

# We are IntechOpen, the world's leading publisher of Open Access books Built by scientists, for scientists

4,400

Open access books available

117,000

International authors and editors

130M

Downloads

Our authors are among the

154

Countries delivered to

TOP 1%

most cited scientists

12.2%

Contributors from top 500 universities



WEB OF SCIENCE™

Selection of our books indexed in the Book Citation Index  
in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?  
Contact [book.department@intechopen.com](mailto:book.department@intechopen.com)

Numbers displayed above are based on latest data collected.  
For more information visit [www.intechopen.com](http://www.intechopen.com)



---

# Nature, Sources, Resources, and Production of Thorium

---

Miloš René

Additional information is available at the end of the chapter

<http://dx.doi.org/10.5772/intechopen.68304>

---

## Abstract

Thorium is a naturally occurring, slightly radioactive element. It is widely distributed in nature with an average concentration of 10.5 ppm Th in the upper earth's crust. In general, thorium occurs in relatively small number in Th-enriched minerals: thorite, thorianite, monazite, bastnaesite, and throgummite. However, the main world resources of thorium are coupled with monazite and bastnaesite. Monazite-enriched placer deposits occurring mainly in India, Brazil, Australia, and the USA form the recently available resources of thorium. Other commercially interested concentrations of thorium are coupled with bastnaesite mined from carbonatite deposits, especially from Bayan Obo deposit in China. Currently, the worldwide thorium resources by major deposit types are estimated to total about 6.2 million tons of Th. Issues associated with thorium's natural radioactivity are a significant deterrent to its commercial use. The monazite concentrates are recently produced only in India, Brazil, Malaysia, Thailand, and Vietnam, with a total amount of about 7000 tons. Consequently, experimental nuclear reactors based on thorium fuel cycle are operated recently only in India. In the long term, consumption of thorium could increase substantially if its use as a nuclear fuel becomes commercialized.

**Keywords:** thorium, geochemistry, mineralogy, monazite, thorium fuel cycle

---

## 1. Introduction

Thorium is a naturally occurring, slightly radioactive element. It is found in small amounts in most rocks, where it is about three times abundant than uranium. Thorium is relatively enriched in acid igneous rocks, especially in granites. The most common thorium mineral is monazite. In uranium ore deposits, thorium is concentrated in thorite and thorianite. In magmatic carbonate-enriched rocks (carbonatites), thorium is associated with rare earth elements (REE) in bastnaesite. However, the most important reserves of thorium occur in placer deposits, which contain monazite. Monazite is in placer deposits mined together with other heavy

minerals, such as rutile, zircon, ilmenite, and cassiterite. The principal monazite-producing countries are India, Brazil, Malaysia, and Thailand. Major end uses of thorium are refractories, lamp mantles, and aerospace alloys. Relatively restricted is using thorium in energy production. Although research into thorium-fuelled nuclear reactors continues, there exist no industrial-scale nuclear reactors using thorium. However, India continued its plan for a development of its nuclear power program based on the thorium-fuelled nuclear reactors.

## 2. History

Thorium was identified as an element in the mineral thorite in 1828 by the Swedish chemist Berzelius. Newly discovered element was named for Thor, the Scandinavian God of thunder and lightning, because of its use in energy. In 1885, thorium came into commercial use when it was discovered that a fabric mantle impregnated with a thorium compounds would give a steady, bright white light when heated. This discovery led to the development of the Welsh mantle, which was adopted in gas lighting and later in kerosene lamps. Thorium derived from monazite occurring in the Brazilian beach sands was produced as early as 1885. In 1911, monazite from the Indian beach sand deposits mastered world monazite markets.

During this time, the German manufacturers organized a monopoly of the thorium nitrate industry. World War I restricted German supplies of thorium compounds and enabled US production of thorium nitrate to expand. In the early 1920s, electricity began to replace gas and kerosene for general lighting purposes, and the need for thorium mantles declined. Up to the end of World War II, dominate monazite producers were India and Brazil. Since 1945 some other countries have started with their monazite production (e.g., Australia and Malaysia). During World War II started new using of thorium as a component in a high-temperature alloys.

