INTRODUCTION

The news of the inauguration of India’s second uranium ore processing plant at Tummalapalle, Kadapa district, Andhra Pradesh during April 2012 by S. Bannermee, former Chairman of AEC, and the establishment of India’s second major belt of uranium deposits with resources of over one lakh tonnes of uranium oxide by AMD, greatly surpassing its earlier discoveries in the Singhbhum belt in Jharkhand during the 1950s and 1960s, took me down the memory lane to the formative days of AMD and the search for atomic minerals in India. The Rare Mineral Survey Unit of GSI, formed during World War II for strategic minerals such as beryl and others transformed into the Raw Materials Division of AEC and later the Atomic Minerals Division of the Department of Atomic Energy during the late 1940s and early 1950s respectively. I had joined the AEC in the early 1950s after my stint with the Mysore Geology Department, soon after graduation from Central College.

It is over six decades since India’s nuclear energy programme got initiated after independence. The first and foremost thoughts then by the founder Homi Bhabha was on developing indigenous resources for both men and material. The promulgation of the Atomic Energy Act in 1948 gave a clear mandate to the newly constituted Atomic Energy Commission that reported directly to then Prime Minister, late Jawaharlal Nehru. The Geological Advisor to the Government of India, Dr. Wadia was given the mandate to seek the atomic minerals.

The formative years in the exploration for atomic minerals in India were very daunting due to a variety of reasons, the foremost among these being the paucity as also the availability of literature on the geology and geochemistry of uranium besides lack of Geiger Muller counters and other physical assay equipments and standards and most importantly trained man power. Nevertheless the spirit of an independent India and the enthusiasm of the earliest recruits in seeking India’s own indigenous nuclear raw materials enabled the challenges to become new opportunities. Thus began the exploration story of seeking nuclear raw materials.

A three pronged exploration programme for atomic minerals was taken up. These included the pegmatite belts of Bihar, Andhra Pradesh and Rajasthan for Nb, Ta, Li and Be, the beach sands for monazite (for the thorium, rare earths). The first surveys for uranium began in 1949 in Singhbhum by a joint team of geologists from the Atomic Energy Commission, Geological Survey of India and Damodar Valley Corporation, a unique venture in mineral exploration history. The reason to choose the Singhbhum copper belt was the Belgian Congo example of uranium associated with Cu in the Katanga belt. Exploitable Indian uranium reserves has almost tripled in the last three decades with the discovery of sandstone deposit in India since the late 1980s.

EXPLORATION FOR ATOMIC MINERALS

Success story of raw materials in the 1950s hosted in the Pegmatite belts of India

The pegmatite belts of India, especially those from Andhra Pradesh (Nellore), Bihar (presently located in Jharkhand) and Rajasthan besides lesser known localities from Tamil Nadu and Karnataka were explored and prospected for radioactive minerals besides associated minerals for seeking elements such as Nb-Ta (columbite-tantalite), Be (beryl, bertrandite) and Li (lepidolite, spodumene).

Saga of uranium discoveries in the Singhbhum Thrust Belt: a unique milestone in uranium exploration in India

Following the world renowned Katanga copper belt and the associated uranium at Shinkolobwe in the then Belgian Congo, the Singhbhum copper belt was taken up for uranium exploration by the AEC soon after its formation in 1949.

It was a unique exploration team comprising some 18 geologists from AEC (7), GSI (7) and the Damodar Valley Corporation (4) under the leadership of Khedkar of GSI. The assignments included detailed geological mapping and radiometric checking of the entire Singhbhum thrust belt, some 120 km long and about 2 to 5 km in width. The belt was divided in to 10 sectors and mapped on a 8 inches to a mile scale. A base camp was established at Harindukri near Ghatsila which served as the head quarters of the Officer-in-Charge Mr. Khedkar who guided the survey. The physicists Dr. A.S. Bhatnagar from GSI serviced the GM counters used during the survey and assayed the samples.

