Atomic minerals: journey of India to self-sufficiency

Vivekanand Kain[1,*], D. K. Sinha[2], Deependra Singh[3] and C. K. Asnani[4]

[1]Materials Group, Bhabha Atomic Research Centre, Mumbai 400 085, India
[2]Atomic Minerals Directorate for Exploration and Research, Begumpet 500 016, India
[3]Indian Rare Earths Limited (India), Prabhadevi 400 028, India
[4]Uranium Corporation of India Ltd, Jaduguda 832 102, India

Atomic minerals include mainly minerals containing uranium, thorium, rare metals, viz. niobium, tantalum, lithium, beryllium, titanium, zirconium, and rare earth elements (REEs) containing uranium and thorium as well as beach sand minerals. In India, these minerals are specified in Part B of the First Schedule to the Mines and Minerals (Development and Regulation) Act, 1957, and a few of these minerals containing uranium, thorium, niobium, tantalum and beryllium are included in the list of 'Prescribed Substances' under the Atomic Energy Act, 1962. After independence, different units of the Department of Atomic Energy have been playing a key role in making India self-reliant in these minerals and their processing. In the front end, the Atomic Minerals Directorate for Exploration and Research shoulders the responsibility for survey, exploration, and augmentation of atomic mineral(s) resources. The Uranium Corporation of India Limited is responsible for mining and processing of uranium ores, while the Indian Rare Earths (India) Limited caters to the mining of monazite-rich beach sands for recovery and processing of thorium and REEs. These three units of the DAE are ably supported by the Materials Group of Bhabha Atomic Research Centre, Mumbai, for technology development for mineral beneficiation and processing to produce metals/alloys/compounds required to support the requirements for expanding the nuclear power programme of India.

Keywords: Atomic minerals, exploration, mining, processing, technology development.

Introduction

In a note entitled 'Organisation of atomic research in India' dated 26 April 1948 to the then Prime Minister of the country, Jawaharlal Nehru, Homi Jegangir Bhabha urged that the development of atomic energy should be done in an organized manner[1]. The Government of India (GoI) accepted his proposal and the Atomic Energy Commission (AEC) of India was constituted on 10 August 1948 (ref. 2). The visionary in Bhabha was evident in including the mission to survey for the minerals related to atomic energy in the geographical territories of India in his historical first note to Nehru. In line with this thought, Bhabha outlined the three-stage nuclear power programme (NPP) considering the abundant thorium resources available in India[3].

In the pre-independence era, during the Second World War (1939–1945), the Geological Survey of India (GSI) established the Rare Minerals Survey Unit (RMSU) with the sole purpose to procure beryl from the mica mines of the country[4]. Bhabha's efforts fructified in transferring RMSU to the Ministry of Natural Resources and Scientific Research, GoI, in 1948 and consequently, RMSU was brought under the control of AEC w.e.f. July 1949. It had a focused mandate of exploring strategic minerals and metallic elements of interest to the NPP of India such as uranium, thorium, beryllium, graphite, etc. Bhabha entrusted the mandate of exploration of atomic minerals in the country to an eminent geologist, D. N. Wadia. Consequently, Wadia, the then geological advisor to the GoI and Head of RMSU (3 October 1950–15 June 1969), set-up the first task force of geologists for conducting a countrywide exploration of atomic minerals by mobilizing geoscientists from various universities and organizations (Figure 1). In 1953, RMSU was renamed as the Raw Material Division (RMD) and later as the Atomic Minerals Division in 1958. On its Golden Jubilee in 1998, the organization was rechristened as Atomic Minerals Directorate for Exploration and Research (AMD).

Figure 1. D. N. Wadia set up the first task force of geologists for atomic minerals exploration.

*For correspondence. (e-mail: vivkain@barc.gov.in)

The erstwhile RMSU initiated extensive surveys for uranium in 1949 in the Singhbhum Shear Zone (SSZ) and the first exploratory drilling for uranium commenced in 1951 in Jaduguda, Jharkhand. After the Jaduguda uranium deposit was established, the Department of Atomic Energy (DAE) set up the Uranium Corporation of India Limited (UCIL), a public sector undertaking under GoI on 4 October 1967, with the sole purpose of mining and processing uranium ore in the country to meet the fuel requirement of the first-stage NPP of India.

Around the same period, during August 1950, with the primary intention of taking up commercial-scale processing of monazite sand, the Indian Rare Earths Limited (IREL) was incorporated as a private limited company jointly owned by GoI and the Government of Travancore, Cochin, with its first unit, namely Rare Earths Division (RED) at Aluva, Kerala, for recovery of thorium. IREL became a full-fledged Central Government Undertaking in 1963 under the administrative control of DAE. In 2019, IREL was renamed IREL (India) Limited.

These three units under DAE, viz. AMD, UCIL and IREL (India) Ltd are responsible for the supply of raw materials required for NPP of the country. The Materials Group of the Bhabha Atomic Research Centre (BARC), Mumbai, is involved in developing technologies for processing and extraction of metallic values from the ores: (a) starting with mineral beneficiation/ore dressing, and (b) developing process flow sheets for separation of the required materials from the ores that meet the specification of materials to be used in NPP of India. The technology development for conversion of the ore to the required material is done by BARC using hydrometallurgical, pyrometallurgical and novel techniques, and the developed technologies are transferred to these three units.

The genesis of the materials development programme in BARC got initiated by a request from Bhabha to Brahm Prakash, then a faculty at the Indian Institute of Science (IISc), Bengaluru, to take up the challenge of establishing a facility for the fabrication of fuel assemblies in the BARC campus. Brahm Prakash and his team at BARC met this challenge in a short time. Brahm Prakash also set up facilities at BARC to study and understand the science required to develop components for plant applications. The Materials Group, BARC follows this legacy and works to fully understand the science, develop a fundamental understanding, and use it to develop materials and processes to support the robust nuclear programme of the country.

BARC, right from its inception, has developed the concept of 'Atmanirbhar Bharat' in its DNA. Although Bhabha knew at that time that Indian uranium ores are too lean to give a commercially viable product, yet with the idea of India becoming a sovereign nuclear state, he went ahead with the exploration and extraction of uranium from Indian mines with U_3O_8 content as low as 0.04%. The same concept was applied in the case of extraction of zirconium from zircon sand. These decisions paid off in later years when sanctions were imposed on India, but all the Indian pressurized heavy water reactors (PHWRs) continued functioning with fuel made in the country. Since then, the spectrum of materials activities in BARC has widened its scope and several entities have flourished (e.g. UCIL, IREL, Nuclear Fuel Complex (NFC) and Heavy Water Board (HWB)) using BARC-developed technologies for targeted production. From the lightest metallic element beryllium (Be) to the heaviest naturally found uranium (U), nearly all the metallic elements of interest to DAE were successfully extracted and processes were developed for utilization in BARC.

Atomic minerals

As envisioned by Bhabha, the basic framework of mineral prospecting and regulation of mineral concession guided by the Mines and Minerals (Development and Regulation) [MMDR] Act, 1957 of GoI and the Rules made there under provided a special status to atomic minerals. Under MMDR Act, 1957 (Part B of the First Schedule), atomic minerals include minerals with uranium, thorium, beryllium, lithium, niobium, tantalum, titanium, zirconium, and rare earth elements (REEs) containing uranium and thorium as well as beach sand minerals. Further, under the MMDR Act, 1957, GoI has promulgated Atomic Minerals Concession Rules (AMCR), 2016 (later amended in 2019) for mineral concession and regulation with respect to atomic minerals above the notified threshold values. The Atomic Energy Act, 1962, clarified the minerals containing uranium, thorium, niobium, tantalum, and beryllium as 'prescribed substance'. These rules are amended by GoI from time to time according to the NPP requirement of the country.

Exploration, mining and processing of uranium

Exploration for uranium

The exploration for atomic minerals by AMD was initiated during the tenure of Bhabha as Chairman, AEC, and Secretary, DAE. The Singhbhum copper belt in eastern India became the obvious first choice for surveys of uranium in India following the analogy of vein-type, structure-controlled, shear-induced, hydrothermal uranium deposits established by that time in Shinkolobwe, Congo[5] and the Rocky Mountains, USA[6]. Torbernite, a secondary uranium mineral known from Singhbhum in the early 1920s by a private prospector (E. F. O. Murray) and documented in the records of the GSI helped in framing the policies for early surveys[7]. The first extensive surveys for uranium began in 1949 in the Singhbhum Shear Zone (SSZ) by a team of geologists from AEC, GSI and Damodar Valley Corporation (DVC), who discovered 57 uranium anomalies[8]. Follow-up exploratory drilling to prove the depth continuity of these anomalies commenced in December 1951 by contracting the services to M/s Associated Drilling & Supply Company, London, UK, who were later joined by the Indian Bureau of Mines (IBM) and RMD (now AMD) between 1953 and 1955 (ref. 9). A total of ~70 km had been drilled and mineable uranium deposits were established at Jaduguda, Bhatin, Narwapahar, and Keruadungri till 1963 (refs 10, 11). The discoveries in the SSZ, surveys carried out in western India during 1955–56 led to the discovery of uranium mineralization in calcareous/carbon phyllite at Umra in the Aravalli Fold Belt and pegmatite in Bhunas, Rajasthan[12,13].

Bhabha's proactive efforts ensured liaising by RMD with the State Government of Bihar for obtaining the mining lease as early as 1954 to commence exploratory mining in Jaduguda, Bihar (now Jharkhand) in 1957. Presently, 7 out of the 16 uranium deposits in the SSZ are under exploitation by UCIL. Exploratory mining was also initiated in Umra, Rajasthan, in 1957 as a second nucleus of AMD's activities (Figure 2). Bhabha also played a key role in the initiation of airborne radiometric surveys in the country, considered to be a major input to the exploration activities for atomic minerals. AMD pioneered airborne surveys in India during 1955 with an indigenously designed and developed total gamma-ray count system to survey large tracts in the country. Bhabha's keen interest in the development of cheaper indigenous instrumentation for radiation surveys by geoscientists and electronic equipment essential for airborne surveys are documented in his letter to A. S. Rao (Founder, Electronics Corporation of India Limited (ECIL)).