After the war, monazite was processed largely for its nuclear fuel potential. The discovery in 1946 that  $^{232}\text{Th}$  could be transmuted into  $^{233}\text{U}$  increased the interest in thorium. However, the decision to develop nuclear reactors based on uranium fuels slowed development of thorium-fuelled reactors and reduced thorium demand. During the 1950s, some became new producers of thorium, namely Canada and South Africa, where uranium ores from uranium-enriched quartz-pebble conglomerates contain also some thorium. At this time distinctly increased interest in the rare earth elements (REE) and monazite was mined in the first place for its REE content. Some other thorium was also acquired from REE bearing bastnaesite, occurring in carbonate-enriched magmatic rocks (carbonatites). Much of thorium contained in residues is being stockpiled by private industry [1].

New interest about using thorium as nuclear fuels started in 1960s together with ideas in the development of Fast Breeder Reactors (FBR). Basic research of thorium fuels cycles are being undertaken by Brazil, Germany, the USA, India, Italy, Australia, Canada, China, France, USSR, Romania, and some other countries. Several experimental and prototype nuclear power reactors were successfully operated from the mid-1950s to the mid-1970s using  $(\text{Th}, \text{U})\text{O}_2$ ,  $(\text{Th}, \text{U})\text{C}_2$ , and  $\text{LiF}/\text{BeF}_2/\text{ThF}_4/\text{UF}_4$  fuel. The activity of the Nuclear Cycle Division of the IAEA in this area was supported mainly by organizing some technical

committee meetings [2–5]. However, thorium fuels have not been introduced commercially because the estimated uranium resources turned out to be sufficient. On the other hand, using thorium in nuclear energy cycle has some significant precedence: (i) the intrinsic proliferation resistance of thorium fuel cycle, (ii) better thermophysical properties and chemical stability of  $\text{ThO}_2$ , as compared to  $\text{UO}_2$ , (iii) lesser long-lived minor actinides than the traditional uranium fuel cycle, (iv) superior plutonium incineration in  $(\text{Th}, \text{Pu})\text{O}_2$  fuel as compared to  $(\text{U}, \text{Pu})\text{O}_2$ , and (v) attractive features of thorium related to accelerated-driven system and energy amplifier. However, there are several challenges in the form and back end of the thorium fuel cycles. Irradiated  $\text{ThO}_2$  and spent  $\text{ThO}_2$ -based fuels are difficult to dissolve in  $\text{HNO}_3$  because of the inertness of  $\text{ThO}_2$ . The high gamma radiation associated with the short-lived daughter products of  $^{232}\text{U}$ , which is always associated with  $^{233}\text{U}$ , necessitates remote reprocessing and refabricating of fuel. The protactinium formed in thorium fuel cycle also causes some problems, which need to be suitably resolved. Consequently, recently the various experimental nuclear reactors based on thorium fuel cycle are operated only in India. Some other basic research on thorium fuel cycle continued in China, France, Japan, Norway, Russia, and the USA [6].

The other thorium's commercial uses included catalysts, high-temperature ceramics, and welding electrodes. Other no energy uses of thorium are in electron tubes, special use lighting such as airport runway lighting, high-refractive glass, radiation detectors, computer memory components, photoconductive films, target material for X-ray tubes, and fuel cell elements. Its use in most of these products is generally limited because of concerns over its naturally occurring radioactivity. Consequently, no radioactive substitutes have been developed for many applications of thorium. Beryllium, aluminium, and yttrium oxides can be substituted for thorium oxide as a refractory. Yttrium compounds have replaced thorium compounds in incandescent lamp mantles. Magnesium alloys containing Zn, Al, REE, Y, and Zr can substitute for magnesium-thorium alloys in aerospace applications. Research is being conducted to find a replacement for thorium in lamp mantles. These substitutions for thorium in no energy uses are expected to increase because of growing public concern and governmental regulations on radioactive materials [7].

