FEBRUARY 2024

RARE EARTH CRITICAL MATERIALS

CSS DIALOGUE REPORT

THE CENTRE FOR SECURITY STUDIES

RARE EARTH ELEMENTS

This report is about Rare Earth Elements (RREs), which consist of seventeen metallic elements that play a crucial role in many high-tech devices. These elements are also called Rare Earth Oxides, as most of them are usually sold as oxide compounds. Currently, China is the largest producer of these rare earth elements.

The aim of this report is to analyse some of the Rare Earth Elements such as Cerium, Dysprosium, Europium, etc. Each element is examined based on its availability, applications, extraction and production methods, environmental effects, and more. In recent years, the demand for these elements has increased rapidly due to their critical importance in various technologies. They are particularly essential for producing high-performance magnets used in electric vehicle motors, wind turbines, and military equipment. Despite their significance in modern industry, the exploration, extraction, and sustainable use of REEs present significant challenges. This report also analyses some of the challenges involved in the use of REEs.

This report, divided into 3 parts, is the work of 9 Research Interns at CSS. They have researched rare earth elements that play a crucial role in modern technologies such as clean energy. It aims to provide valuable insights and perspectives to deepen our understanding of these elements.

This report is a product of the Centre for Security Studies, Jindal School of International Affairs.

Centre for Security Studies
Jindal School of International Affairs
O.P. Jindal Global University

Table of Contents

NEODYMIUM

Harshita Khaund

Introduction to Neodymium

In the periodic table, neodymium is the 60th element and is a constituent element of the team of elements titled ‘Rare Earth Elements’, where it derives its name from the Greek term ‘*neos didymos*’, which means new twins.[1] These Rare Earth Elements (REEs) constitute a class of 17 elements categorised into heavy and light rare earth elements, among the latter of which neodymium is one of the most critical ones.[2]

Firstly, it is imperative to note that the terminology of ‘rare earth’ represents a historical misnomer~~,~~ that~~which~~ has stemmed from the perceived unfamiliarity of the elements rather than their rarity.[3] More abundant REEs such as Yttrium and Scandium are similar in their crustal concentration to other commonly used industrial elements such as copper, zinc, tungsten, or lead. Scholars have further noted that even the least commonly mined REEs, which include t~~T~~hulium and l~~L~~utetium, are nearly 200 times more commonly found than gold.[4]

The rarity of the aforementioned elements is attributed~~prescribed~~ to the fact that, despite being commonly available across the surface of the Earth, their concentration in terms of economically exploitable deposits is relatively sparse. Consequently, most of the global supply of REEs comes from limited sources of mining and extraction, which in recent decades has become a flashpoint of geopolitical concentration owing to the perceived monopolisation of the elements, particularly~~ so~~ because of the key application of the said elements in the making of advanced technologies in strategic sectors such as ~~defense~~defence, telecommunication, electronics, transport, and energy.[5]

Neodymium represents one of the more reactive lanthanides,~~ –~~ a group of elements with similar metallic characteristics numbered 57 to 71 in the periodic table that~~which~~ are chemically similar to lanthanum. It rarely occurs naturally in its metallic form; instead, it is predominantly found in compounds such as halides, nitrides, sulfides, carbides, and hydroxides~~,~~ and needs to be refined for general purposes and usage.[6]

---

[1] (Neodymium, 2024)
[2] (Neodymium, n.d.)
[3] (Neodymium, n.d.)
[4] (Moir, 2010)
[5] (Moir, 2010)
[6] (Neodymium, n.d.)

Austrian chemist Carl Auer von Welsbach was the first to discover neodymium in 1885 in Vienna after a process of separation of ammonium didymium nitrate prepared from didymia (originally extracted from cerium by Carl Gustav Mosander) into a neodymium fraction and a praseodymium fraction through repeated crystallization.[7] It is the fourth most prevalent REE on the surface of the earth after yttrium, lanthanum, and cerium and is believed to be twice as abundant as lead.[8]

Neodymium's major application is in the arena of manufacturing permanent magnets used~~tilised~~ in high-~~-~~performance electric motors and generators, spindle magnets for computer data storage systems, and wind turbines.[9] It also constitutes a crucial component in the field of information technology, with particular usage in mobile phones and audio and video systems of television sets, where its magnetic characteristic acts as a voice coil motor, allowing for the effective operation of auto-focus mechanisms within a fraction of time. Neodymium magnets are also used in magnetic separators, filters, ionis~~z~~ers, and~~ in~~ a variety~~d~~ of security systems.[10] The metal itself is used in the manufacture of steel, and when combined as an alloy with other lanthanides such as erbium, it acts as a regenerator in low-temperature cryocooler applications where it provides cooling down to -269 degrees Celsius.[11] It is further employed in making glasses used in fibre optics, in the manufacturing of modern lasers as a stabilis~~z~~ing agent for yttrium aluminium garnet, and as an absorbent of harmful sodium-D spectral light in glassblower's goggles.[12]

As communities across the globe attempt a transition towards green energy ~~in order ~~to reduce dependence on fossil fuels, there is a switch towards greener alternatives, including electric vehicles, where neodymium magnets are classified as the optimum quality of magnets for their strength and size, particularly in terms of their usage for electric power steering systems, electric compressors, and electric water pumps, thereby enhancing the overall efficiency of the vehicle's performance.[13] First developed by General Motors and Hitachi in the 1980s, neodymium-~~-~~iron-~~-~~boron magnets are used in over 90% of EVs for their brushless DC motors. Neodymium-~~-~~powered alternative sources of energy, transportation, and telecommunication thus go~~es~~ a long way towards realising the vision of a sustainable and circular economy, effectively empowering SDG 11.[14]

---

[7] (Neodymium, 2024)
[8] (Moir, 2010)
[9] (Neodymium)
[10] (Badkar, 2023)
[11] (Neodymium, n.d.)
[12] (Neodymium)
[13] (Badkar, 2023)
[14] (Neodymium, 2024)

Where is Neodymium Found?

Neodymium is generally mined as a conglomerate of minerals such as monazite and bastnaesite, from which it is extracted through processes of ion exchange and solvent extraction.[15] Historically, the Mountain Pass mine, located in California (in the United States of America), extracted and manufactured the majority of the world's rare earth mineral resources, including neodymium. Since production first began in the 1950s, however, China has steadily increased its presence in the rare earth mining sector.[16] While the period between 1960 and 1995 witnessed the dominance of American production of REEs, production eventually started declining owing to stiff Chinese competition augmented by heavy Chinese government-~~-~~backed investments in the REE mining and processing industry, which enhanced quality production at significantly cheaper costs. The imposition of tough environmental regulations, in addition, caused American presence in the market to shrink, especially with the forced closure of the Mountain Pass mine in 2002 because of a toxic spill.[17]

At its peak in 2011, China produced almost 95% of all REE minerals globally. While today this share has declined to 70%, it nevertheless establishes Chinese hegemony in the sector and has raised alarm bells about China's monopolistic tendencies and its repercussions for the West in the trade for REEs.[18] It is also imperative to note that even at the pinnacle of its absolute hegemony, China only accounts for 36% of the global geographical distribution of REEs, with~~at~~ approximately 36 Mt of REE reserves.[19] Such a discrepancy largely arises from China's laxity in terms of environmental hazards and safety regulations, which have been the primary reasons for the United States to ban the mining of REEs. With multiple scientific reports drawing causal relations between unsafe mining and significant health deterioration among~~st~~ people living in close proximity to the mining sites, China is currently facing stiff opposition from environmentalists and locals to~~for~~ its plans for~~of~~ expansion.

---

[15] (Neodymium, 2024)
[16] (Green, 2019)
[17] (Neodymium, n.d.)
[18] (Neodymium, n.d.)
[19] (Moir, 2010)

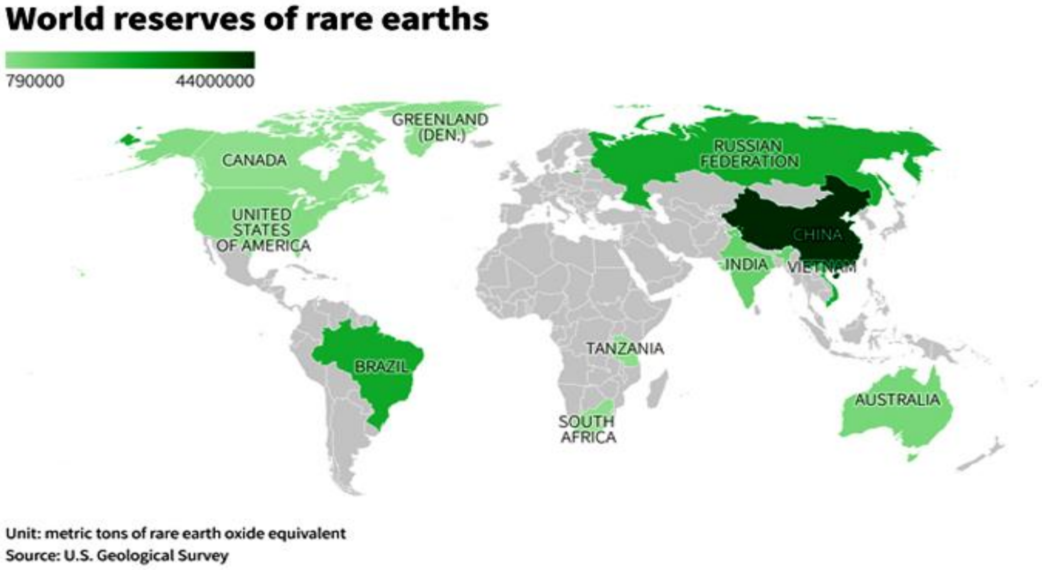


Fig. 1[20]