Gradually, uranium exploration was expanded to other favourable geological domains in India, which resulted in establishing several small uranium deposits such as Bodal and Bhandaritola in erstwhile Madhya Pradesh (now in Chhattisgarh) in amphibolite; Jajawal in erstwhile Madhya Pradesh (now in Chhattisgarh) in sheared migmatite of the Chhotanagpur Granite Gneiss Complex (CGGC), and Walkunji, Karnataka in basal quartz–pebble conglomerate (QPC) of the Dharwar Group[14,15]. During the mid-1970s, exploration targeting sandstone-type uranium deposits resulted in the discovery of a high-grade, medium-tonnage

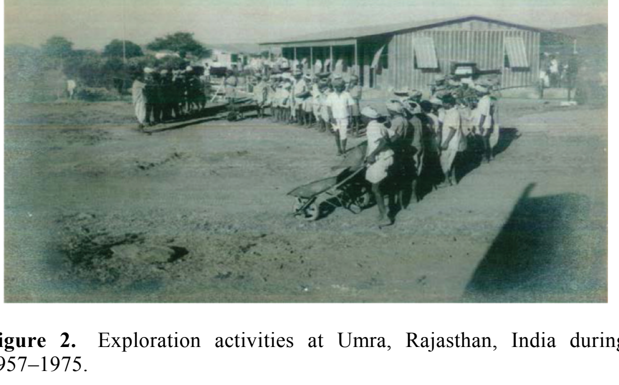

Figure 2. Exploration activities at Umra, Rajasthan, India during 1957–1975.

deposit at Domiasiat (Kylleng–Pyndengsohiong–Mawthabah), Meghalaya, in the sandstone of Mahadek Basin. Later, detailed exploration in contiguous sectors established several small uranium deposits[16–18]. During the mid-1980s, discovery of dolostone-hosted uranium deposits at Tummalapalle, Andhra Pradesh was the hallmark of exploration by AMD[19,20]. Consequent to the development of an economically viable alkali pressure leaching process[21,22], AMD intensified its exploration activities in the southern part of the Cuddapah Basin, targeting dolostone uranium mineralization. Intensive multi-parametric explorations carried out in Tummalapalle and adjacent sectors led to the identification of substantial uranium resources in this geological domain[23]. The Tummalapalle Group uranium deposit is under exploitation by UCIL[24].

During the early 1990s, a near-surface deposit was discovered adjacent to the unconformity contact between the basement granite and the overlying Srisailam Sub-Basin in the northern part of the Cuddapah Basin at Lambapur in erstwhile Andhra Pradesh (now in Telangana). Based on the application of favourable geological criteria and geological modelling, sustained exploration efforts resulted in establishing two more uranium deposits at Peddagattu and Chitrial in a similar geological set-up. Exploration in the adjacent Palnad Sub-Basin (Cuddapah Basin) established a small deposit at Koppunuru[25]. Presently, exploration is continuing in the potential sectors of Palnad Sub-Basin in the northern part of the Cuddapah Basin. Sustained exploration in the North Delhi Fold Belt (NDFB), in parts of Rajasthan and Haryana, targeting metasomatic-type uranium mineralization, led to the discovery of the Rohil uranium deposit in Rajasthan. Exploration is being carried out in different sectors of the ~200 km long albitite line in Rajasthan and Haryana. Intensive exploration in the adjacent sectors of the Rohil deposit has established another deposit at Jahaz, Rajasthan[26,27]. During the late 1990s, multi-parametric exploration in the Bhima Basin in Karnataka proved a medium-grade and small-tonnage uranium deposit at Gogi, hosted by brecciated limestone and granite along the Gogi–Kurlagere–Gundanahalli Fault in the southern part of the Basin. Sustained exploration in this geological domain established two other small- and medium-grade uranium deposits in Kanchankayi and Hulkal[28–30].

Self-sufficiency in uranium resources

The efforts of Bhabha provided a paradigm shift in the uranium exploration strategy by AMD, including sustained multi-parametric exploration in the established/productive uranium provinces of the country for immediate augmentation of uranium resources during the 21st century. Exploration has been intensified in potential geological domains to develop them into productive centres.

In the Proterozoic Cuddapah Basin, the globally unique, phosphatic dolostone-hosted uranium deposit of strata-bound nature have been established at Tummalapalle by continued exploration. AMD established more than 1.4 lakh tonnes of uranium with uniform grade and thickness since 1986 (ref. 31). This huge quantum of available uranium resource led to the establishment of the first mining centre of UCIL outside the SSZ in 2007. The sustained exploration for unconformity-related uranium deposits in the northern part of the Basin in the Srisailam and Palnad Sub-Basins established low-tonnage, low-grade uranium deposits in Lambapur, Peddagattu, Chitrial (Telangana) and Koppunuru (Andhra Pradesh), aggregating over 18,000 tonnes uranium[31]. Based on the breakthrough in the Cuddapah Basin, AMD has extended its exploration inputs in other Proterozoic Basins of India like in the Bhima Basin in Karnataka, where the integrated exploration efforts have brought to light a small-tonnage, medium-grade uranium deposit at Gogi and similar deposits in adjoining Kanchankayi and Hulkal (totalling ~5,000 tonnes uranium)[32].

In the Singhbhum Shear Zone, since the commencement of the first mining centre at Jaduguda in 1957, continued exploration efforts have established 17 low-grade and low- to medium-tonnage uranium deposits, aggregating more than 62,000 tonnes uranium resource in the central and eastern sectors of the SSZ, of which only seven are under active exploitation by UCIL. In recent times, exploration based on a conceptual geological model in the SSZ has helped establish a unique polymetallic deposit (including uranium) hosted by serpentinite at Kudada, Jharkhand[33]. Recent exploration strategies in the SSZ are based on integrated modelling of the geophysical, geological and subsurface exploration data from blocks adjacent to the established deposits and the existing mining centres to augment resources and extend the lifespan of the mines.

The NDFB of Rajasthan and Haryana is known since the 1950s for uranium and associated base-metal mineralization (Cu, Mo, Zn, Pb) along a crustal-scale, linear, petrotectonic feature known as the albitite line[34]. Integrated exploration, including geological and structural mapping, heliborne/ground geophysics and drilling resulted in the discovery of structure-controlled, metasomatite-type uranium deposits near Rohil and Jahaz, Rajasthan (~9000 tonnes uranium) and many other prospects are under active exploration. The association of uranium mineralization with geophysical anomalies, viz. high chargeability, low resistivity and low magnetic zones has helped locate more such exploration targets for concealed uranium mineralization in NDFB.

In the Mahadek Basin, Meghalaya, the Lower Mahadek Formation, exposed along the southern margin of the Shillong Plateau is characterized by the deposition of organic matter and pyrite-impregnated reduced sandstone in small basinal depressions/palaeochannels favouring sandstone-type uranium mineralization[35]. This geological domain hosts seven low- to medium-grade, small to medium-tonnage uranium deposits at Domiasiat, Wahkyn, Wahkut, Gomaghat, Tyrnai, Umthongkut, and Lostoin aggregating ~20,000 tonnes uranium[31].

The uranium resources established in the country by AMD increased from 52,911 tonnes in 1979 to 292,867 tonnes in 2021. In addition, several other potential geological domains have been identified, where the focus is to convert some of the occurrences into uranium deposits in the near future. These are the areas encompassing CGGC in Madhya Pradesh, Uttar Pradesh and Jharkhand; Siwalik Group, Himachal Pradesh; Satpura Gondwana Basin, Madhya Pradesh; Dongargarh–Kotri Belt, Chhattisgarh; Gulcheru Formation in the western part of the Cuddapah Basin, Andhra Pradesh; northern and southeastern margins of the Chhattisgarh Basin; Proterozoic basins such as Bijawar and Vindhyan, Madhya Pradesh, and fracture systems surrounding the Proterozoic basins such as the Cuddapah and Chhattisgarh basins. Additionally, developing the green-field areas into potential sectors is one of the long-term goals of AMD. These geological domains are being developed by AMD through in-house R&D efforts and collaboration with academia. The alkaline intrusive of the Southern Granulite Terrain (SGT), the basement/basinal formations below Deccan Traps, shear/fracture zones, remobilized granulite terrains of the southern Indian Shield, and phosphorite deposits of India are promising zones where exploration strategies have been planned.

Uranium mining in India

Jaduguda is the first mine in the country to produce uranium ore on a commercial scale. Exploratory mine development work in the Jaduguda mine started in 1958 with encouragement and guidance from Bhabha (Figure 3). UCIL shipped its first batch of uranium concentrate from Jaduguda in 1968. Since then, the activity has grown manifold, multiplying uranium production by the opening of new mines and process plants in the country. Figure 4 lists the uranium production milestones in chronological order.

UCIL now operates six underground mines (Bagjata, Jaduguda, Bhatin, Narwapahar, Turamdih and Mohuldih)

Figure 3. Homi Baba during his visit to Jaduguda, Jharkhand.

