium-cobalt magnets for actuators, control systems, and engine components, offering high-temperature resistance.³⁹ Dysprosium improves magnet durability in high-altitude operations.⁴⁰

3.Space Missions: Space missions use yttrium, erbium in satellite communications, laser systems, and thermal imaging.⁴¹ Beryllium, often co-occurring with REEs, is critical for lightweight aerospace structures.

4.Radar and Sonar: REEs like gadolinium and yttrium enhance signal processing in radar systems⁴² for tanks and naval destroyers, improving detection capabilities.

5.Drones and UAVs: Neodymium magnets enable lightweight, efficient motors for unmanned aerial vehicles,⁴³ critical for surveillance and combat.

6.Night Vision and Lasers: Europium and terbium are used in night-vision goggles and laser rangefinders for military operations, providing superior image quality.⁴⁴

India has introduced reforms in the context of global supply chain vulnerabilities

1.National Critical Mineral Mission (NCMM, 2025)⁴⁵: Launched with ₹16,300 crore, the NCMM aims to conduct 1,200 GSI exploration projects by FY31, targeting self-reliance in REEs for defence, aerospace, and clean energy.

2. India Rare Earths Mission: It seeks to streamline regulations and boost private investment in mining, refining, and magnet production.

3. Mining Law Reforms (2023): Removed REEs like niobium and zirconium from the atomic minerals list, issuing over 100 exploration licenses to private firms in 2024.⁴⁶

4.Production-Linked Incentive (PLI) Scheme: A ₹1,000 crore initiative supports domestic manufacturing of NdFeB magnets for defence and EVs.⁴⁷

5.International Collaborations: India joined the U.S.-led Minerals Security Partnership in 2024, focusing on REE supply chain diversification.⁴⁸ Khanij Bidesh India Limited (KABIL) secured lithium and cobalt exploration in Argentina in 2024⁴⁹ and is negotiating REE access in Australia and Brazil.⁵⁰

6.Export Restrictions: In June 2025, India suspended a 13-year REE export agreement with Japan to prioritize domestic aerospace and defence needs, reflecting a sense of resource nationalism.⁵¹

Geopolitical Volatility and Strategic Concerns

Global geopolitical tensions, particularly U.S.-China trade wars and China's REE export restrictions, have heightened India's supply chain vulnerabilities:

China's Dominance: China's 90% control over REE refining and 2025 export curbs on seven HREEs i.e., samarium, gadolinium, terbium, dysprosium, lutetium, scandium, yttrium⁵² is a potential drawback for India's defence and aerospace

programs. For example, dysprosium restrictions have caused delays in magnet shipments for Indian EV and missile production.⁵³

Price Volatility: China's 2010 export ban on Japan caused a staggering 27 fold price surge for dysprosium,⁵⁴ a precedent for current concerns.(46) India's 65% REE import reliance on China⁵⁵ exposes it to similar price shocks.

Defense Vulnerabilities: India's missile programs and fighter jets depend on HREEs, entirely imported, risking production halts.

Global Supply Chain Risks: China's strategic use of REEs as a geopolitical tool, as seen in 2010⁵⁶ and 2023-25,⁵⁷ underscores the need for India to diversify supplies. PM Modi's 2025 BRICS Summit statement urged secure mineral supply chains, implicitly criticizing weaponization of such crucial resources actions.⁵⁸

Regional Power Dynamics: India's rising regional influence, coupled with partnerships like the U.S.-India REE cooperation, aims to counter China's leverage, but progress is slow due to technological gaps.

Challenges

India's REE sector faces significant hurdles, exacerbated by global volatility:

Processing Technology: India needs to invest more in advanced separation technologies e.g., solvent extraction, ion chromatography.

Monazite's Thorium Content: High thorium levels (>5%) in monazite require costly radioactive waste management, delaying mining projects.⁵⁹

Environmental Concerns: Beach sand mining disrupts coastal ecosystems, and fly ash extraction risks pollution, requiring stringent regulations.

Geopolitical Risks: China's export restrictions and U.S.-China tensions could disrupt India's REE imports, impacting defence production timelines.

Future Prospects

India's recent discoveries and policies offer a path to strategic autonomy:

Sustainable Extraction: Fly ash recovery in Singrauli could yield significant amount of REEs, supporting defence radar and laser systems while reducing environmental impact.

Private Sector Growth: Relaxed regulations and PLI schemes could attract global firms thus boosting refining and magnet production for aerospace.