Some 57 uranium anomalies were discovered by this team (Khedkar, 1951; Krishnamurthy, 2006). Exploratory drilling began...
in December 1951 by contracting the services to M/s. Associated Drilling & Supply Company, London at Jaduguda and at Kanyaluka with four Calyx drill boreholes (Vasudeva, 1965). In December 1953 IBM joined the drilling campaign at Jaduguda. Drilling by RMD (became AMD by 1958) commenced in 1955 with L&T rigs that were ordered through Tatas.

By 1963 a total of 2,35,883 feet (c.70.8 km) have been drilled in 33 different anomalous uranium-bearing localities (Vasudeva, 1965). Seventy five percent (75%) of this (c. 50 km) drilling took place in four major prospects namely Jaduguda, Bhatin, Narwapahar and Keruadungri (Bhola et al., 1965; 1966) Exploratory drilling with lesser intensity (10-30 bore holes) were done at Dhatutupa, Khadandungri, Surda, Nimdhi, Nandup and central Keruadongri.

Suggestions to initiate such a dynamic programme came from J.R.D. Tata during the discussions held about exploration in the Singhbhum belt between him and Homi Bhabha, Tata and the author who was looking after the explorations at Singhbhum during early 1960s when Bhabha visited Jaduguda (Rama Rao, 1998). The early exploratory mining activities at Jaduguda through adits and vertical shafts at Keruadongri in Singhbhum and Umra in Rajasthan also enabled a proper evaluation of the then known uranium resource bases in India by Rio Tinto, U.K in 1958 so that investment decisions for opening a commercial uranium mine and mill in India can be taken up. The choice was Jaduguda and ultimately it became the first uranium mine in India with a mill.

Anomalies vs. Deposits: the unique Singhbhum story

Not all anomalies discovered become viable deposits. Many of them may not graduate into a prospective deposit following the exploratory and some initial evaluation drilling. As per IAEA (1996) norms, a uranium deposit is defined as one that contains a minimum of 500 t of U₃O₈ with a grade of 0.03% U₂O₅ and above.

The Singhbhum case studies so far detailed bring out a unique feature with regard to the relation between anomalies discovered and deposits proved is only about 0.1% i.e. one anomaly in a thousand become a deposit (De Voto, 1978). However, in the case of Singhbhum it is very anomalous in the sense that out of the 57 anomalies discovered some 11 became deposits with over 1000t of U₃O₈ (see Fig.1) (c.f. Krishnamurthy, 2006).

The saga of Singhbhum uranium discoveries and the proving of deposits when exploration inputs were primitive and minimal besides surmounting scores of challenges in developing gamma-ray logging probes, standards and core assay (Tewari, 1998) represents a great team effort and reflects the spirit and quest for indigenous resources and the author fondly remembers the ordeals as also the joy after success.

A new open cast mine to the east of Turamdih mine at Bhanduhoran (2003) and the opening up of Mohuldih about 10 km to the west necessitated the opening of a second uranium mill at Turamdih in Singhbhum during 2008 has augmented the uranium inventory for the nuclear power programme.

Symposium on ‘Uranium Prospecting and Mining in India’- 1964.

The first Symposium under the aegis of the Jaduguda Mining Project on the above topic took place at Jaduguda and gave an opportunity to all those concerned with prospecting, evaluating, analyzing and mining uranium resources in India. The proceedings represented a landmark publication and was edited by the author and cyclostyled copies were produced for restricted distribution to all concerned since printing such a volume in the public domain had some constraints. The Jaduguda symposium volume contains the first major account on India’s uranium resources from multiple domains (Bhola, 1965). Case studies of uranium discoveries and methodologies adopted during radiometric surveys, especially in the physical assay of uraniferous samples, bore hole logging techniques, sampling methodologies, core assay of large number of samples, indigenously developed automated systems and others are also presented.