### 3. Geochemistry of thorium and thorium minerals

Thorium is widely distributed in nature with an average concentration of 10.5 ppm Th in the upper earth's crust, while the middle crust has an average of 6.5 ppm Th and the lower crust an average of 1.2 ppm Th [7]. Thorium is relatively depleted in mafic igneous rocks (basalts) where the concentration averages about 1 ppm Th, although alkali varieties enriched in Na and K relative to Ca range up to 5 ppm Th. Granitic rocks show a distinct increase over mafic igneous rocks, averaging 20–30 ppm Th. Thorium together with REE could be accumulated during fractional crystallization of alkali igneous rocks. Under some circumstances by this fractionation, a separate carbonate-enriched melt will form, resulting in carbonatites. With carbonatites are associated some complex fluoro-carbonate minerals such as bastnaesite. During weathering, thorium remains in the refractory solid form and is mostly transported as distinct mineral grains (typically as monazite). Sandstones contain about 2 ppm Th, with

beach sands containing 10 ppm Th, and limestone averages about 2 ppm. Shale contains 10–15 ppm Th, small amounts of thorium may adsorb clay particles during weathering. Twelve isotopes of thorium are known, with atomic masses from 223 to 234. However, natural thorium is present as nearly 100%  $^{232}\text{Th}$  isotope. The other important natural isotope of thorium  $^{230}\text{Th}$  is generally presented in uranium minerals.

In general, thorium occurs in relative small number of Th-enriched minerals: thorite ( $\text{ThSiO}_4$ ), thorianite ( $\text{ThO}_2$ ), monazite [(Ce, La, Nd,Th,U) $\text{PO}_4$ ], bastnaesite [(Ce, La) $\text{CO}_3\text{F}$ ], and throgummitite [ $\text{Th}(\text{SiO}_4)_{1-x}(\text{OH})_{4-x}$ ]. However, the main world resources of thorium are coupled with monazite and bastnaesite. Monazite is a primary source of light REE. Monazite concentrates, which are mined from beach sands in India, Brazil, the USA, Malaysia, Korea, and Sri Lanka, contain 3.1–14.32 wt.%  $\text{ThO}_2$  and 40.7–65.0 wt.% REO (rare earths oxides). However, monazites from some granitic rocks could contain up to 27 wt.%  $\text{ThO}_2$ .

Other, especially, potentially based resources of thorium are coupled with carbonate-enriched magmatic rocks (carbonatites), containing bastnaesite (up to 2.8 wt.%  $\text{ThO}_2$ ), parisite [ $\text{CaREE}_2(\text{CO}_3)_3(\text{F,OH})_2$ ] (up to 4.0 wt.%  $\text{ThO}_2$ ), and synchysite [ $\text{CaREE}(\text{CO}_3)_2(\text{F, OH})$ ] (up to 5.0 wt.%  $\text{ThO}_2$ ). Highly rare alkali-rich nephelinite syenites from the Lovozero pluton on the Kola peninsula (Russia) contain rare REE-enriched mineral loparite (Na,REE,Ca) (Ti, Nb)  $\text{O}_2$  with up to 1.6 wt.%  $\text{ThO}_2$  [8]. Some higher concentrations of thorium have also important apatite ore deposit on the Kola Peninsula in the Russia. Apatite containing higher concentrations of thorium occurs also in the alkalic magmatic rocks on the Vishnevyye Mountains of the Urals range in the Russia [1]. A large variety of other minerals contain minor amounts of thorium (e.g., allanite, xenotime, zircon, and uraninite).

#### 4. Ore deposits

Thorianite, thorite, and uranothorite are the only true thorium minerals, but they are not recently recovered. Some resources of these minerals are coupled with quartz-pebble conglomerates in Canada (Elliot Lake region) and South Africa (Witwatersrand). World thorium resources in terms of the genetic types of ore deposits are displayed in **Table 1** [9].