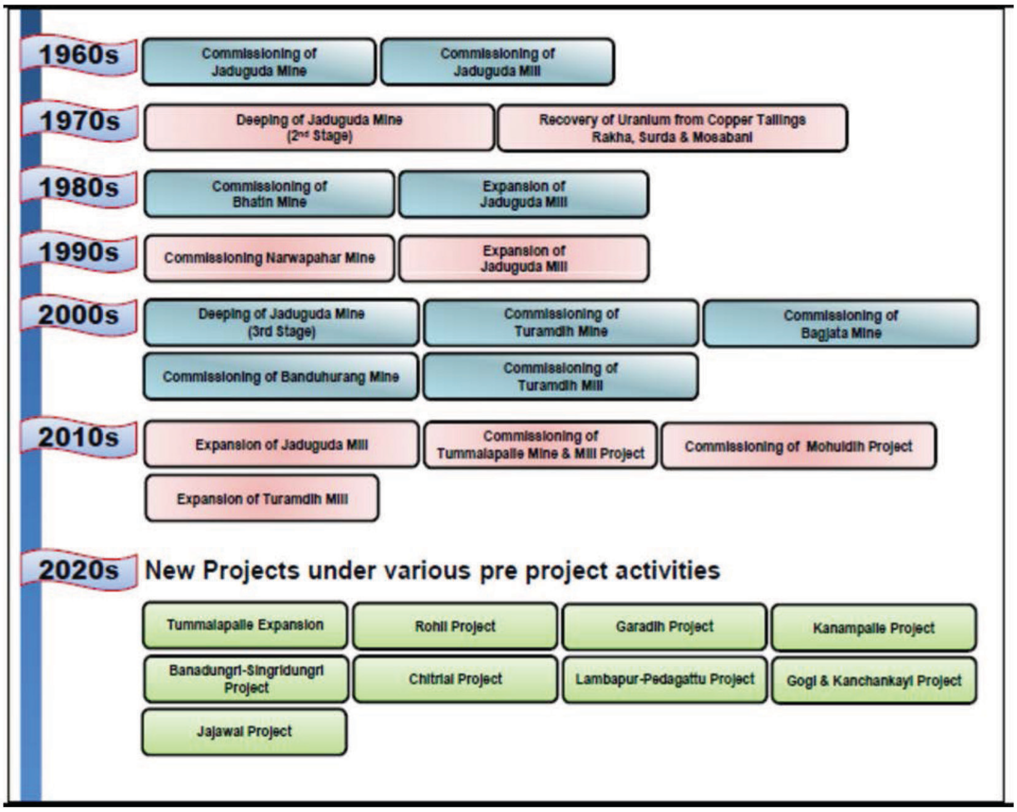

Figure 4. Growth of UCIL mines and mills since inception.

and one open-pit mine (Banduhurang) in the SSZ in Jharkhand[36,37]. It also operates a large underground mine and a processing plant (based on a new indigenous alkaline technology) in the Proterozoic Cuddapah Basin at Tummalapalle[36,38]. Ore produced from these mines is processed in two process plants located at Jaduguda and Turamdih in the same region[36,38]. The uranium concentrate produced from these plants is sent to NFC, Hyderabad, for further purification and fabrication of nuclear fuel rods.

To cater to the fuel requirements of upcoming reactors, AEC has accorded in-principle approval for capacity expansion of some of its existing units as well as for establishing new projects in various parts of the country. In line with DAE's requirements, UCIL has already outlined a plan for massive expansion which includes maintaining sustained supply from existing facilities through debottlenecking of certain deficiencies, modernization and capacity expansion of some existing units and construction of new production facilities (mines and plants) in different parts of the country. UCIL's major production centres are planned in Jharkhand, Andhra Pradesh, Karnataka, Telangana, Rajasthan and Chhattisgarh, taking into consideration the resources already identified in different geological basins by AMD.

If the planned projects of UCIL turn into production centres, the additional quantity of uranium concentrate (yellow cake) can contribute significantly to the fuel requirements of the upcoming reactors of the Nuclear Power Corporation of India Limited (NPCIL) in the next 10–15 years[37,38].

UCIL operating mines

Jaduguda mine: For commercial production, sinking of a vertical shaft of 5 m finished diameter up to 315 m was started in 1964 and commissioned in 1968. The Jaduguda mine is presently the deepest operating mine in India. This mine is now being operated with a rated capacity of 500 tonnes per day (TPD).

Bhatin mine: Bhatin is a small uranium deposit situated 3 km west of Jaduguda, which was commissioned in 1987 with a rated capacity of 250 TPD. Geological settings, mineral assemblages and other host-rock characteristics in this deposit are similar to those of the Jadugdua deposit. The deslimed tailings of Jaduguda mill are sent back for mine back-filling. The mine has now been considered for upgradation due to limitations in layout and accessibility, and AMD has provided inputs for augmentation of unexplored uranium resources in the Jaduguda–Bhatin link area.

Bagjata mine: A small deposit is located at Bagjata which is about 26 km east of Jaduguda. This mine, commissioned

Figure 5. ***a***, Decline entry of Bagjata mine, Bagjata, East Singhbhum district, Jharkhand. ***b***, Shaft at Narwapahar mine, Narwapahar, East Singhbhum district, Jharkhand.

in 2008, is being operated with a rated capacity of 500 TPD. It has been planned in line with the mine layout of Narwapahar employing trackless mining technology with an entry of decline (Figure 5 *a*). AMD is presently exploring the depth continuity of the single uranium lode being mined at Bagjata to evaluate the possibility of deepening the mine for additional resources.

Narwapahar mine: It is a large deposit located 12 km west of Jaduguda. This mine was commissioned in 1995 with a rated capacity of 1000 TPD and was the first trackless mine of its kind in the country. From the decline, ramps are developed as an entry to the stopes at different elevations, which facilitates the movement of drill jumbo, trucks, passenger carriers, graders, scissor-lifts, etc. This system of mining resulted in the early commissioning of the mine with high productivity and low cost. Figure 5 *b* shows the stack of the mine. It has also provided flexibility to adopt different stoping methods that become suitable due to variations in width and inclination of the ore lenses. Cut-and-fill is the principal stoping method adopted here. The deslimed mill tailings of the Jaduguda mill and the waste generated from the mine are used as filling material. The split ventilation system adopted in the Narwapahar mine facilitates supply of clean air to all working places. The microprocessor-based bulk ore assaying system with automatic grade estimation and subsequent computation is a distinctive feature in this mine. More recently, AMD has established substantial additional uranium resources at the western continuity and at deeper levels of the Narwapahar deposit/mine area. UCIL is engaged in developmental activities for a new underground mine at Banadungri, adjacent to the Narwapahar mine lease area.

Turamdih mine: This uranium deposit is located about 24 km west of Jaduguda. It was commissioned in 2003 with a production capacity of 550 TPD. Entry into the mine has been established through a 8° decline which provides facilities for using trackless mining equipment like passenger carriers, drill jumbo, dump trucks, etc. (Figure 6 *a*). A vertical shaft was sunk up to a depth of 260 m and the mine production capacity was augmented to 750 TPD in 2007. The development faces are ventilated by an auxiliary ventilation system using auxiliary fans and flexible ducts.

Banduhurang mine: This deposit is the western extension of Turamdih mineralization, where part of the ore body outcrops at the surface. It is a low-grade, large-tonnage deposit. After the initial evaluation, techniques of computerized ore body modelling and mine planning were applied. The first opencast uranium mine in the country was made operational at Banduhurang in 2007 with a production capacity of 3500 TPD (Figure 6 *b*). The pit will attain the ultimate depth of 160 m with an ore to overburden ratio of 1 : 2.7. It is a conventional opencast mine using an excavator–dumper combination. Careful selection of earth-moving equipment has been done to maintain ore benches of 6 m height and over burden/waste benches of 6/12 m height with due emphasis on the run of mines (ROM) quality as well as stripping requirements.

Mohuldih mine: This mine is situated adjacent to the Banduhurang mine. The Mohuldih underground mine was commissioned in 2012 with a production capacity of 500 TPD. The only decline has been developed as the entry. AMD has got some encouraging results for additional deposits in and around the Mohuldih deposit.

Tummalapalle mine: Andhra Pradesh has the major share with 55% of the total uranium resources in India. Uranium mineralization of over 160 km has already been established. A large mine of 3000 TPD capacity and a processing plant at Tummalapalle in the southwestern parts of the Cuddapah Basin have been successfully commissioned. Presently,

Figure 6. ***a***, Trackless vehicle in operation in Turamdih mine, Turamdih, East Singhbhum district, Jharkhand. ***b***, Aerial view of Banduhurang opencast mine, Banduhurang, East Singhbhum district, Jharkhand.

Figure 7. Decline entry of Tummalapalle uranium mine, Tummalapalle, Kadapa district, Andhra Pradesh.

mining over 7.6 km has been taken up and is already in production through innovative mining technology with three declines and a conveyor hoisting system. The Tummalapalle deposit is hosted by carbonate rocks and has two lodes, i.e. a hang wall lode and a footwall lode. The former is overlain by red shale and has high seepage of water making for poor strata. However, support issues related to mining of the hang wall lode have been overcome with intensive scientific studies and mining of the hang wall lode is being done.

Three declines have been driven in the apparent dip direction (9°) in the ore body (Figure 7). On either side of the decline, advance strike drives (ASDs) are driven in the strike direction at different levels connected by ramps within the ore body. The method of mining adopted in this mine is the room and pillar mining method, with a combination of cut and fill. ROM is being transported to the processing plant at Tummalapalle through a conveyor belt. The combination of flyash and mill tailings will be used as backfill material to fill the voids in the underground mine. Development of another mine at Kanampalle is in progress.

UCIL processing plants

Jaduguda processing plant: The first operating plant in the country at Jaduguda is in operation since 1968, and is based on acid leaching technology (Figure 8 *a*). The process know-how has been indigenously developed at BARC and upgraded time-to-time keeping pace with the global developments. The plant has also been expanded twice; nearly doubling the original processing capacity, i.e. 2500 TPD to treat the ore of Jaduguda, Bhatin, Bagjata, and Narwapahar mines. In the Jaduguda plant, ores of different sizes undergoes crushing followed by two stages of wet grinding. The ground ore in the form of slurry is thickened and leached in leaching pachucas under controlled pH and temperature conditions. The leached liquor is then filtered and undergoes ion exchange in which uranyl ions get absorbed in the resin. The final product of the Jaduguda plant is uranium peroxide, which is sent to NFC, Hyderabad, for further processing and conversion to nuclear-grade fuel.