R&D and Innovation: IREL Technology Development Council (IRELTDC) is formed with an objective of promoting industrial scale R&D that would be beneficial to the overall programme of DAE in both strategic and non-strategic fields utilizing mineral & value-added products of IREL. Council invites funds and monitors R&D project proposals from CSIR, IITs, State & Central laboratories, for large scale application & exploitation on the areas of technology of mutual interest.⁶⁰ A proposed Centre of Excellence⁶¹ for REEs could bridge technological gaps.

Strategic Stockpiling: India should plan a REE strategic stockpiling in the years to come to mitigate supply shocks, ensuring defence and aerospace stability.

International Partnerships: Collaborations with the U.S., Australia, and Brazil could provide technology transfers and secure HREE supplies for India's missile and space programs.

Defence and Aerospace Growth: Scaling up NdFeB and samarium-cobalt magnet production could support indigenous programs reducing import reliance significantly.

Conclusion

Rare Earth Elements stand as the silent enablers of modern technology, especially in aerospace and defence, where their properties fuel everything from advanced radar to precision guided missiles. In case of India, recent discoveries, policy reforms, and strategic collaborations present a solid opportunity to reduce import dependency, enhance domestic production, and to secure supply chains against global instability. However, overcoming technological, environmental, and geopolitical challenges is the need of the hour. By investing in necessary Research and Development domains India can transform its REE potential into a strategic one, ensuring self resilience and a dominant say in an increasingly resource competitive world.

DISCLAIMER

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Reference:

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- ¹ "William Crookes Quote." 2025. A-Z Quotes. 2025. <https://www.azquotes.com/quote/1116916>.
 - ² Spherical Insights. 2025a. "Global Rare Earth Elements Market Size to Exceed USD 10.42 Billion by 2035 | CAGR of 9.40%." Spherical Insights. June 17, 2025. <https://www.sphericalinsights.com/press-release/rare-earth-elements-market>.
 - ³ "Can the US Break China's Grip on Rare Earths?" 2019. Cmcmarkets.com. 2019. <https://www.cmcmarkets.com/en/optox/can-the-us-break-chinas-grip-on-rare-earths>.
 - ⁴ Andrews-Speed, Philip, and Anders Hove. 2023. "China's Rare Earths Dominance and Policy Responses." <https://www.oxfordenergy.org/wpcms/wp-content/uploads/2023/06/CE7-Chinas-rare-earths-dominance-and-policy-responses.pdf>.
 - ⁵ "Rare-Earth Reserves by Country / Rare-Earth Metals by Country 2023." 2025. Worldpopulationreview.com. 2025. <https://worldpopulationreview.com/country-rankings/rare-earth-reserves-by-country>.
 - ⁶ "Government of India Ministry of Mines New Delhi RARE EARTHS and ENERGY CRITICAL ELEMENTS: A ROADMAP and STRATEGY for INDIA." 2012. <https://mines.gov.in/admin/download/64a3f3e6189cf1688466406.pdf>.
 - ⁷ SFA Oxford. 2025. "Critical Minerals in Defence and National Security | SFA (Oxford)." SFA (Oxford). 2025. <https://www.sfa-oxford.com/knowledge-and-insights/critical-minerals-in-low-carbon-and-future-technologies/critical-minerals-in-defence-and-national-security/>.
 - ⁸ "All about Rare Earth Elements." 2018. Stanfordmagnets.com. 2018. <https://www.stanfordmagnets.com/all-about-rare-earth-elements.html>.
 - ⁹ "The Important Role of Dysprosium in Modern Permanent Magnets." n.d. <https://www.arnoldmagnetics.com/wp-content/uploads/2017/10/Important-Role-of-Dysprosium-in-Modern-Permanent-Magnets-150906.pdf>.
 - ¹⁰ the. 2025. "US-China Rare Earths Deal, and More DoD Money Will Not Loosen China's Grip on Military-Grade Rare Earth Magnets – Richard Mills." Aheadoftheherd.com. June 22, 2025. <https://aheadoftheherd.com/us-china-rare-earths-deal-and-more-dod-money-will-not-loosen-chinas-grip-on-military-grade-rare-earth-magnets-richard-mills/>.
 - ¹¹ "Samarium Cobalt Magnets in the Military | Stanford Magnets." 2018c. Stanfordmagnets.com. 2018. <https://www.stanfordmagnets.com/samarium-cobalt-magnets-in-the-military.html>.