The Market for Neodymium

In the face of increasing urgency for countries to comply~~oblige~~ with climate agreements that~~which~~ mandate signatory nations to reduce their per capita emissions, the demand for minerals such as neodymium, which encourage a shift towards cleaner energy, has risen multifold. According to the International Energy Agency, the demand for rare earth elements is expected to multiply by~~etween~~ three to seven times that of current demand levels by 2040. Supply trends, on the other hand, are on track to merely double during the same period.[21]

Particularly for neodymium, the market size was valued at USD 2.82 billion in 2022, driven by a surge in demand for neodymium magnets, whose usage and application in wind turbines, telecommunication products, and electric vehicles have~~s~~ been listed previously.[22]

To analyse the upsurge in demand, it is imperative to draw a closer look at the wind energy sector, which has emerged as the driving source of market growth for neodymium magnets in particular. With a global shift towards clean energy sources, the construction of more and more wind turbines has emerged as a parallel phenomenon~~a~~. A crucial component of all wind turbines is neodymium magnets, which are efficient for electricity generation at affordable rates with low maintenance costs~~ of maintenance~~ and improved

---

[20] Asia Financial, 2023
[21] (International Energy Agency, 2023)
[22] (Reports and Data, 2023)

reliability. Large permanent magnet wind generators, which are built to last up to 20 years, are said to use thousands of neodymium magnets, with additional magnets used for the poles of the rotors. With global wind energy capacities expected to reach 1,120 GW by 2025 (as per reports from the International Energy Agency), the demand for neodymium magnets is further expected to soar.[23]

Another sector that~~which~~ is heavily reliant on neodymium magnets is the electric vehicle~~s~~ sector. As already noted previously, neodymium magnets constitute the primary features of the motors of electric vehicles because of their ability to enhance efficiency and performance. The International Energy Agency further predicts the EV market to expand up to 125 million by 2030, simultaneously driving~~ the~~ neodymium market growth.

Additionally, digital revolutions across the globe have spurred the sale of consumer electronic products, including smartphones, computers, and other electronic devices, all of which require neodymium magnets to maintain their high-~~-~~performance calibre.[24] Neodymium's usage is also enhanced by its chemical compound,~~ of~~ neodymium oxide, which is used for the production of glass, ceramics, steel, and as a catalyst in the petroleum refining process.

A region-~~-~~wise analysis reveals that Asia-Pacific is the largest revenue-~~-~~generating market source for neodymium, largely driven by the increasing adoption of renewable energy infrastructure~~s~~ and electric vehicles. Its status of dominance is solidified by the presence of emerging markets such as China, India, and Japan, which~~o~~ not only generate demand but also represent hubs of rare earth production, with China being the largest global producer of REEs. Thus, while demand levels experience surges owing to the region's industrial infrastructural development needs, supply lines ~~are able to~~can maintain their continuity because of the availability of abundant reserves of REEs and low-cost labour, thus attracting manufacturers and customers alike.[25]

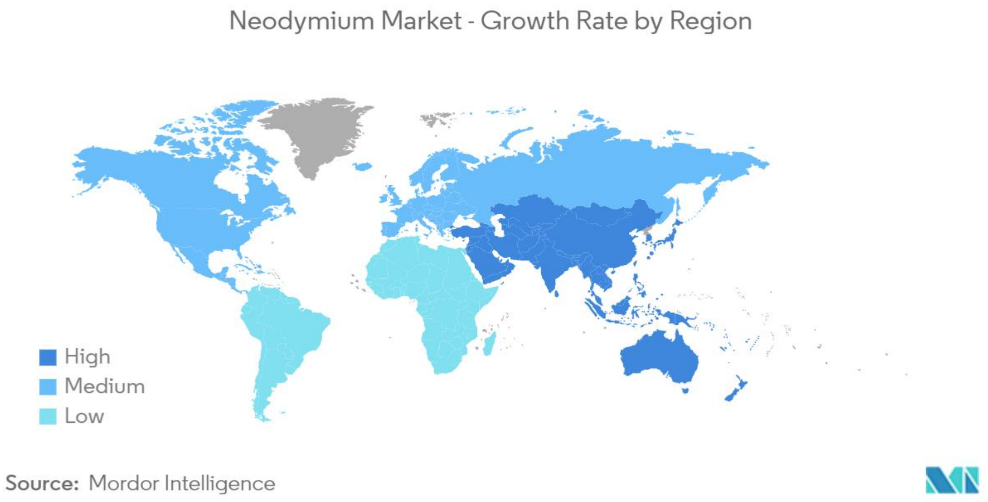
North America emerges as the second largest market for neodymium products, where the policy tilt towards climate-~~-~~friendly practices has encouraged the adoption of stringent climate regulations, paving the way for electric vehicles in the automotive sector. Europe also presents a sizable market for neodymium, driven by heavy investments in renewable energy in countries such as Germany and a large consumer base for electric vehicles, which is largely reflective of the region's ambitious targets set for carbon emissions reduction.[26]

---

[23] (Reports and Data, 2023)
[24] (Reports and Data, 2023)
[25] (Mordor Intelligence, 2023)
[26] (Mordor Intelligence, 2023)

Analysts, however, have also raised concerns about the hazardous environmental impacts posed by excessive mining and processing of REEs, with countries stepping up efforts towards curbing unsafe mining cultures. Most imperatively, geopolitical contentions across the globe have threatened to cause supply chain disruptions, particularly in the face of China's unstable export policies, which frequently retaliate against the policies of certain countries by banning exports of crucial products, including REEs. Such supply chain disruptions have also caused heavy price fluctuations, which has prompted buyers to look towards less-volatile alternatives such as samarium, cobalt, and ferrite magnets, which are easily available in the market.[27]

Fig 2[28]



Source: Mordor Intelligence

Fig. 2

Geopolitical Concerns about Neodymium

In 2018, an article titled 'A Rare Metal Called Neodymium is in Your Headphones, Cellphone and Maybe Even Your Car — and China Controls the World's Supply' was published on CNBC, which generated significant buzz amongst lawmakers, industrialists, and the general public amidst mass paranoia about China's increasing sway in global eco-political affairs.[29] Consider the following statistics:~~–~~ A~~a~~ccording to Benchmark Mineral Intelligence, even though China's unparalleled dominance is expected to decline in the coming years, it is still expected to stand at 75% in 2028.[30]

Historical findings reveal that China's discovery of REEs was first made in 1927 at Bayan Obo, located in I~~i~~nner Mongolia. While production commenced in the 1950s, there was a simultaneous focus on exploring other sites of mineral concentration, which

---

[27] (Reports and Data, 2023)
[28] Source: Mordor Intelligence, 2023
[29] (Isaak, 2018)
[30] (Nguyen, 2023)

included the Shandong and Sichuan Provinces, southern Jiangxi, Guangdong, Fujian, Hunan, and Guangxi regions of China.[31] China's steadfast growth as a major producer of REEs, however, also depended on a sprawling state-~~-~~led infrastructure that~~which~~ recognised the economic potential of REE extraction. The most evident move in this direction was the establishment of the National Rare Earth Development and Application Leading Group in 1975 by the State Council in a bid to boost investments as well as research and development for refining the mining and extracting processes.[32] Scholar Marina Yue Zhang provides an alternative lens for~~of~~ uncovering the factors behind China's meteoric rise in the industry, which looks beyond 'geographical happenstance' explanations that~~which~~ focus on China's geographical abundance of REEs (which amounts to 30% of global concentration). She notes that "By 1990, China [had] mastered the separation of REEs and [had] mapped a strategy of capturing and controlling the downstream production of REE-value-added products."[33]

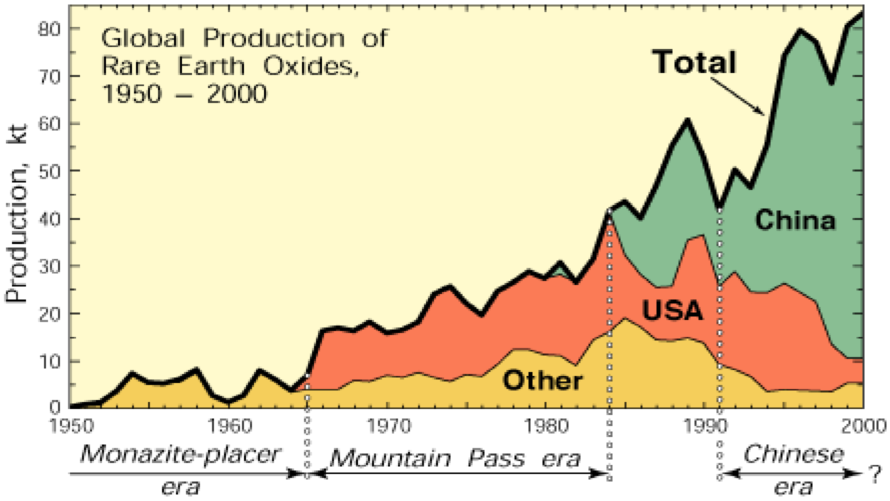


Fig.3[34]