Deposit type	Metric tons of thorium
Placers	2,182,000
Carbonatites	1,783,000
Vein-type	1,528,000
Alkaline igneous rocks	584,000
Others	135,000
Total	6,212,000

**Table 1.** World thorium resources in terms of the deposit types [9].

The main recently available resources of thorium are coupled with monazite-enriched placer deposits in alluvial or marine sediments occurring mainly in Australia, India, Brazil, Venezuela, the USA, and Egypt. These deposits contain variable proportions of monazite, ilmenite, rutile, xenotime, zircon, and/or cassiterite. The main minerals, which are mined on these placer deposits, are ilmenite, rutile, zircon, and cassiterite. Associated minerals, which are rarely of economic significance, can include garnet and kyanite. Monazite, when also extracted, represents only an accidental product.

Placer deposits are found where water waves have concentrated heavy mineral grains on a sea beaches. These deposits may occur in both modern and ancient shorelines. Many of the heavy mineral sand deposits are concentrated by wave action in both parallel and transgressive dunes. Monazite placers are reported from Australia, Egypt, India, Liberia, Brazil, Burma, Malaysia, Sri Lanka, and the USA.

The placer deposits in Australia are mined for their ilmenite, rutile, and zircon content. The monazite content in heavy mineral concentrates varied from 0.2 to 1.5 wt.%. Present-day shoreline deposits are evolved on the east coast in the SE Queensland. The most important placer sand deposits are coupled with the Tertiary fossil shoreline deposits in the Murray Basin, in the southwest Australia. Monazite grades in this deposits are around 1–1.5 wt.%.

Although monazite occurs associated with ilmenite and other heavy minerals in beach sands, skirting the entire Peninsular India, its economic concentration is confined to only some areas with suitable physiographic conditions. The west coast placers are essentially beach or barrier deposits with development of dunes evolved on dry months. On the other hand, the east coasts deposits consist of extensive dunes fringing the coasts. The beach sands of Chavara bar (Kerala) on the West coast contain 73 vol.% heavy minerals, 60–70 vol.% ilmenite, 4–7 vol.% garnet, 5–8 vol.% zircon, and 0.5–1.0 vol.% monazite. The east coast beach placers and dunes are low grade with 8–20 vol.% of heavy minerals. The most important placer deposit on the East coast is the Chatrapur deposit (Orissa) with about 20 vol.% heavy minerals and 0.5 vol.% monazite. In the Malaysian deposits, monazite is associated with columbite, xenotime, and cassiterite. The cassiterite placers at Trengganu contain as much as 58 vol.% monazite. In Sri Lanka, the largest placer deposit near Pulmoddai contains 3 million tons of sand with 0.4 vol.% monazite, 18 vol.% rutile, and 62 vol.% ilmenite [10].

In Brazil, monazite occurs associated with ilmenite and zircon in placer deposits evolved along the eastern and south-eastern Atlantic coast. In Burma, placer deposits occur in the southern Shan states. Weathering of quartz veins and pegmatite dykes injected into the granites derives considerable quantities of cassiterite and wolframite occurring in the placers.

In the USA, alluvial deposits of monazite are known to occur in the intermountain valleys of Idaho, the Carolina Piedmont of North and South Carolina, and the beach deposits of north-eastern Florida to south-eastern Georgia. The three monazite placer districts, namely the North and South Carolina stream deposits, Idaho stream deposits, and Florida-Georgia beaches, are the largest volume known alluvial thorium deposits in the USA. The modern and raised Pleistocene and Pliocene beach deposits of north-eastern Florida and south-eastern Georgia host low-grade but persistent concentrations of thorium. Heavy minerals constitute

a small part of the beach sands. The most abundant heavy mineral in this beach deposits is ilmenite, in many places forming more than 50 vol.% of the heavy-mineral fraction. Monazite forms a minor part of the heavy-mineral fraction, usually less than 1 vol.%. The beach placer deposits of this region contain total reserves of about 14,700 tons of  $\text{ThO}_2$ , which occur in 330,000 tons of monazite. These placer deposits were mined primarily for ilmenite and rutile. Mining ceased in this area in late 1978 since increasing environmental regulations made mining operations more costly [11].