Turamdih processing plant: The ore processing plant at Turamdih was setup in 2007 with a processing capacity of 3000 TPD (Figure 8 *b*) to treat the ores of Turamdih and Banduhurang mines. Now, ore of Mohuldih mine is also being fed in the mill. This plant also follows the acid-leaching process and flow sheet similar to that of Jaduguda plant. With several automated process control mechanisms and on-line monitoring systems, the practices adopted at the Turamdih plant are comparable with the best practised in similar industries anywhere in the world.

Tummalapalle processing plant: The alkaline processing technology adopted for the plant at Tummalapalle has been developed by a team from BARC, AMD and UCIL through pilot plant studies. The processing plant has been in continuous operation since 2017 with the desired capacity of 3000 TPD (Figure 9).

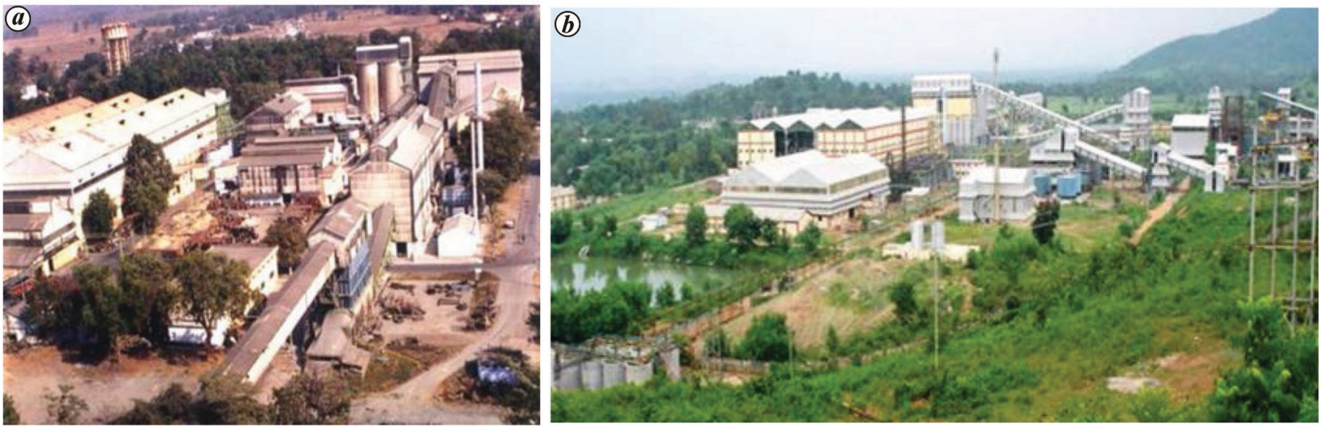

Figure 8. Synoptic view of (***a***) Jaduguda processing plant, Jaduguda and (***b***) Turamdih processing plant, Turamdih.

Figure 9. Synoptic view of Tummalapalle processing plant, Tummalapalle.

Rare earths and associated atomic minerals

Introduction to rare earths and associated atomic minerals

Rare earths (REs) are a group of 17 elements of the lanthanide series from 57 to 71 along with scandium (21) and yttrium (39). The principal source of REs in India is monazite, which is an orthophosphate mineral of REs, uranium, and thorium. Monazite is a prescribed substance and is found in association with a suite of six other atomic minerals, commonly known as heavy minerals (HMs) in the beach sand minerals (BSMs), i.e. ilmenite, rutile and leucoxene, which are titanium-bearing minerals; zircon, a zirconium-bearing mineral; sillimanite, a silicate of aluminium, and garnet, an iron–aluminium silicate. Monazite does not occur as an isolated mineral in any deposit; rather it is always found in combination with associated minerals. These atomic minerals occur along the coastal stretch of peninsular India and also in inland teri deposits.

The monazite content in the BSMs ore ranges from 0.06% to 0.15%. The content of REs in monazite is 58%, which works out to about 0.035–0.087% in the BSM[39]. In contrast, other sources under exploitation the world over contain more than 6% of REEs in the ore. More so, monazite is associated with other elements, making mining all the more attractive. Thus, extraction of REEs from the Indian source monazite is complex, long-drawn, expensive and has a multi-stage concentration process before even reaching the final stage of refining. In addition, the source of REEs being radioactive in nature poses challenges in terms of disposal of radioactive waste and environmental sustainability.

Light rare earths versus heavy rare earths

REs can be broadly classified into light rare earths (LREs) and heavy rare earths (HREs). LREs constitute lanthanum, cerium, praseodymium, neodymium, promethium and samarium, whereas the rest qualify as HREs. Promethium is not found in nature as it exists for a few seconds, gives off energy and gets converted into its isotope. Indian deposits predominantly contain LREs and HREs are not available in economically extractable quantities.

Indian deposits have a major portion of REEs, about more than two-thirds, as cerium and lanthanum, which are otherwise abundantly available in the earth's crust and are of least economic value among REEs. Among light rare earth elements (LREEs), it has been noted that only neodymium and praseodymium have gained importance since the beginning of the 21st century due to their usage in high-power permanent magnets.

Discovery of rare earths in India and the journey of IREL since inception

The voyage of the atomic minerals industry in India dates back to the first decade of the 20th century, when a German chemist, Herr Schomberg discovered a few coloured particles that were sticking to coconut fibre. He identified the particles as monazite, a source of uranium, thorium and

REEs[40]. Herr Schomberg found that the sand particles came as a contaminant to the coir imported from India. On further investigation, he traced its origin to Manavalakurichi in the erstwhile Travancore state at the southern tip of India. This accidental discovery of RE minerals made the beach an area of scientific interest. As such, monazite was in great demand in those days as it was the source of thorium, a chemical required for the manufacture of gas mantles. Encouraged by this supply chain, Herr Schomberg established the first step of the supply chain at Manavalakurichi (MK) in 1910 and subsequently, another source in Chavara along the coastal stretch in the north[40].

Both the facilities were non-operational during World War 1, when Herr Schomberg was arrested. After World War 1, the London Cosmopolitan Mineral Company (LCMC) took control of these resources. In 1920, Hopkins and Williams (H&W), yet another London-based Company took over the operations based on the locked-in value of titanium, another important mineral ilmenite found in association with monazite. The first export of ilmenite from Chavara began in 1922 (ref. 40). Indian ilmenite had been a coveted material and had maintained a virtual monopoly in the global market as a feed source for making white titanium pigment. However, in just one decade, the demand for monazite dwindled due to the advent of the electric bulb.

By the time the demand for ilmenite grow for the manufacture of pigments, many companies had come up to establish mineral-separation plants in the rich coastal stretch from Kanyakumari to Manavalakurichi, and Neendakara to Kayamkulam[40]. The Travancore Minerals Company Ltd (TMC) took over the assets of LCMC in 1930. Another company, F X Pereira & Sons (Trv) Pvt Ltd, the forerunner to the present Kerala Minerals and Metals Ltd also commenced its operations in Chavara in 1932 (ref. 40).

Once India attained independence, there was a great deal of strategic focus which became the base of many decisions. Bhabha envisioned the importance of self-sufficiency in nuclear energy in the new world order formed after World War 2. GoI realized the strategic importance of BSMs. The Atomic Energy Act was passed by GoI on 15 April 1948, which declared monazite as a prescribed substance and brought it under the purview of atomic energy and placed an immediate embargo on its export[40]. Parallelly, the possibility of setting up a facility for processing the mineral for the production of REs and extraction of thorium on a commercial scale was evaluated.

Known and declared resources of REEs

The approximately 6000 km long coastal stretch of India, spanning Odisha, Andhra Pradesh, Tamil Nadu, Kerala, Karnataka, Maharashtra and parts of Gujarat, is endowed with rich deposits of economically important heavy minerals (HMs) commonly known as BSMs[40–43]. India has one of the largest resources of Th and REEs, mainly due to the presence of monazite occurring in the BSM deposits[43]. Bhabha was aware that the extractable thorium resources in the form of monazite in Indian beach sand deposits are significantly more abundant compared to meagre, moderate- to low-grade uranium resources then available in the country. He realized that capital investments for producing the necessary thorium from available Indian resources are negligible[44,45]. Realizing the significance and importance of BSMs, especially monazite in the three-stage NPP, AMD established a separate Group for exploration of BSMs during the 1950s itself. Sustained exploration efforts by this Group led to the discovery of BSM deposits in Chhatrapur, Odisha, and Neendakara–Kayankulam, Kerala in 1971; Kuttumangalam and Vettumadia deposits, Tamil Nadu in 1988; Kalingapatnam coast deposit, Andhra Pradesh in 1992, and Bramhagiri deposit, Odisha in 2002, which are the major landmarks of beach sand investigations by AMD.

Considering the vision of Bhabha for rare metals and critical minerals, the geopolitical scenario for critical elements and the demand for REEs in the nuclear, space and hi-tech industries of India, AMD, in a significant shift in the exploration strategy, has ventured into extensive exploration for these elements in hard rocks of potential geological domains such as carbonatite and acidic–basic intrusive – effusive complexes in India. Besides, large resources of REEs (predominantly LREEs) locked up in monazite (8–10% ThO_2 and 42–65% REE oxide; 95–98% LREEs with minor HREEs) bearing beach sands in coastal regions and inland placers have already been established by AMD and are being exploited by IREL (India) Ltd.

Recent exploration inputs by AMD have established REEs and reactive/rare metals (RMs) resources in the carbonatite complexes of Ambadungar, Panwad–Kanwant (LREE-rich) in Gujarat, and per-alkaline granite–rhyolite of Siwana Ring Complex (HREE-rich) in Rajasthan. Further detailed exploration is in progress. Similarly, other alkaline complexes such as Sung Valley, Meghalaya; Samchampi, Assam; and Sevattur and Pakkanadu, Tamil Nadu are also being investigated. Some of the inland stream placers in Chhattisgarh and Jharkhand containing higher concentration of xenotime (a mineral containing yttrium) are also being collected in small-scale plants set up near the sources[46]. These small-scale collection units are providing a steady supply of RMs for the space and atomic energy programmes of India.