The strategy in focus is one of heavy state-led investment in the sector, augmented by the centralised style of the Chinese state. While it continued pumping money into REE mining and extraction labs and scientific degrees on REE production, other free market economies, such as the United States, were forced to shut down operations owing to stricter environmental regulations.[35] Such trends have amalgamated with China's meteoric rise as a geopolitical power to ensure Chinese absolute hegemony in the industry, most starkly evident in 2010, when a maritime dispute in the South China Sea led to the imposition of a ban on exports of REE to Japan by Beijing, which in turn caused global prices to jump 300%.[36] ~~-~~China's monopolising trends also see no borders; ~~–~~ it has actively pursued mining contracts in several parts of Africa and Asia, the

---

[31] (Speed & Hove, 2023)
[32] (Speed & Hove, 2023)
[33] (Valentino, 2023)
[34] Source: USGS Publication Warehouse, 2018.
[35] (Valentino, 2023)
[36] (Valentino, 2023)

operations of which have been led by a consolidated state-owned REE enterprise that~~which~~ dominates up to 70% of the country's sector. As China's domestic production slows down, it has resorted to exporting from other countries, the most notable of which is the neighbouring state of Myanmar, which exported over a billion dollars worth of REEs to China between 2017 and 2021.[37] China has also gained access to over 70% of mines located in the Democratic Republic of the Congo in return for enhancing infrastructure capacities. Similarly, in Kenya, China has agreed to build a ~~$~~666 million-dollar data centre while obtaining commercial licences for REE mining.[38] It points towards the broader Chinese strategy of engaging developing nations in its debt-trap diplomatic tactics and heavy cycles of lending followed by strategic acquisitions, emerging as a source of concern for the global economic framework.

The risks of a Chinese REE monopoly have not gone unnoticed; W~~w~~estern powers are actively seeking to decouple from Chinese manufacturing by exploring alternatives. In 2021, the Biden administration of the United States announced investigations probing the "possible national security risks of over-relying on imports of certain magnets used in fighter aircraft and missile guidance systems."[39] Unable to bar imports through higher tariffs owing to continued dependence, it has instead pursued a policy of enhancing domestic production and engaging with allies to~~for~~ bolster~~ing~~ supply chain resilience in case of trade wars with China.[40] In 2022, the U.S. Commerce Department announced a planned investment of $35 million in M.P. Materials as part of its efforts to~~of~~ revamp~~ing~~ domestic production across the Mountain Pass mining zone.[41] Increased susceptibility to threats of Chinese export bans has~~ve~~ further prompted countries across the Western alliance to invest in downstream technologies, led by the European Union's European Raw Materials Fund, launched in 2022 with an initial budget of €2 billion.[42] In Australia, the MacIntyre Wind Farm, with a generation capacity of 1,026 MW, is slated to open by 2024.[43]

Such global efforts to~~of~~ minimise~~ing~~ supply chain disruptions caused by Chinese hegemony have found their~~its~~ most crystallised vision in the form of a 'Minerals Security Partnership' - a U.S.-~~-~~led initiative of 11 partners including Australia, Canada, Finland, France, Germany, Japan, the Republic of Korea, Sweden, the United Kingdom, and the European Union. Founded in 2022, the MSP aims to "ensure that critical minerals are being produced, processed, and recycled in a manner that supports the ability of countries to realise the full economic development benefit of their geological endowments."[44]

---

[37] (Valentino, 2023)
[38] (Nayar, 2021)
[39] (Reuters, 2021)
[40] (Import Restrictions on Neodymium Magnets Declined, 2022)
[41] (Easley, 2023)
[42] (Onstad, 2022)
[43] (Power plant profile: MacIntyre Wind Farm, Australia, 2022)
[44] (International Energy Agency, 2022)

The Emergence of India as a Player in the Minerals Security Game

India’s historical dependence on China for heavy REEs has elicited cautious steps towards monitoring imports of critical minerals. In 2023, India joined the Minerals Security Partnership, becoming the 14th member of the transnational association, where it hopes to lead the drive towards clean energy as an emerging leader of the Global South.[45] The ongoing construction of the Pinnapuram Integrated Renewable Energy Project in Andhra Pradesh, which includes a 5,230 MW integrated hybrid renewable energy project, ~~takes a~~ leaps in this direction.[46]

India currently boasts a largely untapped reservoir of critical minerals, with the Centre’s Department of Atomic Energy reporting that India holds the fifth largest reserve of REEs in the globe. A large concentration of this is, however, shored up in areas that~~which~~ are heavily regulated by Coastal Regulation Zones. Additionally, India’s untapped reservoir is composed mainly of light rare earth minerals, forcing it to look outside its borders for heavy elements like dysprosium and terbium.[47]

The lengthy and expensive extraction process has not deterred India’s resolve to gain self-dependency in the sector. In May ~~of~~ 2023, Prime Minister Narendra Modi laid the foundations for India’s first rare earth permanent magnet plant on the Bhabha Atomic Research Centre campus in Visakhapatnam. Valued at Rs. 165 crore, the plant is designed to produce neodymium-iron-boron magnets and samarium-cobalt magnets, providing viable alternate hubs to replace Chinese supply links.[48]

Environmental Concerns regarding Neodymium Production

Rare e~~E~~arth e~~E~~lements hold the potential to revolutionise the green energy sector;~~ – ~~their central usage in low-carbon technologies places them at the pinnacle of spearheading the shift towards non-fossil fuel resources.

All is not green, however, with REEs. If we consider the two dominant methods for mining, we can navigate the extent to which environmental challenges lie at the intersections of REE production and the future of~~for~~ green technology.[49] For instance, the process of removing the topsoil to create a leaching pond by adding chemicals to extract and separate metals holds high risks of contaminating groundwater~~s~~ through

---

[45] (Sasi, 2023)
[46] (Power plant profile: Pinnapuram, India, 2022)
[47] (Badkar, 2023)
[48] (Badkar, 2023)
[49] (How Rare-Earth Mining Has Devastated China’s Environment, 2020)

chemical erosion. The alternative method of drilling holes using polyvinyl chloride pipes to infuse chemicals into the ground runs into similar environmental roadblocks. The toxic waste generated as a result of such processes further combines with rare earth element ores to contaminate air, water, and soil and cause detrimental health effects. Overall, approximately 2000 tons of toxic waste are~~is~~ produced for every ton of REE.[50]

We have already noted China's predominance in the rare earth mineral extraction market, which is largely possible owing to lax environmental regulation standards. Infamous mines such as the Bayan Obo mine have produced tailing mines storing up to 70,000 tons of radioactive thorium, which have continually spilled over to contaminate groundwater and are~~,~~ eventually expected to mix with the water of the Yellow River, which is a crucial source of drinking water in the region.[51] Reports from~~of~~ other mines detail how the administration has been forced to build treatment facilities to clean up to 40,000 tons of wastewater every day before letting it flow into the river.[52] The obvious health complications arising from exposure to such toxic chemicals have long been ignored by authorities, with several mines citing blatant human rights abuses. While in recent years the Chinese government has acknowledged the presence of 'cancer villages', where large clusters of people in~~of~~ a particular region have terminally fallen ill with cancer~~,~~ due to mining-related pollution, the larger response has been largely in favour of subduing dissenting voices.[53] In 2018, when farmers from Yulin noticed their crops being affected by REE extraction and decided to protest against the state's lack of intervention, ten protestors were detained.[54]

Solutions proposing environmentally feasible methods of REE extraction have gained widespread attention, with the most frequently used methods being recycling and green mining. Green mining policies have been particularly renowned for affecting meaningful change at the ground level, the most notable of which was the Chinese government's adoption of the Rare Earth Industrial Development Policy, which lists the following key regulations:

- From 2009 to 2015, China will not issue any new mining licences for rare earths.
- Efforts to shut down illegal mines and inefficient separating and smelting enterprises will continue.
- Increased monitoring of the industry will be done by the Ministry of Industry and Information Technology.