The ore bodies constituting quartz-pebble conglomerates are represented in particular by the Blind River-Elliot Lake deposits in Ontario, Canada and the Witwatersrand deposits in South Africa. These ore bodies occur mainly in pyrite-bearing oligomictic conglomerates. In the Blind River-Elliot Lake deposits, thorium together with uranium occurs mainly in a brannerite-uraninite-monazite mineral assemblage. Principal ore minerals are uraninite, brannerite, and monazite, with minor coffinite, uranothorite, xenotime, and gummite. Uraninite is partly enriched in thorium with average content of 6.5 wt.%  $\text{ThO}_2$ . The Witwatersrand reefs are not only rich in gold but also represent significant uranium deposit. The principal uranium minerals are uraninite and lesser uranothorite, brannerite, and coffinite. Uraninite from this deposit is enriched in thorium (average 3.9 wt.% Th) [12].

Carbonatites, which recently represented the most important source of REE, are also considered as potential source of thorium. Carbonatites are igneous rocks containing >50% of primary carbonate minerals. The most carbonatites are actually polygenetic and show evidence of hydrothermal and metasomatic reworking. These rocks generally contain <50 ppm Th; however, some contain higher concentrations. The majority of carbonatites occur in association with broadly coeval ultramafic and alkaline silicate rocks.

From the mid-1960s to 1985, the carbonatite-hosted Mountain Pass deposit in the USA was the world's main source of REE, producing over 20 kt REO at its zenith. Recently, almost all (~97%, or 120–130 kt REO in 2006–2010) of the world's REE supply comes from China, with 40–50% of this production contributed by the giant Fe–REE–Nb deposit at Bayan Obo [8].

Carbonatite-related deposits can be subdivided into deposits where magmatic and/or hydrothermal processes are important and those where secondary processes such as supergene enrichment and laterization predominate. The most important primary carbonatite-related deposit is the Bayan Obo deposit in Inner Mongolia, China, which represents 70% of the world's REE resources. The most abundant REE minerals at Bayan Obo are monazite and bastnaesite. Carbonatites with appreciable REE and Th mineralization have been reported also at Khibiny (Kola, Russia), Ozerny and Arshan (Siberia, Russia), Fen (Norway), Sokli (Finland), Mount Weld, Cummins Range, Mud Tank (Australia), Palabora (South Africa), Khanneshin (Afghanistan), Amba Dogar (India), Barra do Itapirapuã (Brazil), Tundulu and Kangankunde (Malawi), and Wigu Hill (Tanzania) among many others [13].

Highly potential sources of REE and Th represent intrusions of alkaline and peralkaline igneous rocks. Some well-known examples of these rock series being the Ilímaussaq intrusion in southern Greenland, Lovozero and Khibiny alkaline plutons on the Kola Peninsula (Russia), the Red Wine-Letitia alkaline province in Canada, alkaline laccolith at Poços de Caldas

(Brazil), and alkaline syenite body at Pilanesberg (South Africa) [14, 15]. All these magmatic complexes are zoned or layered, enriched with Na and K, and contain a variety of relatively rare minerals including thorite, monazite, loparite, zircon, and apatite. Thorium is present in thorite, monazite, zircon, loparite, and some other accessory minerals of REE. Local thorium contents in these rock complexes may range up to 1500 ppm Th, but overall they rarely contain in excess of 50 ppm Th [16].

On the Ilímaussaq complex is bounded highly interested REE-Y-U-Th mineralization at Kvanefjeld (Kuannersuit) coupled on agpaitic nepheline syenites. Recently performed exploration is concentrated on potential recovery of REO, Y, together with production of U and Zn as valuable by-products. The Lovozero complex in the Kola Peninsula is represented by layered intrusion of varied varieties of nepheline syenite with loparite as main economic interested mineral. Several loparite-rich units were mined since 1951 as the major source of LREE, Nb, and Ta for Soviet industry [13].