Rare earths mining and processing

The construction work of rare earths plant at Aluva, Kerala, commenced in April 1951, based on technology provided by the French firm, Societe de Produits Chimiques des Terres Rares, Paris (now Solvey)[47]. The plant was dedicated to the nation by the then Prime Minister Jawaharlal Nehru on 24 December 1952 in the presence of Bhabha[48]

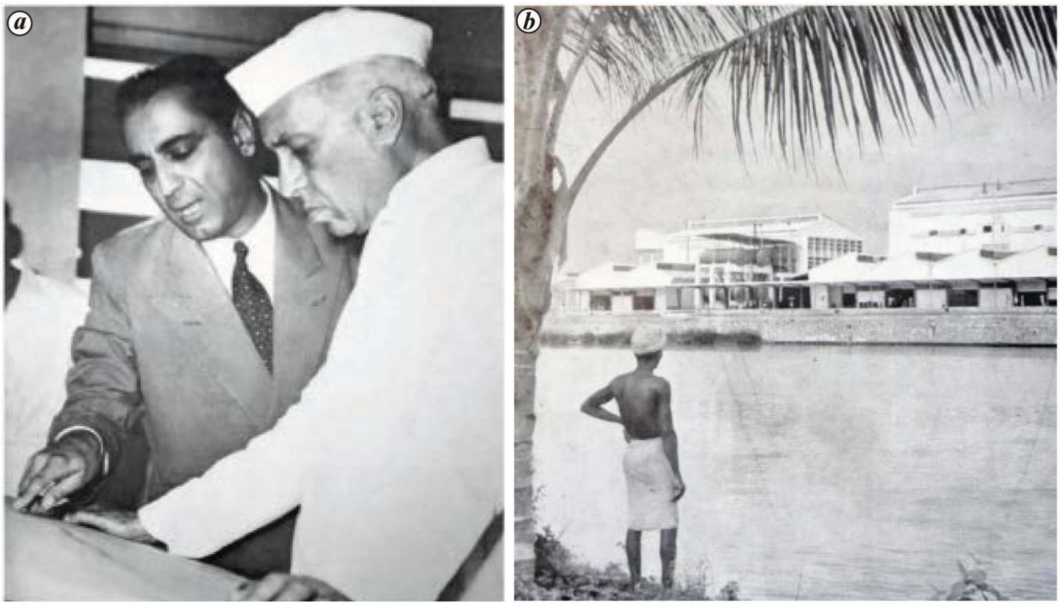

Figure 10. Initial stages of organized mining and processing of rare earth ores in India. ***a***, Bhabha explaining to the then Prime Minister of India, Jawaharlal Nehru, the flow sheet of Monazite Processing Plant in 1952. ***b***, View of RED, Aluva from the banks of River Periyar, Kerala[40].

Figure 11. Sand collection from the beaches of Manavalakuruchi, Tamil Nadu[40,52].

(Figure 10). While inaugurating the plant Bhabha said ‘Profit earning was only secondary as against the greater role IREL had to play’.

Soon after, IREL was entrusted by AEC to set up a thorium plant at Trombay. The plant commissioned in 1955, was one of the largest in the world, meeting the requirements of the vast gas mantle industry in India as well as abroad. Thorium was meant to be used initially by the gas mantle industry till it could be utilized for third stage nuclear power generation. However, the REs produced as a by-product of the above process were not able to find a market due to the non-availability of domestic industrial consumption and international market.

The Atomic Energy Act, 1962 was promulgated with stricter controls, under which minerals associated with monazite were brought into the category of atomic minerals, and private players were prohibited in the sector. In addition, a considered thought process established that the associated minerals occurring with the prescribed substance should also be placed under a similar category. As such, ilmenite, rutile and zircon along with monazite were occurring as a suite together and could not be differentiated prior to physical separation. Hence the status of the prescribed substance was extended to all these minerals, grouping them as atomic minerals. More so, zircon itself is a coveted material for NPP to be used in reactors for fuel bundles.

The first three plants being operated by private players closed in 1963 as their operations became unviable. GoI had been looking for supply security of monazite and under the new Act, acquisition of mineral-processing plants became imminent. Furthermore, by then it was a well-conceived fact that processing monazite on a stand-alone basis would require support from the Government in terms of funds[39]. Hence a business model was developed which included extraction of other atomic minerals along with monazite and their processing for strategic purposes, so that IREL could be without any Government support.

IREL was made a full-fledged Central Government undertaking in 1963, under the administrative control of DAE. Thereafter, it took over a number of private companies (Hopkins & Williams, Travancore Minerals Limited, etc.) and established two mineral divisions at Chavara, Kerala and Manavalakuruchi, Tamil Nadu. Thus began the mineral operations of the company (Figure 11).

During the same time, the Japanese started experimenting on REs sourced from IREL which they found to be an interesting material, and initiated in-house research to learn how best it could be utilized. IREL established itself with a firm footing in Europe and Japan. It also set up a

Figure 12. Initial days of export of ilmenite from IREL being shifted through barges for loading at anchorage area[40].

10 tonne per month plant at Alwaye, Kerala, for the manufacture of rare earths fluoride to meet the demand of the carbon arc industry[52]. It was indeed a matter of pride that this plant was designed by IREL's own technical staff based on a process developed in-house and was able to meet pan-India requirements.

Connection with the aviation industry

Based on ilmenite sourced from IREL (MK), a beneficiation plant was set up by Dhrangadhra Chemical Works (DCW) Ltd at Tuticorin, Tamil Nadu, to produce synthetic rutile. This was supplied to Japan for the production of titanium sponge and metal, which in turn was provided to Boeing and Airbus for use in the aviation industry (Figure 12)[40]. This was the origin of setting up a value-added industry in India. In addition, India joined the club of the international supply chain by exporting value-added products of ilmenite rather than the export of ilmenite itself. GoI visualized a potential in the supply chain of titanium and envisioned a flagship programme along the coastal stretch of eastern India. The flagship unit of IREL, Orissa Sands Complex (OSCOM), was set up in Odisha and was commissioned in 1986.

Downstream industries

In the Indian context, the partial opening up of the minerals industry and the strategic importance to medium and small enterprises (MSEs) witnessed a number of small industries that began operations in the value-addition initiative of the sector. Many MSEs started building their industry plan using IREL's products and consumption of mineral products enhanced in the industry in a complementary manner. IREL extends support to over 2200 industries operating in the downstream area.

In the late 1980s, in the case of REEs, there seemed to be some change in the usage pattern in the world, thus necessitating diversification of the product range. Steps were taken by the company in this direction and a project for separating various elements from mixed REs was also taken up. In the Rare Earth Division (RED), Aluva, Kerala, the MOHUR (Modernization of Helium and Uranium Recovery) and HERO (Heavy Rare Earths Oxide) plants for separation of heavy REs, which are value-added materials, were set up (Figure 13)[51].

The Thorium Plant at Trombay had become very old and beyond economical repair for which a New Thorium Plant was set up in the OSCOM unit based on the solvent extraction process developed by BARC.

Figure 13. HERO plant of IREL for value-addition in the rare earths supply chain[40,51].

By the last decade of the 20th century, IREL was known in the world market as a prominent producer and exporter of BSMs and REs with both international as well as domestic markets showing an upward trend and the company consistently earning valuable foreign exchange for India. In fact, IREL had enjoyed a unique position of having a wide spectrum of products – from mineral sands, REs to thorium production facilities. Moreover, it has always been an almost silent partner and ally to millions of customers with its products finding applications in many facets of daily life like paints, detergents, ceramics, refractories, welding electrodes, gas mantles, petroleum products, colour television, optical lenses, etc.

The beginning of the 21st century witnessed the closure of monazite-processing operations in RED, on the recommendations of the statutory body, Atomic Energy Regulatory Board (AERB). The operations of the plant were retrofitted and IREL took up thorium retrieval uranium recovery restorage (THRUST) operation to process the crude thorium hydroxide stored in silos, to recover the coveted strategic values and store thorium values in purer form as thorium oxalate.

In order to meet the obligations of GoI, IREL had taken up the challenge to set up a new monazite-processing plant in the OSCOM premises at Odisha and a refining plant to produce high-purity rare earths (HPRE) at RED. The process of setting up a new Monazite Processing Plant (MoPP)/ RE plant in Odisha with increased capacity had its own regulatory challenges. IREL had also set up the refining facility at RED, Aluva, for the production of HPRE, which was a first of its kind facility in India. Post-2015, IREL entered a new phase to overcome its shortcomings. It surpassed its turnover of Rs 1038 crores in 2019–20, by registering a mammoth threefold increase over the turnover achieved in 2015–16. Overcoming operational issues, the reduced output from the southern mines was compensated by increasing the output of OSCOM. Towards evacuation of RE chloride, which had no domestic market, an agreement was signed with M/s Toyotsu Rare Earths India Limited, an Indian subsidiary of Toyota Tusho Corporation, Japan, post-cabinet approval culminating from a Government to Government understanding. The agreement helped in understanding and improving the qualitative aspects of rare earth chloride, which are acceptable on an international level. This factor was especially important since several foreign companies were now operational in this field with improved and next-level technology. Further, IREL with the assistance of BARC, Mumbai managed to implement flow sheets developed by the latter for extraction of dysprosium (Dy) and gadolinium (Gd), elements, which are available in the BSM ore in traces. During FY 2020, profit crossed Rs 400 crores, which was in itself a new benchmark. Increased profits helped the company to enhance the operational environment and wellness of its employees, enhanced dividend to GoI and has built reserves for fuelling the envisaged planned growth. This resulted in the initiation of more than three projects at a time. In 2020–21, IREL issued 100% equity bonus shares amounting to Rs 86.37 crores.

Expansion plan for REs

IREL has undertaken concerted efforts with value addition pertaining to strategic use by forming an Special Purpose Vehicle (SPV) to set up the Sm–Co magnet plant at Visakhapatnam, Andhra Pradesh, based on technology developed by BARC and Defence Metallurgical Research Laboratory (DMRL). After obtaining statutory clearances, work was started and is currently progressing on schedule to be commissioned in 2022.