---

[50] (Nayar, 2021)
[51] (Liu, 2017)
[52] (Standeart, 2019)
[53] (BBC, 2013)
[54] (Nayar, 2021)

- Requirements for an efficient electricity supply and specifications concerning the maximum energy demand per ton of rare earth~~s~~ produced are also indicated.
- The m~~M~~inimum recycling rate for ore dressing waste water of mixed rare earth minerals (85%) and bastnaesite and ion adsorption deposits (90%) is~~are~~ set, as well as yield rates (92%).[55]

Revolutions in the Health Domain

The health sector represents a field where neodymium magnets have been used for dynamic purposes. Frequently touted as ‘magic magnets’, they are used in a myriad of medical appliances, including magnetic resonance imaging devices, to diagnose and treat chronic pain syndrome, arthritis, wound healing, insomnia, and headaches, among others, because of their ability to generate a static field.[56] The push-pull forces generated by the magnets are used as motion-generating devices for orthodontic treatments, molar distillation, and palatal expansion.[57]

Particularly in the realm of skin cancer, neodymium-~~-~~based laser irradiation has proven its efficacy in treating high-~~-~~stage skin melanoma.[58] Milestone developments have also been achieved in the field of psychotherapy, where neodymium magnets have been used in recurrent transcranial magnetic stimulation as a treatment for major depression.[59] Neodymium magnets have also been used for laparoscopic surgeries for easy access to gastrointestinal tumours.[60]

---

[55] (Speed & Hove, 2023)
[56] (Yuksel, 2018)
[57] (Noar, 1999)
[58] (Moskalik, 2009)
[59] (Yuksel, 2018)
[60] (Warnick, 2013)

References

1. Badkar, S. (2023). What is Neodymium. *CNBC*.
2. BBC. (2013). China acknowledges 'cancer villages'. *BBC*.
3. Easley, M. (2023). *U.S. Begins Forging Rare Earth Supply Chain.* National Defense.
4. Green, J. (2019). The collapse of American rare earth mining — and lessons learned. *Defense News*.
5. (2020). *How Rare-Earth Mining Has Devastated China's Environment.* Earth.Org.
6. (2022). *Import Restrictions on Neodymium Magnets Declined.* Sandler, Travis and Rosenberg.
7. International Energy Agency. (2022). *Minerals Security Partnership.* International Energy Agency.
8. International Energy Agency. (2023). *The Role of Critical Minerals in Clean Energy Transition.* International Energy Agency.
9. Isaak, A. (2018). A rare metal called neodymium is in your headphones, cellphone and electric cars like Tesla's Model 3 — and China controls the world's supply. *CNBC*.
10. Liu, H. (2017). *As China Adjusts for "True Cost" of Rare Earths, What Does It Mean for Decarbonization?* New Security Beat.
11. Moir, A. (2010). *The Chemistry, Economics and Politics of Neodymium.* Retrieved from Physics 240, Stanford University: http://large.stanford.edu/courses/2010/ph240/moir2/
12. Mordor Intelligence. (2023). *Neodymium Market - Growth, Trends, COVID-19 Impact, and Forecasts (2024 - 2029)* . Mordor Intelligence.
13. Moskalik, K. (2009). The efficacy of facial skin cancer treatment with high-energy pulsed neodymium and Nd:YAG lasers. *National Library of Medicine*.
14. Nayar, J. (2021). *Not So "Green" Technology: The Complicated Legacy of Rare Earth Mining.* Harvard Law Review.
15. *Neodymium*. (n.d.). Retrieved from American Chemical Society: https://www.acs.org/greenchemistry/research-innovation/endangered-elements/neodymium.html

16. *Neodymium*. (n.d.). Retrieved from Brittanica: https://www.britannica.com/science/neodymium
17. *Neodymium*. (2024). Retrieved from Royal Society of Chemistry: https://www.rsc.org/periodic-table/element/60/neodymium
18. Nguyen, M. (2023). China's rare earths dominance in focus after it limits germanium and gallium exports. *Reuters*.
19. Noar, J. (1999). Rare earth magnets in orthodontics: an overview. *Pub Med*.
20. Onstad, E. (2022). European fund for critical minerals projects to launch next year. *Reuters*.
21. (2022). *Power plant profile: MacIntyre Wind Farm, Australia.* Power Technologies.
22. (2022). *Power plant profile: Pinnapuram, India.* Power Technology.
23. Reports and Data. (2023). *Neodymium.* Reports and Data.
24. Reuters. (2021). U.S. probes security impact of importing magnets used in fighter jets, missiles. *Reuters*.
25. Sasi, A. (2023). India joins US-led critical mineral club, boost likely for EV, electronics. *Indian Express*.
26. Speed, P., & Hove, A. (2023). *China's rare earths dominance and policy responses.* Oxford Institute for Energy Studies.
27. Standeart, M. (2019). *China Wrestles with the Toxic Aftermath of Rare Earth Mining.* Yale Environment 360.
28. Valentino, A. (2023). *Decoding China's dominance in global rare earth market.* NS Energy.
29. Warnick, P. (2013). Intraoperative localization of occult colorectal tumors during laparoscopic surgery by magnetic ring markers-a pilot study. *Pub Med*.
30. Yuksel, C. (2018). The use of neodymium magnets in healthcare and their effects on health. *National Library of Medicine*.

PROMETHIUM

Renuka Sreekumar

Abstract

Promethium (Pm) is a rare earth metal of the lanthanide series of the periodic table[61]. It is the only element among the series that does not naturally occur on Earth. However, its presence in the Earth's crust is debated in small amounts.[62] While there is no agreement as to whether Promethium is found in the Earth's crust, there is resounding agreement that, regardless, Promethium is a scarce element. This paper aims to study the element in detail, with facts ranging from its origin, extraction, applications, and contemporary uses and significance.

Etymology

The word "Promethium" originates in the story of the Greek Titan Prometheus, who stole fire from the gods and gave it to humans. Throughout its known existence, the element has had several names, with I~~i~~llinium, F~~f~~lorence and C~~c~~yclonium being a few of them. It was named "Prometheum" at the suggestion of the wife of one of the chemists who discovered the element. However, in 1950, the International Atomic Balance Commission christened the element "Promethium", thereby discounting all other names and spellings.

Origin

Discovered in 1945 by American chemists Jacob A. Marinsky, Lawrence E. Glendenin, and Charles D. Coryell[63], Promethium was the last of the rare earth materials to be discovered. It is the 61st element in the periodic table, located between Neodymium and

---

[61] Promethium | Rare Earth Element, Atomic Number 61. (1998, July 20). Encyclopedia Britannica. https://www.britannica.com/science/promethium

[62] Elkina, V. D., & Kurushkin, M. (2020, July 10). Promethium: To Strive, to Seek, to Find and Not to Yield. Frontiers in Chemistry. https://doi.org/10.3389/fchem.2020.00588

[63] *Promethium*. (n.d.). Assignment Point. https://assignmentpoint.com/promethium

S~~s~~amarium. Promethium was the last of the rare earth materials of the lanthanide series to be discovered.

The existence of Promethium was irrefutably established when American scientists identified it from fission products of uranium. However, alternative means of manufacturing Promethium have been sought. One among these is the process of neutron capture of the element Neodymium.

History of the Discovery of the Element

In 1902, Bahuslov Banner speculated that there should be an element in the periodic table between Neodymium and samarium[64]. However, unbeknownst to him, all the isotopes of said element were radioactive, rendering it with a short shelf life. Several attempts were made to discover it, but all were unsuccessful. It was eventually found that Promethium exists in small amounts in uranium, i.e., by about less than a microgram per million tonnes of ore[65]. In 1939, the 60-inch cyclotron at the University of California was used to make Promethium, but it was not proven.[66]

Extraction

Promethium can be produced in one of two ways- by the nuclear fission of uranium and the neutron bombing of Neodymium.

Nuclear Fission of Uranium

Promethium is produced when a thermally charged neutron is launched toward an atom of uranium to produce a neutron and a fission product. Said fission product is Promethium. The yield from this process is painfully small. The thermal neutron-induced fission of uranium has a cumulative yield of 2.25%. This means that every 100 units of uranium produces 2.25 units of Promethium. This process of thermal neutron bombing produces promethium-147.

Decaying of Neodymium

The bombing of Neodymium- 146 with neutrons produces Neodymium- 147, which decays over time to produce promethium- 147.

Physical Properties of Promethium

---

[64] Promethium. (n.d.). Assignment Point. https://assignmentpoint.com/promethium

[65] Promethium. (n.d.). Assignment Point. https://assignmentpoint.com/promethium

[66] Promethium. (n.d.). Assignment Point. https://assignmentpoint.com/promethium

Promethium is silvery white in appearance and forms salts that glow in the dark with a pale blue or green light[67]. The element has exceptionally high melting and boiling points of 1441 K and 3000K, respectively. The atomic radius of Promethium is the largest among all lanthanides, making it the largest element in the series. Promethium has multiple isotopes, all radioactive, which accounts for its poor shelf life. The isotopes of Promethium are highly unstable, discouraging extensive research on the element. Of the lot, promethium 145 is by far the most stable. However, promethium 147 is used for all practical applications of the element. Excluding nuclear isomers, 38 radioactive isotopes of Promethium are known.

Applications of Promethium

The applications of Promethium are limited primarily to research purposes because of the instability of its isotopes. In addition, it is limited in supply.

Generating Electricity in Atomic Batteries

The beta particles produced by promethium-147 are converted into electric current when a small promethium source is sandwiched between two semiconductor plates[68]. This means that Promethium is a source of electricity that can produce astronomical amounts, even in the most minuscule amounts.

Phosphor to Give Off Light

The radioactive decay of Promethium is used to make a phosphor to give off light, which is converted into electricity by a solar cell[69]. Hence, the element is widely used in night lighting devices. This illuminative nature of Promethium is also harnessed in light sources encased within LCD watches. In this instance, the material's luminosity decreases over time. Most self-illuminating entities have Promethium in them. They have acted as replacements for radium in this regard once its harm was recognized.