Some other potential sources of thorium represent Th-bearing granites and pegmatites, which are known in many parts of world. The thorium-enriched pegmatites most commonly occur in near granitic or syenitic bodies or in high-grade metamorphic rock series near their contacts with granitic stocks or batholiths. The principal thorium-bearing minerals in these deposits are uraninite, thorite, brannerite, uranothorite, monazite, and some other REE-, Th-, and U-bearing accessory minerals.

Most of the Th-enriched granites and pegmatites are not of commercial importance at present but provide a large reserve of thorium and uranium for the future. Thorium-bearing granitic rocks and pegmatite-bearing rock complexes occur in the Bancroft area of Ontario (Canada), Rössing (Namibia), Crockers Well, Greenbushes, Radium Hill (Australia). The Th-bearing minerals are represented by allanite, betafite, brannerite, davidite, monazite, thorite, and some others rare REE-, Th-, and U-bearing minerals. The ore zones at the Greenbushes contain low levels of thorium with average grades in range 3–25 ppm Th [17]. The uranium deposits in the Bancroft area coupled with anatectic pegmatites produced a total of 5700 tons U between 1956 and 1982. The principal ore minerals were uraninite, with up to 10 wt.% ThO<sub>2</sub>, and uranothorite.

Uranium mineralization associated with leucogranite dykes on the Rössing deposit in Namibia was derived by the partial melting of U-rich sedimentary rocks. Uraniferous leucogranite bodies are located in high-grade metasediments of the Damara Pan-African belt. Within mineralized leucogranites, the distribution of uranium can be extremely variable. Main uranium mineral is Th-bearing uraninite with 3.3–8.0 wt.% ThO<sub>2</sub>. The Rössing uranium deposit is mined from 1976 and total production by the end of 2007 was slightly over 90,000 tones U [18].

Relatively rare thorium-bearing vein deposits are distributed throughout the world. They are localized in shear zones, faults, breccias zones in metasedimentary and metavolcanic rocks and are often associated with alkalic rocks complexes and carbonatites. The principal Th-bearing minerals in vein deposits are thorite, throgummite, and monazite, which are associated with some REE-minerals (allanite, bastnaesite, and xenotime). Examples of these ore deposits include the Lemhi Pass in the USA, Steenkampskraal and Vanrhynsdorp in South Africa, Eskisehir deposit in Turkey, and Nolans Bore in Australia [16, 19].



The Lemhi Pass district on the Montana-Idaho border in the USA contains numerous thorium-rich veins in the central Beaverhead Mountains. This district is thought to represent the largest concentration of thorium resources in the USA. The district contains total reserves of 64,000 tons of ThO<sub>2</sub> [20]. Most of mineralized veins are quartz-hematite-thorite veins, which fill fractures, shears, and brecciated zones in quartzitic rocks. Rare-earth- and Th-bearing allanite and monazite are locally abundant. The thorite veins of the Lemhi Pass district are approximately equally enriched in thorium and REE. The total REE-oxide contents range from 0.07 to 2.20 wt.%, with an average value of 0.43 wt.%. The average concentrations of Th are 0.43 wt.%. [11].

At Steenkampskraal (South Africa) from the 1950s to 1963 about 50,000 tons of monazite concentrates were extracted, which contained between 3.3 and 7.6 wt.% Th before operation of the mine was halted. New economic assessment of this deposit was completed in 2012 and currently were established resources of 86,900 wt.% of REO [9].

The Nolans Bore deposit in the Northern Territory (Australia) is coupled with mineralized shear zones evolved in variably deformed and altered granitic gneiss, pegmatite, and minor calcisilicate rocks. Massive fluorapatite dykes enriched in REE and Th form the mineralization. The thorium content of Nolans Bore fluorapatite generally ranges from 0.07 to 0.59 wt.% Th (average 0.23 wt.% Th) [21].