Another initiative in terms of the REs value chain was an understanding entered with BARC towards the development of various technologies based on REs. The work has commenced on an REs theme park focused on housing scaled-up plants for REs metal/recycling based on BARC technology and developing skills, including quality consciousness to create trained manpower for developing future entrepreneurs for the industry. Both these initiatives are done with the financial assistance of DAE. In addition, an initiative towards the setting up of a high pure titania and zirconia plant at the pilot level based on in-house technology development and financial assistance of DAE has also been taken up. The environment clearance was obtained and accordingly, work has been initiated.

IREL is contemplating taking forward the vision 2032 of DAE by a multifold increase in operations at each stage towards self-reliance of India, especially in areas of e-mobility and energy security from non-fossil fuel sources, which envisages multifold capacity. In order to improve its footprint, harnessing of the BSM deposits at Hrushikulya–Bajrakot–Brahmapur, Odisha, has been initiated by forming a Joint Venture Company with Industrial Development Corporation of Odisha Limited (IDCOL).

Departmental requirement for specific REs

The departmental requirement of REs includes samarium, gadolinium, and dysprosium. While samarium is available in the BSM ore to the tune of 14 ppm, gadolinium and dysprosium are available to the tune of 7 and 1 ppm respectively, making their extraction highly complex. Samarium is used captively by IREL for the production of samarium cobalt magnets based on the technology developed by BARC and DMRL. Gadolinium is supplied to NPCIL for use as burnable poison in nuclear reactors, while dysprosium is supplied to BARC for use as control-rod material. The technologies for these are developed by BARC and with its help implemented in IREL plants. In addition to meeting the requirements of various units of DAE, IREL also supplies a coveted mineral, zircon to NFC for the production of zircaloy tubes to house the nuclear fuel, garter spring, pressure tubes and calandria tubes.

Other application of REs

REEs being a performance-enhancing material and not a core or structural material find applications in multiple industrial segments and sectors ultimately contributing to a nation's economy, safety and security. These sectors include defence, space, energy, etc. and therefore REs are considered a strategic material. The rate of consumption of REEs in such industries and products is minuscule, which is evident from the global consumption patterns in terms of a few hundred thousand and that too rendering elements like cerium and lanthanum (about 65% of total rare earth oxide (TREO) global production) as surplus. Due to the unique nature of these materials, low global consumption, complex and large value chain, there is a higher dependence on the core sector for development.

REs have a crucial and critical role in realizing green technologies for sustainability and mitigation of climate change. REEs are extensively used in auto and fluid catalysts, metallurgy, medical systems, high technology, clean energy, catalytic converters, thin-film technologies, space applications, defence-related systems, wind turbines, hybrid electric vehicles, Ni–MH battery packs, portable electronics and high-performance alloys.

Export of REs

There has been a limited market for REs in India since inception, which continues till date due to the lack of downstream end-use industry. Hence, IREL had to look outside to evacuate the REs produced at RED. Initially, IREL started with exports of mixed rare earths chloride to Japan and later to USA, Europe and Brazil[40]. Subsequently, rare earths carbonate and rare earths fluoride were added to the portfolio. These mixed REs compounds were exported for applications as catalysts for polishing, etc. Separated REs such as cerium hydrate and lanthanum chloride were exported in limited quantities to Japan and USA respectively, around the 1990s. IREL continued to export mixed REs till the initial years of the 21st century before the monazite cracking operation was halted in 2004. Post restarting of REs production at OSCOM, IREL has restarted export of mixed REs in the form of chloride by way of deemed export to M/s Toyotsu Rare Earths India Pvt Ltd, a wholly-owned subsidiary of M/s Toyota Tsusho Corporation, Japan, located in Special Economic Zone (SEZ) in Vishakhapatnam[52]. A limited quantity of Nd–Pr oxide is also being exported to markets in Japan and Vietnam with a focus on fine-tuning the product quality for the manufacturing of magnets and keeping pace with evolving specifications for the end-use market.

IREL's plan for facilitating domestic production

In India, a major source of REs is monazite, which is a prescribed substance containing U and Th meant for the atomic energy programme in the country. The prima facie mandate of IREL has been to extract such radioactive elements (U and Th) for appropriate use in DAE and provide REs in liberated (from radioactivity) and marketable form to the industry for commercial applications. REs are therefore kept under the open category free from license regime or any restriction. It has been expected as in any other commercial product that the private sector would play a significant role thereafter in the manufacturing of products. However, this did not manifest in reality, which may be due to certain inherent economic constraints. The private sector did not find the REs sector suitable in the downstream, due to low profits, consumption in selective global pockets, lack of a domestic market, a long gestation period, non-availability of industry scalable technology and lack of instant returns. We witnessed the origin of this sector as early as when India attained independence. The primary need, then however was to cater to the requirements of the atomic energy programme.

Production depends on deposits and the end industry consuming the products. IREL is one of the pioneers in the processing of REs and these capabilities are available in terms of capacity, technology and skill. LREEs produced within the country are in surplus. The import is in minuscule quantities comprising certain other elements along with REs for specialized applications mostly in the form of proprietary compounds. HREEs are imported for applications on a laboratory scale. The REs produced by IREL, liberated from radioactivity, are available for consumption by the domestic industries. According to the vision plan, the Government has targeted increasing REO producing capacity by three times by the year 2032.

Role of the IREL Technical Development Council

Aiming to derive the benefits of the development of new technologies on an industrial scale, the IREL Technical Development Council was formed in 2006 with corpus funds aided by DAE and support from BARC, other R&D wings of DAE, and educational institutions engaged in applied research. The sole objective is to achieve value-addition to strategic and non-strategic materials with R&D. Projects are awarded to research institutions of eminence such as CSIR laboratories, IITs, etc. to develop alternative uses of REs or scalable technologies for the manufacture of RE metals and alloys, improve recoveries, etc.

Advancements and way forward in the exploration of atomic minerals

The direction provided by Bhabha for progressive technological, instrumental and conceptual advancements in the exploration of atomic minerals in India facilitated the discovery of several new uranium and other atomic mineral(s) occurrences/deposits over the last seven decades[46]. Presently, multidisciplinary techniques comprising high-resolution remote sensing, airborne and ground-based geophysical/ geochemical surveys are adopted for exploration of deep-seated, concealed uranium and other atomic mineral(s) deposits. The data accrued by heliborne gamma-ray spectrometric, magnetic and time domain electromagnetic (TDEM)/ audio frequency magneto telluric (AFMAG)/Z-axis Tipper Electromagnetic system (Z-TEM) methods are integrated with ground geological/geochemical data to narrow down the exploration targets. In tune with the keen interest of Bhabha in the development of cheaper, indigenous instrumentation for survey and exploration of atomic minerals, AMD has indigenously fabricated cost-effective, portable pads for the calibration of airborne gamma-ray spectrometers, which can be easily transported to various helibases for supporting their heliborne geophysical surveys. Besides, indigenous design and fabrication of several instruments for borehole logging (viz. count rate meters, detectors, standards, borehole trajectory logging system), surveys (viz. radiation survey meters, multi-channel gamma-ray spectrometers, etc.) and laboratory instruments (core analyser, core scanner, bulk uranium ore analyzer, etc.) have facilitated the exploration activities of AMD.

Subsequently, follow-up subsurface exploration is carried out by deploying modern hydrostatic rigs for achieving greater drilling output, which leads to a quick assessment of the target area. AMD's drilling productivity has increased manifold during recent years and has also become a benchmark for other exploration agencies in the country. The exploration programme for atomic minerals is supported by significant advancements in analytical capabilities during recent years. BARC is providing the required support for specialized analytical needs and indigenous design/development of state-of-the-art instruments like the prompt fission neutron (PFN) logging system (enables direct *in situ* measurement of uranium oxide in boreholes) for enhancing AMD's exploration capabilities.

An exploration strategy for future augmentation of uranium resources has been planned systematically. Exploration inputs are to be intensified in the first-order target areas for enhanced resource augmentation, whereas R&D and phase-wise exploration inputs in the identified greenfield areas will be focused on developing these areas for further exploration. Around two million line kilometres of heliborne geophysical surveys and five million metres of exploratory drilling have been envisaged to establish nearly 300,000 tonnes uranium within a period of 10–15 years (2020–2035), which is approximately the same quantum of uranium resources established in India in the last seven decades[53].

AMD in collaboration with GSI has systematically planned the layout of the exploration strategy for augmentation of REE resources and vision through a joint plan[54].

Self-sufficiency in other atomic minerals

Beryllium ore and its processing

Identification of several beryl (silicate mineral containing beryllium)-bearing pegmatites, especially in Bihar and Rajasthan mica belts became the telltale sign of a success story during the early 1950s. Subsequently, India exported over 15,000 tonnes of beryl to USA and Japan during the 1950s. A typical composition of Indian beryl ore is about 11–12% BeO, 19% Al_2O_3, 64% SiO_2, 1–2% alkali metal oxides and minor amounts of other oxides[55,56]. The process flow sheet developed by BARC for extraction and processing of beryllium consists of several steps involving ore-processing, hydrometallurgy, pyrometallurgy and powder metallurgy operations[55–57]. In the hydrometallurgy processes, beryllium value is selectively leached out and subsequently converted to beryllium hydroxide. Beryllium oxide powder is produced by calcining beryllium hydroxide which is further processed employing powder metallurgy techniques to get BeO ceramic components. For beryllium metal production, beryllium hydroxide is converted into anhydrous beryllium fluoride which is subsequently reduced by magnesium to get beryllium metal. Beryllium metal is obtained in the form of pebbles which are purified through vacuum melting. Typically, the powder metallurgy route is employed for making beryllium components.