Space Activities

Promethium batteries are particularly useful when other batteries would prove comparatively heavyweight, for example, in satellites and space probes. Such batteries

---

[67] Green, J. (2022, June 15). The Rare Earth Element Promethium - An Overview | Stanford Advanced Materials. Global Supplier of Sputtering Targets and Evaporation Materials | Stanford Advanced Materials. https://www.sputtertargets.net/blog/the-rare-earth-element-promethium-an-overview.html

[68] Green, J. (2022, June 15). The Rare Earth Element Promethium - An Overview | Stanford Advanced Materials. Global Supplier of Sputtering Targets and Evaporation Materials | Stanford Advanced Materials. https://www.sputtertargets.net/blog/the-rare-earth-element-promethium-an-overview.html

[69] Green, J. (2022, June 15). The Rare Earth Element Promethium - An Overview | Stanford Advanced Materials. Global Supplier of Sputtering Targets and Evaporation Materials | Stanford Advanced Materials. https://www.sputtertargets.net/blog/the-rare-earth-element-promethium-an-overview.html

are particularly useful in instances that require low power generation over long periods. The average lifespan of promethium-powered batteries is about ten years, but recent research poses the potential to extend this lifespan up to 15 years. Promethium is also used as a source of energy for space probes. Promethium was used to illuminate instruments involved in the Apollo moon landings.

Batteries in Pacemakers

Beta voltaic batteries like Betacel are used as power sources in pacemakers. It also satisfies both corrosion and cremation fire standards and is suitable for clinical use.

Portable X-Rays

Promethium-147 is a source of soft beta rays. Irradiation of heavy elements with beta particles generates X-ray radiation. Radiation sources typically contain a radioactive isotope like promethium-147 between two non-radioactive metal sources.

Measuring the Thickness of Materials

Promethium is used to measure the thickness of materials like paper, plastics, and metals[70]. The process involves a radiation source, i.e., Promethium, and a radiation detector. A bulk source of the Promethium is placed above the material investigated, while a radiation sensor is placed below. The sensor calculates the amount of radiation passing through the material. The thinner the material, the more radiation that passes through it.

In Agriculture

The promethium-based measuring technique is used to measure the thickness of orange and sweet lime citrus leaves. This gauging technique is also used to measure the water content in leaves during the drying and wetting cycles. In addition, promethium 147 is used to detect pesticides in water environments.

Lasers

Promethium is used in the lasers involved in communicating with submerged submarines.

Healthcare

---

[70] Green, J. (2022, June 15). The Rare Earth Element Promethium - An Overview | Stanford Advanced Materials. Global Supplier of Sputtering Targets and Evaporation Materials | Stanford Advanced Materials. https://www.sputtertargets.net/blog/the-rare-earth-element-promethium-an-overview.html

Appropriately stored Promethium poses no danger and can be used in clinical and healthcare settings. In medicine, promethium beta therapy can be used to cure lumbosacral radiculitis. Promethium-142 was used in an in vivo generator for preclinical positron emission tomography. Promethium-149 is a suitable radilolanthanide for receptor-targeted radiotherapy. Promethium can also prevent hair loss, promote hair regrowth, and black hair formation, and is also used to prevent and treat dandruff.

Environmental Impact of Promethium

Promethium has no known biological role or existence. Sealed promethium-147 is not dangerous. However, if its packaging is damaged, the element poses a danger to both humans and the environment. This is owing to its highly radioactive nature.

Conclusion

In conclusion, much of what we know of the element promethium operates in the realm of the hypothetical. This is because of its immense radioactivity and volatility. Regardless, this paper details how the element has a vast array of uses, and its properties leave its horizons wide and open.

SCANDIUM

Aditya Gulati

Introduction

Scandium, denoted by the symbol Sc and possessing an atomic number of 21, stands as a captivating element with a rich history. Its discovery is intertwined with the visionary work of Dmitri Mendeleev, who, in 1869, predicted the existence of several yet-to-be-known elements when formulating the periodic table.[71] These hypothetical elements were temporarily named Ekea boron, Ekea aluminium, and Ekea silicon, reflecting their presumed locations beneath specific elements. Remarkably, Mendeleev's predictions materialized, leading to the identification of these elements.

The first element to be discovered following Mendeleev's predictions was gallium, referred to as Ekea Aluminium. Subsequently, scandium, known as Ekea Boron, was the second element unveiled.[72] This discovery marked a pivotal moment in the acceptance of Mendeleev's contributions to the periodic table, shifting perception from mere luck to serious consideration.

Discovery

In 1879, the Swedish scientist Lars F. Nilson made the groundbreaking discovery of scandium in Uppsala, Sweden.[73] Nilson, engaged in the study of rare earth elements while attempting to isolate ytterbium from minerals like euxenite and gadolinite, applied heat to his samples. This process revealed the presence of a previously unknown element characterized by a low atomic weight. Spectral analysis, revealing 30 distinctive spectral lines, confirmed the existence of this new element. In homage to its prevalence in rare minerals found in Scandinavia, Nilson named the element scandium, derived from the Latin word 'Scanda.'[74]

---

[71] Scandium - Element information, properties and uses | Periodic Table. (n.d.-b) https://www.rsc.org/periodic-table/element/21/scandium
[72] Ibid
[73] Ibid
[74] Ibid

Nilson further contributed to the understanding of scandium by determining its atomic weight as 44. The isolation of metallic scandium was achieved in 1937 by Fischer and colleagues through electrolysis.[75] This involved the use of molten scandium, lithium, and potassium chlorides in a graphite crucible, with a tungsten wire and molten zinc serving as electrodes. This pioneering work marked a significant milestone in the development and comprehension of the properties of scandium.

Characteristics

One of the notable properties of scandium is its lightweight nature, especially when used as an alloying element. When scandium is added to certain metals, such as aluminum, it forms lightweight alloys with improved strength and other desirable properties. Scandium distinguishes itself as an exceptionally lightweight metal, boasting a density just below 4 grams per cubic centimetre.[76] This places it significantly below the densities of most conventional metals, such as copper, which approaches 10, and heavy metals like lead and gold, which are close to 20.[77] The notably low density of scandium renders it an intriguing and valuable material for various applications.

The significance of lightweight metals, including scandium, lies in their ability to fulfill specific engineering requirements where minimizing overall weight is paramount. In instances where the use of a metal is essential but a substantial reduction in the object's mass is desired, scandium becomes an optimal choice. This attribute finds practical applications in diverse fields.

Scandium's rarity, characterized by its relatively low natural abundance in the Earth's crust at about 22 parts per million, underscores its distinctiveness among elements.[78] This scarcity, compared to more prevalent elements, contributes to its high economic value. Scandium's electronic configuration [Ar] $3d^{14}$ $4s^{2}$ places it uniquely in the periodic table, reflecting its transitional nature.[79] This uniqueness manifests in its ability to enhance the properties of alloys, particularly when combined with aluminium. Scandium's applications, notably in the aerospace industry, where its rarity justifies the cost, highlight its specialized role. The challenges associated with the limited commercial production of scandium, along with fluctuations in supply and demand, further emphasize its unique market dynamics. Efforts in research and development continue to explore alternative sources and enhance the sustainable production of scandium, recognizing its distinctive properties in niche applications, such as high-

---

[75] Cotton, S. A. (2003). Scandium, yttrium, and the lanthanides. In Elsevier eBooks (pp. 93–188). https://doi.org/10.1016/b0-08-043748-6/02004-

[76] The Editors of Encyclopaedia Britannica. (1998b, July 20). Scandium | Chemical Element, Properties & Uses. Encyclopedia Britannica. https://www.britannica.com/science/scandium

[77] Ibid

[78] Ibid

[79] Ibid

intensity discharge lamps and certain catalysts. Overall, scandium's rarity and uniqueness contribute to its special status, with its application in specific industries reflecting a balance between its unique properties and associated economic considerations.

Scandium, as a transition metal, showcases an array of metallic characteristics that contribute to its versatility and utility in various industrial applications. One of the most prominent features is its distinctive metallic luster, which imparts a shiny, reflective surface. This visual property is a hallmark of metals, indicating their ability to efficiently reflect light.

The conductivity of electricity and heat in metals is a fundamental attribute, and scandium excels in this regard. Its structure allows for the presence of delocalized electrons that can move freely within the metal lattice, facilitating the efficient transmission of both electrical current and thermal energy.[80]

Scandium's malleability and ductility are crucial aspects of its metallurgy. The metal can be easily shaped, hammered into thin sheets, and drawn into thin wires without fracturing.[81] These qualities make scandium amenable to various manufacturing processes, contributing to its use in the production of specialized alloys.

The relatively low density of scandium is noteworthy. When combined with other metals, such as aluminum, scandium contributes to the formation of lightweight alloys. This property is particularly valuable in industries like aerospace, where the demand for materials that balance strength and weight is critical.

Scandium's high melting and boiling points are indicative of its metallic nature. These temperatures are characteristic of metals, which typically have high melting points due to the strength of metallic bonds that hold the atoms together in a crystalline lattice structure.