-
- ¹² ———. 2025b. “Critical Minerals in Defence and National Security | SFA (Oxford).” SFA (Oxford). 2025. <https://www.sfa-oxford.com/knowledge-and-insights/critical-minerals-in-low-carbon-and-future-technologies/critical-minerals-in-defence-and-national-security/>.
- ¹³ Solanki, Dr Gaurav. 2023. “ND Yag Laser.” Cult Aesthetics Dermatology | Best Skin Care Clinic in Gurgaon. Cult Aesthetics Dermatology. July 7, 2023. <https://www.cultaestheticsderma.in/nd-yag-laser/>.
- ¹⁴ “Critical Minerals in Lighting and Phosphors | SFA (Oxford).” 2025. SFA (Oxford). 2025. <https://www.sfa-oxford.com/knowledge-and-insights/critical-minerals-in-low-carbon-and-future-technologies/critical-minerals-in-electronics/critical-minerals-in-lighting-and-phosphors/>.
- ¹⁵ “Lanthanum Oxide in Glass Production: Key Benefits and Applications.” 2024. Stanfordmaterials.com. 2024. <https://www.stanfordmaterials.com/blog/lanthanum-oxide-in-glass-production.html>.
- ¹⁶ US Department of Energy. 2024. “Alternative Fuels Data Center: Batteries for Electric Vehicles.” Afdc.energy.gov. 2024. <https://afdc.energy.gov/vehicles/electric-batteries>.
- ¹⁷ “EP1587898A1 - Cerium Oxide Nanoparticles as Fuel Additives - Google Patents.” 2004. Google.com. January 23, 2004. <https://patents.google.com/patent/EP1587898A1/en>.
- ¹⁸ “Aluminum Scandium Master Alloys: Pioneering the Future of Aerospace and Automobiles.” 2019. Stanfordmaterials.com. 2019. <https://www.stanfordmaterials.com/blog/aluminum-scandium-master-alloys-pioneering-the-future-of-aerospace-and-automobiles.html>.
- ¹⁹ ReAnIn. 2025. “Gallium Arsenide (GaAs) Radio Frequency (RF) Semiconductor Market Size to Reach USD 1,070.13 Mn by 2031.” Reanin.com. Research | Analysis | Insights. August 2025. <https://www.reanin.com/reports/global-gallium-arsenide-gaas-radio-frequency-rf-semiconductor-market>.
- ²⁰ Pappalardo, Joe. 2015. “How Patriot Missiles Will Stay a Step ahead of the Enemy.” Popular Mechanics. August 27, 2015. <https://www.popularmechanics.com/military/research/a17100/patriot-missiles-radar-gallium-nitride/>.
- ²¹ Shivani. 2024. “Is Optical Fiber Communication the Future of Information? - Smowcode Blogs.” Smowcode Blogs - Your Gateway to Embedded Systems. August 6, 2024. <https://blog.smowcode.com/is-optical-fiber-communication-the-future-of-information/>.
- ²² Michot Foss, Michelle, and Jacob Koelsch. 2022. “Of Chinese Behemoths: What China’s Rare Earths Dominance Means for the US.” Baker Institute. December 19, 2022. <https://www.bakerinstitute.org/research/chinese-behemoths-what-chinas-rare-earths-dominance-means-us>.
- ²³ Evenett, Simon, and Johannes Fritz. 2023. “Revisiting the China–Japan Rare Earths Dispute of 2010.” CEPR. July 19, 2023. <https://cepr.org/voxeu/columns/revisiting-china-japan-rare-earths-dispute-2010>.
- ²⁴ “The Holmium (Ho) Market | SFA (Oxford).” 2025. SFA (Oxford). 2025. <https://www.sfa-oxford.com/rare-earths-and-minor-metals/rare-earths-elements/holmium-market-and-holmium-price-drivers/>.
- ²⁵ Ministry of Mines, GOI. 2023. “Indian Minerals Year Book 2022.” December 2023. [https://ibm.gov.in/writereaddata/files/17125771666613da8e2e6a6Rare_Earths_2022.pdf#:~:text=The%20principal%20sources%20of%20REE%20are%20bastnaesite,alkaline%20igneous%20rocks%20and%20monazite%20\(a%20phosphate\)..](https://ibm.gov.in/writereaddata/files/17125771666613da8e2e6a6Rare_Earths_2022.pdf#:~:text=The%20principal%20sources%20of%20REE%20are%20bastnaesite,alkaline%20igneous%20rocks%20and%20monazite%20(a%20phosphate)..)
- ²⁶ Indian Bureau of Mines . 2023. “RARE EARTHS.” December 2023. https://ibm.gov.in/writereaddata/files/17125771666613da8e2e6a6Rare_Earths_2022.pdf.