To meet the demands of beryllium in different sectors, a pilot-scale facility was set up at BARC as a joint collaborative venture among the Department of Electronics, DAE and Department of Space in 1982. The integrated flow sheet for the extraction of beryllium from beryl ore and powder metallurgy processing of beryllium was developed at a special laboratory set up at BARC. In the pilot-scale facility, vacuum hot-pressed beryllium blocks and sintered beryllia ceramics are produced. The sintered beryllium metal blocks are precision machined to various components according to the requirement of the users.

Nb and Ta ore and its processing

The demand for Nb and Ta (as also Li and Cs) which enhanced during the early 1970s, for the indigenous nuclear programme, necessitated the identification of new sources for these elements. The exploration to augment the resources of rare metals was initiated in 1950. The pegmatite belts of Bihar, Andhra Pradesh, and Rajasthan were the obvious choice for the exploration of rare metals (Nb, Ta, Li and Be). Lepidolite, ambligonite, spodumene (Li minerals), beryl (Be minerals), columbite–tantalite, pyrochlore–microlite, ixiolite (Nb–Ta minerals) and monazite, xenotime (Y, REE minerals) were the important rare metal and REE minerals in the pegmatite belts and carbonatite complexes of India, which attracted RMSU/RMD's early exploration[58–60]. Based on the recommendations by N. B. Prasad and H. N. Sethna, the press note related to the proposal for stockpiling columbite–tantalite for indigenous use was approved by Bhabha in 1953, and this led to the stockpiling of substantial quantities of Nb, Ta, Li and Be minerals.

Continuing with the rare metals requirement of the country, AMD subsequently identified the tin-bearing pegmatites in erstwhile Madhya Pradesh (now in Chhattisgarh) and pegmatites within and surrounding the Nagamangala Schist Belt, Karnataka, as the most promising for the exploration of rare metals. The *in situ* and eluvial soils derived from the mechanical weathering of these pegmatites, typically contain rare metals minerals, namely columbite–tantalite (niobium–tantalum), beryl (beryllium), and spodumene and lepidolite (lithium). The soils containing these minerals are excavated, treated and collected in pilot plants set up in Marlagalla, Karnataka, and Bodenar, Chhattisgarh[61,62].

Research on the preparation of niobium began in the Materials Group of BARC in the mid-1960s. Although India does not have deposits of niobium minerals which could be called ores a good stockpile of columbite–tantalite had been accumulated as a byproduct of mica mining. A method to dissolve this ore in HF media, isolation of niobium and tantalum in organic media, and subsequent separation of niobium and tantalum by solvent extraction using Tributyl phosphate (TBP) was developed. This technology was transferred to the Special Metals Plant (SMP) at NFC in the early 1970s for producing tantalum, which was immediately required for capacitors; niobium was then considered a byproduct[63]. Research on the preparation of niobium continued in BARC and many reductants like calcium, sodium, carbon and aluminium for niobium compounds (oxides, chlorides and fluorides) were studied. Open aluminothermic reduction of Nb_2O_5 followed by purification by electron beam (EB) melting was finalized as the technology to be adopted at the industrial level. This technology was transferred to SMP in the early 1990s when the requirement of Zr–2.5Nb for pressure tubes in Indian pressurized heavy water reactors was firmed up[64].

Based on these technologies from the Materials Group in BARC, NFC now operates a plant for treating indigenous columbite–tantalite mix to separate niobium and tantalum and obtain Nb_2O_5, which is used for carrying out aluminothermic reduction of Nb_2O_5 (10 kg Nb per batch) and to purify this niobium by EB melting (up to 100 kg per batch).

Summary

With the emphasis provided by Homi Bhabha for atomic minerals right from including it in the mandate of AEC, India has made significant advances in the exploration, processing and conversion of ores to useful metals/alloys/products that are required by its ambitious NPP. AMD is the oldest unit of DAE that has the responsibility for the exploration of these minerals in the country. The technologies for mineral beneficiation, processing and conversion to useful products are developed by the Materials Group of BARC. UCIL takes the mining leases and operates the mines and mills to produce uranium compounds to be used as fuel for India's NPP. IREL (India) Ltd takes the mining leases and operates processing plants to produce mixed as well as individual RE compounds for DAE, as well as markets it in the country and abroad. Thorium, niobium, lithium and titanium are other key metals for which DAE has key requirements.

The progressive technological, instrumental and conceptual advancements brought about in the exploration strategies and techniques have facilitated several leads and the discovery of several new uranium occurrences/deposits in

India. AMD has systematically planned the future layout for its exploration strategy for resource augmentation of atomic minerals, including uranium. UCIL and IREL have also diversified their activities and have laid out plans for further expansion of their production capacity. BARC too has expanded its scope of R&D activities to support the exploration and processing of atomic minerals. Considering the availability of huge thorium resources and significant progress in the augmentation and production of uranium and other atomic mineral resources in India, the technically ambitious and innovative three-stage NPP envisioned by Bhabha is on the right track to ensure energy security of the country.

1. Wadia, S. R., Homi Jegangir Bhabha and the Tata Institute of Fundamental Research. *Curr. Sci*., 2009, **96**(5), 725–733.
2. Government of India Notification No. F-402/DSR/48 – under clause 13 of the Atomic Energy Act, 1948.
3. Bhabha, H. J. and Prasad, N. B., A study of the contributions of atomic energy to a power programme in India. In Proceedings of the Second United Nations International Conference on the Peaceful uses of Atomic Energy, International Atomic Energy Agency (IAEA), Geneva, 1958, vol. 1, pp. 89–101.
4. Chaudhuri, N. P., *Story of GSI, 1851–2001*. Geological Survey of India, Commemor. vol. 150th Anniversary Celebrations of GSI, 2001, pp. 159–160.
5. Derriks, J. J. and Vaes, J. F., The Shinkolobwe uranium deposit: current status of our geological and metallogenic knowledge. In Proceedings of the International Conference on the Peaceful Uses of Atomic Energy, United Nations, New York, USA, 1956, pp. 94–128.
6. Sims, P. K. and Sheridan, D. M., Geology of uranium deposits in the Front Range, Colorado. *US Geol. Surv. Bull*., 1964, **1159**, 116.
7. Fermor, L., The mineral resources of Bihar and Orissa. *Rec. Geol. Surv. India*, 1921, **53**, 239–319.
8. Khedkar, V. R., Report on the iso-rad survey and prospecting for uranium in the belt of uraniferous rocks in Singhbhum district, Bihar. Field Season Report for 1950–51. Un published RMSU (AEC) Report, 1951.
9. Vasudeva, S. G., Preliminary geological observations on the drill cores in Singhbhum thrust belt. In *Proceedings of the Symposium on Uranium Prospecting and Mining in India – 1964* (ed. Rama Rao, Y. N.), Jaduguda, Bihar (now Jharkhand), 1965, pp. 88–95.
10. Bhola, K. L., Radioactive deposits of India. In Symposium on Uranium Prospecting and Mining in India, Department of Atomic Energy, Jaduguda, 1965, pp. 1–41.
11. Bhola, K. L., Rama Rao, Y. N., Sastry, C. S. and Mehta, N. R., Uranium mineralisation in the Singhbhum Thrust Belt, Bihar India. *Econ. Geol.*, 1966, **61**, 162–173.
12. Saraswat, A. C., Uranium exploration in India: perspectives and strategy. *J. Expl. Res. Atomic Min., India*, 1988, **1**, 1–11.
13. Kaul, R., Yadava, R. S., Gupta, K. R., Singh, G. and Bahuguna, R., Structure and uranium mineralisation in the Proterozoic Aravalli Supergroup of Umra area, Udaipur district, Rajasthan, India. *J. Expl. Res. Atomic Min., India*, 1991, **4**, 13–25.
14. Udas, G. R. and Mahadevan, T. M., Controls and genesis of uranium mineralisation in some geological environments in India. In Proceedings of the Symposium on Formation of Uranium Ore Deposits, International Atomic Energy Agency (IAEA), Vienna, 1974, pp. 425–436.
15. Saraswat, A. C., Uranium resources for India's nuclear power programme – overview. In Proceedings of IAEA Technical Committee Meeting on Assessment of Uranium Resources and Supply, IAEA-TECDOC-597, Vienna, Austria, 29 August–1 September 1989, pp. 109–120.
16. Saraswat, A. C., Rishi, M. K., Gupta, R. K. and Bhaskar, D. V., Recognition of favourable uraniferous area in sediments of Meghalaya, India. In Proceedings of the Symposium on Recognition and Evaluation of Uraniferous Areas, International Atomic Energy Agency, Vienna, Austria, 1977, pp. 165–181.
17. Phadke, A. V., Mahadevan, T. M., Narayan Das, G. R. and Saraswat, A. C., Uranium mineralisation in some Phanerozoic sandstones in India. International Atomic Energy Agency, IAEA-TECDOC-328, Vienna, Austria, 1985, pp. 121–134.
18. Sengupta, B., Bahuguna, R., Kumar, S., Singh, R. and Kaul, R., Discovery of sandstone type uranium deposit at Domiasiat, West Khasi Hills District, Meghalaya, Northeast India. *Curr. Sci*., 1991, **61**, 46–47.
19. Sundaram, S. M., Sinha, P. A., Ravindra Babu, B. and Muthu, V. T., Uranium mineralisation in Vempalle dolomite and Pulivendla conglomerate/quartzite of Cuddapah Basin, Andhra Pradesh. *Indian Miner*., 1989, **43**(2), 98–103.
20. Vasudeva Rao, M., Nagabhushana, J. C. and Jeyagopal, A. V., Uranium mineralisation in the middle Proterozoic carbonate rocks of the Cuddapah Super Group, Southern Peninsular India. *J. Expl. Res. Atomic Min., India*, 1989, **2**, 29–38.
21. Suri, A. K., Ghosh, S. K. and Padmanabhan, N. P. H., Recent pilot-plant experience on alkaline leaching of low grade uranium ore in India. In International Symposium on Uranium Raw Material for Nuclear Fuel Cycle (URAM 2009), IAEA-CN-175/65, IAEA, Vienna, Austria, 22–26 June 2009, pp. 231–246.
22. Suri, A. K. *et al.*, Process development studies for the recovery of uranium and sodium sulphate from a low-grade dolostone hosted stratabound type uranium ore deposit. *Miner. Process. Extract. Metall.*, 2014, **123**(2), 104–115.
23. Rai, A. K., Zakaulla, S. and Anjan, C., Proterozoic stratabound carbonate rock (dolostone) hosted uranium deposits in Vempalle formation in Cuddapah basin, India. In: International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2009), IAEA-CN-175/27, IAEA, Vienna, Austria, 22–26 June 2009, p. 95.
24. Gupta, R., Technical developments in uranium mining and milling in India. In International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2009), IAEA-CN-175/63, IAEA, Vienna, Austria, 22–26 June 2009, p. 35.
25. Sinha, R. M., Shrivastava, Y. K., Sarma, G. Y. G. and Parthasarathy, T. N., Geological favourability for unconformity-related uranium deposits in the northern parts of the Cuddapah basin: evidence from Lambapur uranium occurrences, Andhra Pradesh, India. *J. Expl. Res. Atomic Min., India*, 1995, **8**, 111–126.
26. Nanda, L. K., Katti, V. J. and Maithani, P. B., Prospects and potentialities for uranium in North Delhi Fold Belt: a case study from Rohil, Rajasthan, India. In International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2009), IAEA-CN-175/26, IAEA, Vienna, Austria, 22–26 June 2009, p. 97.
27. Mishra, B., Kumar, K., Khandelwal, M. K. and Nanda, L. K., Uranium mineralization in the Khetri Sub-Basin, North Delhi Fold Belt, India. In International Symposium on Uranium Raw Material for the Nuclear Fuel Cycle: Exploration, Mining, Production, Supply and Demand, Economics and Environmental Issues (URAM-2018), Vienna, Austria, 25–29 June 2018, pp. 285–288.
28. Achar, K. K., Pandit, S. A., Natarajan, V., Kumar, Mary, K. and Dwivedy, K. K., Uranium mineralisation in the Neoproterozoic Bhima Basin, Karnataka, India. In Recent Developments in Uranium Resources. Production and Demand, IAEA, Vienna, Austria, 1997, pp. 1–22.
29. Chaki, A., Panneerselvam, A. and Chavan, S. J., Uranium exploration in the Upper Proterozoic Bhima Basin, Karnataka, India: a new