Corrosion resistance is crucial for metals in various applications, and scandium's ability to form a protective oxide layer when exposed to oxygen and water vapor contributes to

---

[80] Ганиев, И. Н., Норова, М. Т., Эшов, Б. Б., Иброхимов, Н. Ф., & Иброхимов, С. Ж. (2020). Effect of scandium additions on the temperature dependences of the heat capacity and thermodynamic functions of Aluminum–Manganese alloys. Physics of Metals and Metallography, 121(1), 21–27. https://doi.org/10.1134/s0031918x2001006

[81] Vipin. (2022, November 1). Scandium element - Physical properties, fun facts and FAQ. Infinity Learn by Sri Chaitanya. https://infinitylearn.com/surge/chemistry/scandium/n

its durability and resistance to corrosion.

Applications

Aerospace Industry and Defence Sector

Scandium plays a pivotal role in the aerospace industry through its incorporation into aluminium-scandium alloys, which are renowned for their exceptional strength-to-weight ratio.[82] These lightweight alloys find extensive use in the construction of various aircraft components, including fuselage structures, wings, and other critical parts. The utilization of scandium in the aerospace sector extends to spacecraft manufacturing, where the imperative to minimize weight is paramount due to the high costs associated with launching payloads into space.[83] The addition of scandium enhances the performance of these alloys, ensuring they maintain their strength and durability under the demanding conditions of aerospace applications. Moreover, scandium-aluminium alloys exhibit improved fatigue resistance, contributing to the longevity of components subjected to cyclic loading. The reduced maintenance costs associated with the alloys, coupled with their durability and resistance to corrosion, make them instrumental in both commercial and military aircraft.[84]

The utilization of aluminium-scandium alloys in lieu of conventional alloys represents a transformative breakthrough in aerospace technology, promising a substantial reduction in aircraft weight by an impressive 15% to 20%, all the while maintaining, and in many cases enhancing, overall alloy performance.[85] This advancement is particularly noteworthy as weight reduction is a critical factor in enhancing fuel efficiency, extending range, and improving overall aircraft performance.

An early exemplification of the effectiveness of Scandium-Aluminium alloys in aerospace and defence applications is evident in the production of the renowned Russian military aircraft, the MiG-21.[86] The integration of these alloys played a crucial role in achieving a balance between structural integrity and reduced weight, contributing to the MiG-21's operational success.

---

[82] Aluminium-scandium alloys, aerospace industry, airframes | RTFT. (n.d.). https://www.elementnorth21.com/aerospace/

[83] Ibid

[84] Ibid

[85] The addition of Scandium to aerospace casting alloys - ProQuest. (n.d.). https://www.proquest.com/openview/3f3dbf9ebf75d4890f84857f5dad0633/1?pq-origsite=gscholar&cbl=51922&diss=y

[86] Ibid

In a pioneering collaboration between Airbus and AutoDesk, a revolutionary lightweight solution has been introduced for commercial airplanes.[87] This innovative solution involves the utilization of Scalmalloy, an aluminium-magnesium-scandium alloy, in the construction of a bionic partition structure.[88] This structure, weighing a mere 30kg compared to the conventional 63kg, not only achieves a significant reduction in weight but also serves multifunctional purposes.[89] Beyond its primary role as a structural component, the Scalmalloy partition structure doubles as an emergency stretcher and features foldable seating for crew members, showcasing the alloy's versatility in design and functionality.

The success of these applications underscores the pivotal role that aluminium-scandium alloys play in advancing aerospace technology. Their ability to reconcile the competing demands of weight reduction and performance enhancement makes them instrumental in shaping the future of aircraft design, where efficiency, versatility, and innovation converge to redefine the standards of the industry. The aerospace industry is poised to dominate the market, and the strategic addition of trace amounts of scandium (approximately 0.1 to 0.5 percent) to aluminium is anticipated to be a game-changer.[90] This alloy modification not only enhances the strength of the metal but also leads to a substantial reduction in weight by 15 to 20 percent. This transformative property positions scandium as a crucial element in the aviation sector. The ongoing global trends toward urbanization, coupled with a rising population, increasing disposable income, and evolving lifestyles, are fostering the development of more airplanes and airports, especially in developing nations. This, in turn, is expected to propel the market growth of scandium throughout the forecast period. Notably, the surge in airport construction, particularly in countries like China, Qatar, India, and others, reflects a growing demand for airplanes.[91] As airports multiply, the need for lightweight, high-strength materials such as scandium-aluminium alloys is set to rise, establishing scandium as a key player in meeting the evolving demands of the aerospace industry.[92]

RUSAL, a distinguished Russian aluminium producer, has secured approval for its innovative aluminium-scandium alloy, ScAlution, for integration into the shipbuilding

---

[87] Autodesk and Airbus show the future of aerospace design and manufacture in pioneering generatively designed 3D printed partition | Autodesk News. (2018, January 24). Autodesk News. https://adsknews.autodesk.com/en/news/autodesk-and airbus-show-the-future-of-aerospace-design-and-manufacture-in-pioneering-generativelyd/

[88] Ibid

[89] Ibid

[90] Admin. (2023, February 11). The potential metal of the future Scandium. Resources. https://www.knowledgesourcing.com/resources/thought-articles/the-potential-metal-of-the-future-scandium/

[91] Ibid

[92] Ibid

industry.[93] This approval comes from the esteemed Russian Maritime Register of Shipping, the regulatory authority governing shipbuilding standards, materials, and methodologies.[94] ScAlution stands out by delivering a compelling synergy of diminished weight and heightened strength, surpassing alternative alloys.[95] Its application in commercial vessels holds the promise of significant fuel efficiency improvements. The infusion of scandium into the aluminium matrix not only fortifies strength but also reduces weight, offering a dual benefit of enhanced structural integrity and increased operational efficiency. Furthermore, ScAlution exhibits heightened resistance to corrosion, further solidifying its position as a superior choice in maritime applications.[96] This development signifies a significant leap forward in advancing materials technology within the shipbuilding sector, setting the stage for enhanced performance and efficiency in maritime endeavours.

Medical Sector – Scandium 44

Scandium-44 emerges as a promising medical isotope for advancing positron emission tomography (PET) imaging, a critical diagnostic tool for evaluating cellular activity and identifying conditions such as cancer and heart disease.[97] This isotope can be efficiently produced through the radioactive decay of titanium-44, presenting a valuable resource for prolonged PET scan applications.[98] The extended decay period of scandium-44, in contrast to titanium-44, ensures a sustained supply for many years of medical imaging.[99]

However, a key challenge lies in the separation of scandium-44 from titanium-44 within hospital settings. Addressing this concern, researchers have introduced an innovative solution utilizing an organic molecule called hydroxamate to immobilize titanium-44 on a resin.[100] Subsequently, a specially designed liquid is passed through the resin to selectively remove scandium-44. This process, repeatable as more scandium-44 is generated daily, offers a reliable and efficient means of isotope separation within hospital environments.[101]

---

[93] AZoM.com. (2021b, November 9). Advantages of Aluminum-Scandium alloy in shipping. https://www.azom.com/article.aspx?ArticleID=20947
[94] Ibid
[95] Ibid
[96] Ibid
[97] Energy.gov. (2023, August 3). Scientists identify an alternative system for producing the medical isotope Scandium-44. https://www.energy.gov/science/ip/articles/scientists-identify-alternative-system-producing-medical-isotopescandium-44#
[98] Ibid
[99] Ibid
[100] Roesch, F. (2012). Scandium-44: Benefits of a Long-Lived PET Radionuclide Available from the 44Ti/44Sc Generator System. Current Radiopharmaceuticals, 5(3), 187–201. https://doi.org/10.2174/1874471011205030187
[101] Ibid

Traditionally, isotopes employed in PET imaging are predominantly produced on-site at hospitals using particle accelerators, restricting access to PET procedures. The researchers' introduction of this resin technology represents a significant paradigm shift. By incorporating the new resin into an isotope generator, a portable device compatible with standard hospital facilities, the approach facilitates simplified access to isotopes like scandium-44.[102].

In 2023, The Korean Atomic Energy Research Institute (KAERI) has successfully localized the production of two medical and industrial radioactive isotopes, germanium-68 and scandium-44.[103] Previously, South Korea relied entirely on foreign suppliers for these isotopes

Solid Oxide Fuel Cells

Solid Oxide Fuel Cells (SOFCs) represent a cutting-edge electrochemical technology designed to convert fuel and oxygen into electricity, water, CO2, and heat.[104] Operating at approximately 1,000 ºC, SOFCs utilize a robust ceramic material as the solid electrolyte situated between an anode and a cathode, effectively segregating reactants.[105] Two pivotal transformations occur at this temperature: the solid ceramic electrolyte becomes selectively porous and conductive, and the reactant molecules become highly excited. In this state, oxygen molecules acquire electrons, becoming ions, and are then selectively drawn through the solid conducting electrolyte, separating them from the hydrogen fuel source.