-
- ²⁷ Rai, S D, K L Mundra, P S C Pandit, H S Sahoo, and M B Verma. 2018. "REE and Nb Mineral Potentialities of Amba Dongar Carbonatite Complex and Kadipani Fluorspar Mine Waste Dumps." *Exploration and Research for Atomic Minerals* 27 (2018): 115–27. https://www.researchgate.net/publication/355336700_REE_and_Nb_Mineral_Potentialities_of_Amba_Dongar_Carbonatite_Complex_and_Kadipani_Fluorspar_Mine_Waste_Dumps.
- ²⁸ N. Angusamy, J. Dajkumar Sahayam, M. Suresh Gandhi, and G.V. Rajamanickam. 2005. "Coastal Placer Deposits of Central Tamil Nadu, India." *Marine Georesources & Geotechnology* 23 (3): 137–74. <https://doi.org/10.1080/10641190500192102>.
- ²⁹ Singh, Yamuna, S.D Rai, R.P Sinha, and Ravi Kaul. 1991. "Lithium Pegmatites in Parts of Bastar Craton, Central India." *Exploration and Research for Atomic Minerals* 4 (1991): 93–108. https://www.researchgate.net/publication/326098225_Lithium_pegmatites_in_parts_of_Bastar_Craton_Central_India.
- ³⁰ ———. 2023b. "NGRI Scientists Find Rare Earth Elements in Anantapur District." *Thehansindia.com*. *The Hans India*. April 9, 2023. <https://www.thehansindia.com/telangana/ngri-scientists-find-rare-earth-elements-in-anantapur-district-791986>.
- ³¹ Online, Et. 2025. "India Discovers Rare Earth in MP Coalfields as China Curbs Squeeze Industries: Minister." *The Economic Times*, July 28, 2025. <https://economictimes.indiatimes.com/industry/india-goods/svs/metals-mining/india-discovers-rare-earth-in-mp-coalfields-as-china-curbs-squeeze-industries-minister/articleshow/122951194.cms?from=mdr>.
- ³² thepulseindia, *The Pulse*. 2025. X (Formerly Twitter). 2025. <https://x.com/ThePulseIndia/status/1952654627003941162>.
- ³³ FP News Desk. 2025. "India Finds Rare Earth Treasure Trove in Rajasthan, Auction Soon for Mining 17 Critical Minerals in Balotra." *Firstpost*. July 17, 2025. <https://www.firstpost.com/india/india-finds-rare-earth-treasure-trove-in-rajasthan-auction-soon-for-mining-17-critical-minerals-in-balotra-13907992.html>.
- ³⁴ Pistilli, Melissa. 2021. "10 Top Countries for Rare Earth Metal Production | INN." *Investing News Network*. March 23, 2021. <https://investingnews.com/daily/resource-investing/critical-metals-investing/rare-earth-investing/rare-earth-metal-production/>.
- ³⁵ "Topic: Rare Earths Industry Worldwide." 2025. *Statista*. July 31, 2025. <https://www.statista.com/topics/1744/rare-earth-elements/>.
- ³⁶ Pistilli, Melissa. 2021. "10 Top Countries for Rare Earth Metal Production | INN." *Investing News Network*. March 23, 2021. <https://investingnews.com/daily/resource-investing/critical-metals-investing/rare-earth-investing/rare-earth-metal-production/>.
- ³⁷ Robinson, Michael A. 2019. "Defense Media Network." *Defense Media Network*. 2019. <https://www.defensemedianetwork.com/stories/rare-earths-provide-critical-weapons-support/>.
- ³⁸ "Dysprosium and Terbium Metals - Australian Strategic Materials." 2025. *Australian Strategic Materials Ltd (ASM)*. 2025. <https://asm-au.com/metals/products/dy-tb-metals/>.
- ³⁹ "Military Weapons & Rare Earth Magnets Used in Defense Applications | Apex Magnets Blog." 2025. *Apexmagnets.com*. 2025. <https://www.apexmagnets.com/news-how-tos/military-weapons-rare-earth-magnets-used-in-defense-applications/>.
- ⁴⁰ "The Important Role of Dysprosium in Modern Permanent Magnets." n.d. <https://www.arnoldmagnetics.com/wp-content/uploads/2017/10/Important-Role-of-Dysprosium-in-Modern-Permanent-Magnets-150906.pdf>.
- ⁴¹ ———. 2025c. "Critical Minerals in Defence and National Security | SFA (Oxford)." *SFA (Oxford)*. 2025. <https://www.sfa-oxford.com/knowledge-and-insights/critical-minerals-in-low-carbon-and-future-technologies/critical-minerals-in-defence-and-national-security/>.

⁴² Ibid.