target area. In IAEA Proceeding Series, Uranium Production and Raw Materials for the Nuclear Fuel Cycle – Supply and Demand, Economics, the Environment and Energy Security, 2005, pp. 183–194.
30. Roy, D., Bhattacharya, D., Mohanty, Patnaik, S., Pradhan, A. K., Chakrabarty, K. and Zakaullah, S., Deformation pattern in Gogi–Kurlagere fault zone at Gogi–Kanchankayi sector of Proterozoic Bhima Basin of northern Karnataka: implication in control of uranium mineralization. *J. Expl. Res. Atomic Min., India*, 2016, **26**, 157–176.
31. Uranium 2020: Resources, Production and Demand, Joint Biennial Report NEA and IAEA, NEA No. 7551, © OECD-2020, 2020, pp. 237–249.
32. Pandit, S. A., Natarajan, V. and Dhana Raju, R., Exploration for uranium in the Bhima Basin in parts of Karnataka, India. *J. Expl. Res. Atomic Min., India*, 2002, **14**, 29–58.
33. Sinha, D. K., Gupta, S., Nautiyal, K., Akhila, V. R., Shrivastava, V. K., Padhi, A. K. and Verma, M. B., Serpentinized peridotite-hosted uranium mineralisation (U–Cr–Ni–Mo–REE–Fe–Mg) in Kudada–Turamdih area: a new environment of metallogeny in Singhbum Shear Zone, India. *Curr. Sci*., 2019, **117**(5), 830–838.
34. Ray, S. K., Mineral potential of the albitite line of Rajasthan, *Geol. Surv. India, Spec. Publ*., 2004, **72**, 487–496.
35. Kumar, P., Panigrahi, B. and Joshi, G.B., Palaeochannel controlled cretaceous sandstone-type uranium deposit of Lostoin area, Mahadek Basin, Meghalaya. *J. Geol. Soc. India*, 2016, **87**, 424–428.
36. Gupta, R. and Sarangi, A. K., Overview of Indian uranium production scenario in coming decades. *Energy Procedia*, 2011, **7**, 146–152.
37. Gupta, R. and Sarangi, A. K., Emerging trend of uranium mining: the Indian scenario. In IAEA Symposium on Uranium Production and Raw Materials for the Nuclear Fuel Cycle – Supply and Demand, Economics, the Environment and Energy Security, IAEA-CN-128/6, IAEA, Vienna, Austria, 20–24 June 2005.
38. Gupta, R. and Sarangi, A. K., Uranium mining potential of India. *Indian Min. J*., 2008, **47**(10), 55–59.
39. IREL, Rare Earth in India – The Incredible Voyage of Endurance, Indian Rare Earths Limited (India), Mumbai, 2020.
40. Mahadevan, C. and Sriramdas, A., Monazite in the beach sands of Visakhapatnam district. *Proc. Indian Acad. Sci.*, 1948, **27**(A), 275–278.
41. Vishwanathan, P., Studies on Travancore beach sands. *J. Ind. Min., Spec. Issue*, 1957, 109–122.
42. Rao, G. D., Shetty, B. K. and Rami Naidu, Ch., Heavy minerals content and textural characteristics of coastal sands in Krishna, Godavar, Gosthani, Champavathi and Pennar River deltas of Andhra Pradesh: a comparative study. *J. Expl. Res. Atomic Min., India*, 1989, **2**, 147–155.
43. Ali, M. A., Krishnan, S. and Banerjee, D. C., Beach and inland heavy mineral sand investigations and deposits in India – an overview. *J. Expl. Res. Atomic Min., India*, 2002, **13**, 1–21.
44. Bhabha, H. J., The role of atomic power in India and its immediate possibilities. In Proceedings of the International Conference on the Peaceful uses of Atomic Energy, Geneva, 1955, vol. 1, pp. 103–109.
45. Bhabha, H. J., The need for atomic energy in the under-developed countries. In Proceedings of the Second United Nations International Conference on the Peaceful uses of Atomic Energy, Geneva, 1958, vol. 1, pp. 395–407.
46. Sinha, D. K., Atomic Minerals Directorate for Exploration and Research. Institutional Report. *Proc. Indian Natl. Sci. Acad.*, 2020, **86**(1), 755–758.
47. IREL, Annual Report 1951–52, Indian Rare Earths Limited, Mumbai, 1952.
48. IREL, Annual Report 1952–53, Indian Rare Earths Limited, Mumbai, 1953.
49. IREL, Annual Report 1958–59, Indian Rare Earths Limited, Mumbai, 1959.
50. IREL, Annual Report 1988–89, Indian Rare Earths Limited, Mumbai, 1989.
51. IREL, Annual Report 1964–65, Indian Rare Earths Limited, Mumbai, 1965.
52. IREL, Annual Report 2015–16, Indian Rare Earths Limited, Mumbai, 2016.
53. Sinha, D. K., Emerging concepts in uranium exploration in India: an overview and way forward. In Vietnam Conference on Nuclear Science and Technology (VINANST-14). IAEA-CN-175/65, Vietnam Atomic Energy Institute and the Department of Science and Technology of Lam Dong Province, Da Lat city, Vietnam, 9–10 December 2021.
54. GSI-AMD, Strategic plan for enhancing REE exploration in India, 2020; https://amd.gov.in/WriteReadData/userfiles/file/GSI_AMD_Vision_Document_REE.pdf
55. Thorat, D. D., Tripathi, B. M. and Sathiyamoorthy, D., Extraction of beryllium from Indian beryl by ammonium hydrofluoride. *Hydrometallurgy*, 2011, **109**, 18–22.
56. Saha, S., Hydrometallurgy of beryllium in the Indian perspective. *Miner. Process. Extract. Metall. Rev.*, 1994, **13**, 43–52.
57. Sharma, B. P. and Sivasubramanian, N., Processing of beryllium for high technology applications. *Miner. Proc. Extract. Metall. Rev.*, 1994, **13**, 229–242.
58. Banerjee, D. C., Krishna, K. V. G., Murthy, G. V. G. K., Srivastava, S. K. and Sinha, R. P., Occurrence of spodumene in the rare metal bearing pegmatites of Marlagalla–Allapatna area, Mandya district, Karnataka. *J. Geol. Soc. India*, 1994, **44**, 127–139.
59. Ramesh Babu, P. V., Rare metal and rare earth pegmatites of Central India. *J. Expl. Res. Atomic Min. India*, 1999, **14**, 59–78.
60. Banerjee, D. C., Rare metal and rare earth pegmatites of India: an overview and some perspectives. *J. Expl. Res. Atomic Min., India*, 1999, **12**, 1–6.
61. Ramachar, T. M., Shivananda, S. R., Dwivedy, K. K. and Jayaram K. M. V., The rare metal and REE occurrences in South Bastar, Madhya Pradesh. *Geol. Surv. India, Spec Publ.*, 1979, **13**, 104–107.
62. Banerjee, D. C., Ranganathan, N., Maithani, P. B. and Jayaram, K. M. V., Rare metal bearing pegmatites in parts of southern Karnataka, India. *J. Geol. Soc. India*, 1987, **30**, 507–513.
63. Jena, P. K., Gupta, C. K. and Taneja, A. K., The present status and the projected programme on niobium–tantalum metallurgy in India. National Metallurgical Laboratory, Jamshedpur, 1969, vol. 3, pp. 173–180.
64. Bose, D. K., Pyrometallurgy of niobium, tantalum and vanadium – development work at Bhabha Atomic Research Centre. *Min. Process. Extract. Metall. Rev.*, 1992, **10**(1), 217–237.

doi: 10.18520/cs/v123/i3/293-309