Upon passing through the electrolyte barrier, oxygen combines with hydrogen or hydrocarbon molecules, generating water or CO2 and heat. The surplus electrons created during oxygen transport follow a direct return path to the cathode (+), establishing a recurrent flow of electrons that can be harnessed as electrical current. This continuous and emission-free operation distinguishes SOFCs from traditional batteries, offering

---

[102] Ibid

[103] Herh, M. (2019, October 25). Korean Atomic Energy Research Institute localizes two radioactive isotopes. Businesskorea. https://www.businesskorea.co.kr/news/articleView.html?idxno=37370

[104] Gua, H. (2004). Synthesis and assessment of La0.8Sr0.2ScyMn1−yO3−ı as cathodes for solid-oxide fuel cells on scandium-stabilized zirconia electrolyte. Journal of Power Sources. https://www.researchgate.net/profile/Jeongmin-Ahn 2/publication/245107535_Synthesis_and_assessment_of_La_08Sr_02Sc_y_Mn_1-_y_O_3-_d_as_cathodes_for_solid oxide_fuel_cells_on_scandium-stabilized_zirconia_electrolyte/links/59e987c9458515c36377d7e1/Synthesis-and assessment-of-La-08Sr-02Sc-y-Mn-1-y-O-3-d-as-cathodes-for-solid-oxide-fuel-cells-on-scandium-stabilized-zirconia electrolyte.pdf

[105] Ibid

advantages in energy efficiency, fuel flexibility, and low pollution levels.[106]

SOFCs demonstrate remarkable efficiency, reaching approximately 60-85% when running on natural gas.[107] With heat recycle capabilities, efficiency can surpass 85%.[108] This efficiency far exceeds traditional coal or gas-fired facilities and internal combustion engines in automobiles. Furthermore, SOFCs exhibit low emissions, making them cleaner processors of fuels compared to combustion-based systems. The decentralized nature of SOFCs allows for localized power generation, reducing transmission losses and bypassing much of the traditional utility-provided electrical service infrastructure.

Scandium plays a pivotal role in enhancing SOFC technology. When utilized as the stabilizing agent for zirconia in the solid electrolyte (ScSZ), scandium significantly improves ionic electrical conductivity.[109] This enhancement enables the electrolyte to operate at lower temperatures (750-800ºC), reducing the need for expensive alloys and thermal shielding materials. Scandia-stabilized SOFCs are anticipated to achieve extended commercial operating cycles of over 10 years, making them economically competitive with grid-supplied electrical power.[110]

Presently, leading SOFC technologies incorporate scandium, with Bloom Energy emerging as a technical leader.[111] Bloom Energy produces Bloom Energy Servers in various sizes, operating primarily on natural gas and delivering cost-effective electricity. Despite scandium's higher cost compared to yttria, its impact on overall operating parameters is deemed indispensable for ensuring the commercial competitiveness of SOFC products. [112]

Extraction Process

The extraction process of scandium involves several steps and typically relies on the presence of scandium in certain ores or waste products associated with other mining activities. Scandium is not commonly found in concentrated deposits, so its extraction often involves complex processes. One common source of scandium is as a byproduct of the processing of various minerals, such as uranium, titanium, and rare earth elements.[113] Below is a generalized description of the extraction process:

---

[106] Ibid
[107] Kilner, J. A., Druce, J., & Ishihara, T. (2016). Electrolytes. In Elsevier eBooks (pp. 85–132). https://doi.org/10.1016/b9780-12-410453-2.00004-x
[108] Ibid
[109] Ibid
[110] Ibid
[111] Energy, B. (2022, May 19). Everything you need to know about solid oxide fuel cells. Bloom Energy. https://www.bloomenergy.com/blog/everything-you-need-to-know-about-solid-oxide-fuel-cells/
[112] Ibid
[113] Zhang, Y., Zhao, H., Sun, M., Zhang, Y., Meng, X., Zhang, L., Lv, X., Davaasambuu, S., & Qiu, G. (2020b).

Mining: Scandium is often obtained as a byproduct during the mining of other minerals. For example, uranium and rare earth element ores, as well as some phosphate rock deposits, may contain trace amounts of scandium.

Ore Processing: Once the ore is extracted, it undergoes processing to isolate scandium. This step may involve crushing, grinding, and chemical treatment to break down the ore and release scandium into solution.

Leaching: Scandium is often found in the ore in the form of various compounds. Leaching is a common method to extract scandium from the ore by using acids or other chemical solutions. The leaching process helps dissolve scandium-containing compounds, leaving other impurities behind.

Separation and Purification: After leaching, the solution contains a mixture of scandium along with various other elements. Separation techniques, such as solvent extraction or ion exchange, are employed to isolate scandium from the rest of the solution. These methods take advantage of the different chemical properties of scandium compared to other elements.

Precipitation: Once scandium is separated from other elements, it may be precipitated from the solution using chemical reactions. Precipitation helps concentrate scandium into a solid form.

Calcination and Reduction: The solid scandium compounds obtained from precipitation are subjected to calcination, a process involving heating to high temperatures in the presence of air. This step converts scandium compounds into an oxide form. Subsequent reduction processes, often using metallic reductants, are applied to obtain metallic scandium or scandium compounds.

Refining: The obtained scandium might still contain impurities. Additional refining steps may be necessary to achieve a high-purity scandium product. Techniques such as distillation or zone refining may be employed.

Final Product: The final product of the scandium extraction process depends on the intended application. Scandium can be produced in the form of metal, oxide, or other

---

Scandium extraction from silicates by hydrometallurgical process at normal pressure and temperature. Journal of Materials Research and Technology, 9(1), 709–717. https://doi.org/10.1016/j.jmrt.2019.11.012

compounds based on the requirements of end-users.

Global Developments

Market

The current market for scandium lacks a formalized buy/sell structure.[114] Scandium oxide and metal do not undergo trading on metals exchanges, and the absence of terminal or futures markets means that no official pricing mechanism is in place for buyers and sellers.[115] Transactions involving scandium products occur privately, with prices undisclosed. Quotes for scandium oxide are subject to various factors, including product quality, volume, availability, source, and prevailing demand. While some internet-based traders offer scandium material, the quantities available are generally limited. Price for pure scandium fluctuates between $4,000 and $20,000 per kilogram.[116]

At present, a substantial portion of scandium is obtained as a by-product in the processing of other ores, such as uranium or various rare earths. Additionally, scandium can be reclaimed from previously processed tailings. Consequently, the supply of scandium is intricately linked to the dynamics of the metals with which it is co-produced. This interdependence adds a layer of complexity to understanding the already intricate dynamics governing scandium's supply and demand landscape.

Kerala Minerals & Metals Limited

The Kerala Minerals and Metals Limited (KMML) entered into a formal Memorandum of Understanding (MoU) with the Council of Scientific & Industrial Research (CSIR) through the National Institute for Interdisciplinary Science & Technology (NIIST).[117] The purpose of this collaboration is to commence the extraction of scandium from spent acid utilized in the ilmenite beneficiation process at the pigment unit. This collaborative initiative, developed in partnership with KMML's Research and Development Department, seeks to cater to the significant industrial demand for scandium.[118] Scandium, a rare mineral predominantly used in aerospace and nuclear applications and valued higher per gram than gold, sees a global annual production of only 50 tonnes, with no other state presently engaged in its production.[119] The envisioned success of this innovative project is poised to become a noteworthy asset for both the nation and the

---

[114] Pistilli, M. (2023, December 1). How to invest in Scandium. INN. https://investingnews.com/daily/resource-investing/critical-metals-investing/scandium-production-the-problem-and-the-opportunity/

[115] Ibid

[116] Ibid

[117] The Hindu Bureau. (2023b, March 18). KMML signs MoU with CSIR-NIIST. The Hindu. https://www.thehindu.com/news/national/kerala/kmml-signs-mou-with-csir-niist/article66634809.ece

[118] Ibid

[119] Ibid

state.

HAT Project

Doubleview Gold Corp., through its wholly-owned Hat Project, potentially possesses the world's largest concentration of easily extractable scandium, a revelation that took several years for the company to fully comprehend.[120] Acquired as a greenfield prospect over a decade ago, the 6,308-hectare Hat Project in northwestern British Columbia proved significant with the discovery of the Hat deposit during the inaugural drill program.[121] Subsequent aggressive drilling led to the identification of the Lisle Zone, a higher-grade segment. Further exploration in 2015, 2016, and 2021 affirmed the existence of a substantial porphyry deposit, with dimensions yet to be precisely determined.[122] The Lisle zone alone spans 1,450 meters by 1,400 meters, comparable to the Mount Milligan deposit, currently the third-largest copper mine in Canada. While initial exploration indicated an alkalic-type gold copper porphyry, 2021 marked a turning point as detailed analysis revealed not only the significant presence of scandium but its remarkable homogeneity throughout the Hat deposit, differentiating it from other porphyry systems.[123]

Rio Tinto

In 2020, Rio Tinto unveiled a significant advancement in scandium recovery at its Sorel-Tracy facility in Quebec, specifically designed for titanium slag production sourced from the Lac Tio iron-titanium deposit.[124] Subsequently, in mid-2021, Rio Tinto initiated commercial-scale operations at a new scandium oxide production facility, marking a pivotal moment for the scandium sector. By mid-2022, the company proudly announced the successful production of its inaugural batch of high-purity scandium oxide, a development acknowledged as transformative for the industry by experts like Kaiser.[125]

The company has also formally entered into a binding agreement to acquire the Platina scandium project, a high-grade scandium resource situated in New South Wales, from

---

[120] Scandium increases the value of Doubleview Gold’s Hat deposit – Resource World Magazine. (n.d.). RW Mag. https://resourceworld.com/scandium-increases-the-value-of-doubleview-golds-hat-deposit/