## 5. Resources

The by-product nature of the occurrence of thorium and a lack of economic interest has meant that thorium resources have seldom, if over, been accurately defined. Information on thorium resources was published in a joint report by the OECD Nuclear Energy Agency and the International Atomic Energy Agency (IAEA)—“Red Books” between 1965 and 1981, typically using the same terminology as for uranium resources at that time (e.g., reasonably assured resources and estimated additional resources I and II, the latter two categories which are recently termed inferred and prognosticated resources, respectively). No further information was published until 2003 when a global estimate of thorium resources of 4.5 million Th was presented in the 2003 Red Book. A more comprehensive report was presented in the 2007 Red Book where resource estimates were given by deposit type and by countries and this was updated in the 2009 edition. Currently, the worldwide thorium resources by major deposit types are estimated to total about 6.2 million tons Th, including undiscovered resources (**Table 1**). In 2011 and 2013, the IAEA conducted technical meetings on thorium resources. Based on the inputs given in the meetings and details available in other open sources, identified uranium resources, regardless of resource category or cost category, have been updated for 16 countries and published in the most recent Red Book (**Table 2**) [9]. However, these identified resources (reasonably assured and inferred resources) may not have the same meaning in terms of classification as identified U resources.

The main world resources of thorium are associated with monazite placer deposits in India, Brazil, Australia, the USA, Egypt, and Venezuela. The second most important thorium resources could be mined as by-product of REO from carbonatites (China, Greenland,

Country	Metric tons of thorium
India	846,000
Brazil	632,000
Australia	595,000
The USA	595,000
Egypt	380,000
Turkey	374,000
Venezuela	300,000
Canada	172,000
Russia	155,000
South Africa	148,000
China	100,000
Norway	87,000
Greenland	86,000
Finland	60,000
Sweden	50,000
Kazakhstan	50,000
Other countries	1,725,000
World total	6,355,000

**Table 2.** Identified resources of thorium [9].

Norway, Finland, and Sweden). Some other thorium resources are coupled with various uranium deposits in Canada, the USA, South Africa, and Kazakhstan. Thorium in Kazakhstan could be recovered as a by-product together with REO bounded on complex U-REE-Th ores. These ores are recently processed in the SARECO plant by Stepnogorsk [9].

## 6. Production

The monazite concentrates are recently produced only in five countries (**Table 3**) [22]. However, substantial but unquantifiable quantities of thorium produced in China during the processing of domestic and imported mineral concentrates for production of rare-earth compounds. Issues associated with thorium's natural radioactivity are a significant deterrent to its commercial use. Limited global demand for thorium continued to create an oversupply of thorium compounds and residues. Excess thorium that was not designated for commercial use was either disposed of as a low-level radioactive waste or stored. Although research into thorium-fuelled nuclear reactors continues, there are currently no industrial-scale nuclear reactors using thorium.

Country	Metric tons
India	5500
Brazil	600
Malaysia	500
Thailand	210
Vietnam	180
Total	6990

**Table 3.** World production of monazite concentrates [22].

Recently, worldwide only minor amounts of  $\text{ThO}_2$  are typically used annually. Principal uses include chemical catalysts, lighting, welding electrodes, and heat-resistant ceramics, in descending order of use.

## 7. Conclusion

Extraction of thorium as a by-product of REE recovery from monazite and other REE- and Th-bearing minerals (bastnäesite) seems to be the most feasible source of thorium production recently. Processing of monazite to recover REE and thorium has been done in the past in many countries. Main monazite concentrate production is currently taking place in India, Brazil, Malaysia, Thailand, and Vietnam. Substantial but unquantifiable quantities of thorium produced China during the processing of domestic and imported mineral concentrates for production of rare-earth compounds. However, issues associated with thorium's natural radioactivity are a significant deterrent to its commercial use. Consequently, recently the various experimental nuclear reactors based on thorium fuel cycle are operated only in India. In the long term, consumption of thorium could increase substantially if its use as a nuclear fuel becomes commercialized.

## Acknowledgements

This work was carried out thanks to support of the long-term conceptual research organization RVO: 67985891.