⁴³ Ibid

⁴⁴ Li, Mengjiao, Xiaoshuai Zhang, Xiaoyi Ma, Jia Li, and Zhijun Wang. 2025. "Luminescence Characterization and Performance Modulation of CaScBO₄: Eu Near-Infrared Phosphors for Night Vision Lighting Applications." *Optics Express* 33 (4): 8043–54. <https://doi.org/10.1364/OE.547449>.

⁴⁵ Mission, Mineral. 2025. "National Critical Mineral Mission – Policies - IEA." IEA. 2025. <https://www.iea.org/policies/25735-national-critical-mineral-mission>.

⁴⁶ Mines. 2023. "Mines and Minerals (Development & Regulation) Amendment Act, 2023 – Policies - IEA." IEA. 2023. <https://www.iea.org/policies/17968-mines-and-minerals-development-regulation-amendment-act-2023>.

⁴⁷ Site Admin. 2025. "Govt Plans to Roll out over Rs 1,000 Cr Subsidy Scheme to Promote Rare Earth Magnets Production." *Newsair.gov.in*. 2025. <https://www.newsair.gov.in/govt-plans-to-roll-out-a-rs-1345-crore-subsidy-scheme-to-promote-rare-earth-magnets-production/>.

⁴⁸ Walia, Aggam. 2025. "The India-US TRUST Initiative: What Is It, and How Will It Strengthen the Critical Minerals and Pharma Supply Chains." *The Indian Express*. February 16, 2025. <https://indianexpress.com/article/explained/explained-economics/us-trust-initiative-9835961/>.

⁴⁹ "India Signs Agreement for Lithium Exploration & Mining Project in Argentina." 2024. *Pib.gov.in*. 2024. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=1996380>.

⁵⁰ "Measures Initiated to Attain Self-Reliance in Critical Minerals." 2023. *Pib.gov.in*. 2023. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=1985839>.

⁵¹ Arora, Neha, and Aditi Shah. 2025. "Exclusive: India Moves to Conserve Its Rare Earths, Seeks Halt to Japan Exports, Sources Say." *Reuters*, June 15, 2025. <https://www.reuters.com/world/india/india-moves-conserve-its-rare-earth-seeks-halt-japan-exports-sources-say-2025-06-13/>.

⁵² Baskaran, Gracelin, and Meredith Schwartz. 2025. "The Consequences of China's New Rare Earths Export Restrictions." *CSIS*. April 14, 2025. <https://www.csis.org/analysis/consequences-chinas-new-rare-earth-export-restrictions>.

⁵³ "China's Rare Earth Power Play: Why India Should Be Worried." 2025. *Smallcase*. June 12, 2025. <https://www.smallcase.com/blog/chinas-rare-earth-power-play-what-is-it-and-why-india-should-be-worried/>.

⁵⁴ "CHARTS: Rare Earth Export Restrictions, Price Spikes and the Risks of Demand Destruction." 2025. *MINING.COM*. April 25, 2025. <https://www.mining.com/featured-article/charts-rare-earth-export-restrictions-price-spikes-and-the-risks-of-demand-destruction/>.

⁵⁵ Mondal, Dipak. 2025. "Rare Earth Magnet: Govt in Talks at Diplomatic, Commercial Levels." *The New Indian Express*. June 16, 2025. <https://www.newindianexpress.com/business/2025/Jun/16/rare-earth-magnet-govt-in-talks-at-diplomatic-commercial-levels>.

⁵⁶ Baskaran, Gracelin, and Meredith Schwartz. 2025. "The Consequences of China's New Rare Earths Export Restrictions." *CSIS*. April 14, 2025. <https://www.csis.org/analysis/consequences-chinas-new-rare-earth-export-restrictions>.

⁵⁷ Ibid.

⁵⁸ Parashar, Sachin. 2025. "Can't Allow Weaponisation of Critical Minerals: PM Modi at Brics." *The Times of India*. *The Times Of India*. July 7, 2025. <https://timesofindia.indiatimes.com/india/cant-allow-weaponisation-of-critical-minerals-pm-modi-at-brics/articleshow/122305970.cms>.

⁵⁹ <https://world-nuclear.org/information-library/current-and-future-generation/thorium#:~:text=The%20most%20common%20source%20of,action%20with%20other%20heavy%20minerals>.

⁶⁰ "IRELTDC - IREL (India) Limited." 2025. Irel.co.in. 2025. <https://www.irel.co.in/ireltdc>.

⁶¹ "Ministry of Mines Issues Guidelines for Setting up of Centres of Excellence under the National Critical Mineral Mission." 2025. Pib.gov.in. 2025. <https://www.pib.gov.in/PressReleasePage.aspx?PRID=2122219>.