[121] Ibid

[122] Ibid

[123] Harmantas, A. (n.d.). Doubleview Gold reveals new analytical data showing scandium grades from the Lisle deposit at its
Hat project in British Columbia. Proactiveinvestors NA.
https://www.proactiveinvestors.com/companies/news/980613/doubleview-gold-reveals-new-analytical-data-showing-scandium-grades-from-the-lisle-deposit-at-its-hat-project-in-british-columbia-980613.html

[124] Scherer, S. (2021). Canada, Rio Tinto to invest in R&D, cutting emissions at Quebec plant. Reuters. https://www.reuters.com/business/sustainable-business/canada-invest-rd-cutting-emissions-quebec-rio-tinto-plant-2022-111/

[125] Ibid

Platina Resources Limited at a valuation of $14 million.[126] Located near Condo Bolin in central New South Wales, the project boasts a long-life, high-grade scalable resource with the potential to yield up to 40 tonnes per year of scandium oxide over an estimated operational period of 30 years.[127] Rio Tinto, currently engaged in the production of scandium oxide from titanium dioxide production waste streams in Sorel-Tracy, Quebec, Canada, anticipates that the Platina scandium project will more than double its annual scandium production once operational.[128]

Challenges

The extraction and utilization of scandium encounter multifaceted challenges that impact its widespread application. Firstly, the scarcity of scandium in the Earth's crust poses a significant obstacle to obtaining substantial quantities of the element in an economically viable manner. The extraction process is further complicated by its association with other minerals, adding complexity and cost to the overall procedure. This, coupled with the limited sources from which scandium is primarily derived as a by-product, ties its supply to the dynamics of other metals. The resultant high market price of scandium impedes its broader adoption across various industries. Additionally, the absence of standardized procedures and specifications for scandium's use in different sectors hinders consistency and interoperability. Challenges persist in the development and standardization of scandium-aluminium alloys, despite their potential for high strength and reduced weight. As the market for scandium is still evolving, issues related to awareness, infrastructure, and regulatory frameworks need to be addressed. Overcoming these challenges necessitates continuous research, technological advancements, and collaborative efforts to unlock the full potential of scandium in diverse applications.

Conclusion - The Future Outlook

The future outlook for scandium presents a dynamic landscape with both challenges and opportunities. The current scenario involves obstacles related to its scarcity, extraction complexities, and high market price due to limited sources. However, ongoing research and development efforts hold the promise of addressing these challenges. Advancements in extraction technologies could lead to more efficient and cost-effective methods, potentially mitigating the economic barriers associated with scandium production. Furthermore, the exploration and identification of new sources of scandium, beyond traditional rare earth element ores, could contribute to a diversified supply chain. This diversification is crucial for enhancing availability and reducing dependency on specific mining operations, ensuring a more sustainable and stable supply of scandium.

---

[126] Gleeson, D. (2023b, April 28). Rio Tinto to expand scandium output with Platina project acquisition in Australia.
International Mining. https://im-mining.com/2023/04/28/rio-tinto-to-acquire-platina-scandium-project-in-australia/

[127] Ibid

[128] Ibid

In terms of applications, the demand for lightweight and high-strength materials, particularly in industries such as aerospace and automotive, presents a significant opportunity for scandium. The adoption of scandium-aluminium alloys, known for their exceptional strength-to-weight ratio, may increase as industries seek advanced materials to meet their evolving needs. With major players entering the market, there is a growing trend toward expanding the scandium market. This influx of expertise and investment could spur further innovations, propel awareness, and establish regulatory frameworks conducive to the widespread utilization of scandium.

In summary, while challenges persist, the future outlook for scandium appears promising, driven by advancements in extraction technologies, source diversification, and the increasing demand for its unique properties in various industrial applications. Continued research and collaborative efforts are essential to unlock the full potential of scandium and facilitate its integration into diverse sectors.

References

1. Admin. (2023, February 11). The potential metal of the future Scandium. Resources. https://www.knowledgesourcing.com/resources/thought-articles/the-potential-metal-of-the-future-scandium/

2. Aluminium-scandium alloys, aerospace industry, airframes | RTFT. (n.d.). https://www.elementnorth21.com/aerospace/

3. Autodesk and Airbus show the future of aerospace design and manufacture in pioneering generatively designed 3D printed partition | Autodesk News. (2018, January 24). Autodes News. https://adsknews.autodesk.com/en/news/autodesk-and airbus-show-the-future-of-aerospace-design-and-manufacture-in-pioneering-generativelyd/

4. AZoM.com. (2021b, November 9). Advantages of Aluminum-Scandium alloy in shipping. https://www.azom.com/article.aspx?ArticleID=20947

5. Cotton, S. A. (2003). Scandium, yttrium, and the lanthanides. In Elsevier eBooks (pp. 93–188). https://doi.org/10.1016/b0-08-043748-6/02004-1

6. Energy, B. (2022, May 19). Everything you need to know about solid oxide fuel cells. Bloom Energy. https://www.bloomenergy.com/blog/everything-you-need-to-know-about-solid-oxide-fuel-cells/

7. Energy.gov. (2023, August 3). Scientists identify an alternative system for producing the medical isotope Scandium-44. https://www.energy.gov/science/ip/articles/scientists-identify-alternative-system-producing-medical-isotopescandium-44#

8. Gua, H. (2004). Synthesis and assessment of La0.8Sr0.2ScyMn1−yO3−ı as cathodes for solid-oxide fuel cells on scandium-stabilized zirconia electrolyte. Journal of Power Sources.

9. Gleeson, D. (2023b, April 28). Rio Tinto to expand scandium output with Platina project acquisition in Australia International Mining. https://im-mining.com/2023/04/28/rio-tinto-to-acquire-platina-scandium-project-in-australia/

10. Harmantas, A. (n.d.). Doubleview Gold reveals new analytical data showing scandium grades from the Lisle deposit at its Hat project in British Columbia. Proactiveinvestors NA. https://www.proactiveinvestors.com/companies/news/980613/doubleview-gold-r analytical-d

11. Herh, M. (2019, October 25). Korean Atomic Energy Research Institute localizes two radioactive isotopes. Businesskorea. https://www.businesskorea.co.kr/news/articleView.html?idxno=37370

12. Kilner, J. A., Druce, J., & Ishihara, T. (2016). Electrolytes. In Elsevier eBooks (pp. 85–

132). https://doi.org/10.1016/b9780-12-410453-2.00004-x

13. Pistilli, M. (2023, December 1). How to invest in Scandium. INN. https://investingnews.com/daily/resource-investing/critical-metals-investing/scandium-

14. Roesch, F. (2012). Scandium-44: Benefits of a Long-Lived PET Radionuclide Available from the 44Ti/44Sc Generator System. Current Radiopharmaceuticals, 5(3), 187–201. https://doi.org/10.2174/1874471011205030187

15. Scandium - Element information, properties and uses | Periodic Table. (n.d.-b) https://www.rsc.org/periodic-table/element/21/scandium

16. Scandium increases the value of Doubleview Gold's Hat deposit – Resource World Magazine. (n.d.). RW Mag. https://resourceworld.com/scandium-increases-the-value-of-doubleview-golds-hat-deposit/

17. Scherer, S. (2021). Canada, Rio Tinto to invest in R&D, cutting emissions at Quebec plant. Reuters. https://www.reuters.com/business/sustainable-business/canada-invest-rd-cutting-emissions quebec-rio-tinto-plant-2022-111/

18. The addition of Scandium to aerospace casting alloys - ProQuest. (n.d.). https://www.proquest.com/openview/3f3dbf9ebf75d4890f84857f5dad0633/1?pq-origsite=gscholar&cbl=51922&diss=y

19. The Editors of Encyclopaedia Britannica. (1998b, July 20). Scandium | Chemical Element, Properties & Uses. Encyclopedia Britannica. https://www.britannica.com/science/scandium

20. The Hindu Bureau. (2023b, March 18). KMML signs MoU with CSIR-NIIST. The Hindu. https://www.thehindu.com/news/national/kerala/kmml-signs-mou-with-csir-niist/article66634809.ece

21. Vipin. (2022, November 1). Scandium element - Physical properties, fun facts and FAQ. Infinity Learn by Sri Chaitanya. https://infinitylearn.com/surge/chemistry/scandium/n

22. Zhang, Y., Zhao, H., Sun, M., Zhang, Y., Meng, X., Zhang, L., Lv, X., Davaasambuu, S., & Qiu, G. (2020b). Scandium extraction from silicates by hydrometallurgical process at normal pressure and temperature. Journal of Materials Research and Technology, 9(1), 709–717. https://doi.org/10.1016/j.jmrt.2019.11.012

23. Ганиев, И. Н., Норова, М. Т., Эшов, Б. Б., Иброхимов, Н. Ф., & Иброхимов, С. Ж. (2020). Effect of scandium additions on the temperature dependences of the heat capacity and thermodynamic functions of Aluminum–Manganese alloys. Physics of Metals and Metallography, 121(1), 21–27. https://doi.org/10.1134/s0031918x2001006

Centre for Security Studies

Jindal School of International Affairs

O.P. Jindal Global University