## Author details

Miloš René

Address all correspondence to: rene@irsm.cas.cz

Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, Prague 8, Czech Republic

## References

- [1] Hedrick JB. Thorium. In: Mineral Facts and Problems 1985 Edition. Bull Bureau of Mines. 1985;**675**:835-846.
- [2] Thorium-Based Nuclear Fuel: Current Status and Perspectives. IAEA-TECDOC-412. Vienna: IAEA; 1987. p. 161.
- [3] Thorium-Based Fuel Options for the Generation of Electricity. Developments in the 1990s. IAEA-TECDOC-1155. IAEA; 2000. p. 144.
- [4] Thorium Fuel Utilization: Options and Trends. IAEA-TECDOC-1319. IAEA; 2002. p. 376.
- [5] Thorium Fuel Cycle—Potential Benefits and Challenges. IAEA-TECDOC-1450. Vienna: IAEA; 2005. p. 105.
- [6] Thorium. U.S. Geological Survey, Mineral Commodity Summaries. U.S. Geological Survey; Washington; January 2016.
- [7] Rudnick RL, Gao S. Composition of the continental crust. In: Holland HD, Turekian KK, editors. Treatise on Geochemistry 3. Amsterdam: Elsevier; 2004. pp. 1-64.
- [8] Chakhmouradian AR, Wall F. Rare earth elements: Minerals, mines, magnets (and more). Elements. 2012;**8**:333-340. DOI: 10.2113/gselements.8.5.333
- [9] Uranium 2014: Resources, Production and Demand. Paris: OECD; 2014. p. 508.
- [10] Jayaram KMV. An overview of world thorium resources, incentives for further exploration and forecast for thorium requirements in the near future. In: IAEA-TECDOC 412. Vienna: IAEA; 1987. pp. 8-26.
- [11] Van Gosen BS, Gillerman VS, Armbrustmacher TJ. Thorium deposits of the United States—Energy resources for the future? U.S. Geological Survey Circulation. 2009;**1336**:1-29.
- [12] Frimmel HE. Archaean atmospheric evolution: Evidence from the Witwatersrand gold fields, South Africa. Earth Science Reviews. 2005;**70**:1-46.
- [13] Chakhmouradian AR, Zaitsev AN. Rare earth mineralization in igneous rocks: Sources and processes. Elements. 2012;**8**:347-353. DOI: 10.2113/gselements.8.5.347
- [14] Wooley AR. Alkaline Rocks and Carbonatites of the World. Part 3: Africa. London: The Geological Society; 2001. p. 372.
- [15] Kogarko LN, Kononova NA, Orlova MP, Wolley AR. Alkaline Rocks and Carbonatites of the World. Part Two: Former USSR. London: Chapman and Hall; 1995. p. 226.
- [16] Boyle RW. Geochemical Prospecting for Thorium and Uranium Deposits. Amsterdam: Elsevier; 1982. p. 498.
- [17] Partington GA, McNaught NJ, Williams IJ. A review of geology, mineralisation and geochronology of the Greenbushes pegmatite, Western Australia. Economic Geology. 1995;**90**:616-635.

- [18] Cuney M, Kyser K. Hydrothermal uranium deposits related to igneous rocks. In: Cuney M, Kyser K, editors. *Recent and Not-So-Recent Developments in Uranium Deposits and Implications for Exploration. Short Course Series. Mineralogical Association of Canada: Québec City; Vol. 39; 2009. pp. 117-160.*
- [19] Gultekin AH, Örgün Y, Suner F. Geology, mineralogy and fluid inclusion data of the Kirilcaören fluorite-barite-REE deposit, Eskisehir, Turkey. *Journal of Asian Earth Science.* 2003;**21**:365-376.
- [20] Staatz MH. Geology and mineral resources of the Lemhi Pass thorium district, Idaho and Montana. *U.S. Geological Survey Circular.* 1979;**1336**:1-29.
- [21] Mernagh TP, Mieztis Y. A review of the geological processes controlling the distribution of thorium in the Earth's crust and Australia's thorium resources. *Geoscience Australia Record.* 2008;**5**:1-48.
- [22] Gambogi J, Aquino KC. Thorium. In: *USGS 2013 Minerals Yearbook.* U.S. Geological Survey. 2013:761-764.