Success stories for high grade uranium ores from Umra-Udaisagar and in some pegmatites of Nellore

Closely following the discoveries in the Singhbhum belt, uranium mineralisation hosted in Precambrian black shales at Umra was located. The mineralization had both primary and secondary uranium minerals with higher grades recovered through a shaft and processed for its contained uranium at the AEET, the precursor to BARC. The ores were pocketful with very limited reserves.
Some of the book mica bearing pegmatites from the Nellore mica belt had hosted pockets of pure uraninite crystals. Some of these ores have been used for making calibration pads for airborne surveys.

Concept of Thorium province in the Precambrians of India

Exploration for uranium in the Precambrian terrains of India began with the search for quartz-pebble conglomerate (QPC) type deposits along the Eparchean unconformity following the models of the Witwatersrand in South Africa and the Blind River in Canada where primary, detritus uraninite grains are found along with other heavy minerals such as zircon, monazite, xenotime, ilmenite, rutile and others. Detrital gold is the primary product at Rand for which the QPC is mined and uranium is a by-product.

One of the earliest radiometric surveys in the Proterozoic Cuddapah basin under the author’s guidance (Sharma, 1956) led to discoveries of radioactivity along the Eparchean unconformity in the Gulpcheru conglomerates. When searches for such uranium at the base of the Cuddapah basin proved negative with only thorium anomalies. It was suspected that the uranium might have been leached in hexavalent state and migrated to the centre of the basin and trapped in a suitable host rock. When I went to Tummalapalli to inaugurate the pilot shaft and observed that the fugitive uranium was caught in the strata bound algal Vempalli dolomite, my memory went back to 1955 and happy to note that the prediction has come true.

The abundance of thorium resources contained in the monazite reserves, proved along the Kerala and Tamil Nadu coasts in SW India further influenced the thought that the Indian Precambrians represent a thorium province. The relatively poor reserves of uranium in the early 1960s compared to the thorium resources influenced strongly the nuclear scientists led by Bhaba to formulate nuclear energy options based on thorium besides uranium. Such ground realities of large indigenous thorium resources led to the three phase power programme using the uranium, first in pressurized heavy water reactors (PHWR, 1st phase), separating the plutonium from spent fuels and using the plutonium to breed U\(^{233}\) from thorium in the mixed oxide reactors (2nd phase), followed by the separation of U\(^{233}\) and using it in fast breeder reactors (3rd phase) wherein U\(^{233}\) will be burnt and also Th\(^{232}\) will be converted to U\(^{233}\).

Resources of monazite were further augmented through exploration of the inland Teri sands of Tamil Nadu and also new reserves established from the Andhra coast around Bhimunipatnam and Visakapatnam during the 1980s and 1990s. Such a rich endowment of thorium resources led to the view that India in all probability is a thorium province. Uranium grades, wherever new discoveries were made were consistently of low, which further seems to corroborate the concept of a thorium province.

However, developments in Precambrian geology in the Indian shield established that the Eparchean unconformity at the base of the Purana basins, especially Cuddapah, is in fact a Proterozoic unconformity. The real late Archaean and Early Proterozoic unconformity is at the base of the Dharwar Supergroup at Chickamagalur in the western Dharwar craton. In fact the Chickamagalur conglomerates were checked for QPC type mineralization and some feeble uraniferous zones due to rare detrital uraninites were found. Thus uranium exploration concepts have changed with time due to increased knowledge on the geology of a terrain.

Introduction of relatively new tools of exploration: airborne surveys of the late 1950s

India has been one of the pioneers in using the airborne surveys for uranium since such surveys can cover large areas and lead to fairly quick location of anomalies. Dr. Gosh’s initiatives to strengthen exploration activities coupled with robust laboratory support came in to the planning during the 1950s with close liaison with IISc, Bangalore and the Andhra University. The first airborne surveys were conducted from the Jakkur airport, Bangalore over parts of Karnataka. A primitive total (U, Th and K) counting system was used and ground navigations/locations were done by the geologist as a navigator using a toposheet as the aircraft was on the move at low altitudes (200 feet?), was quite challenging since reaction time to locate a feature in the ground with the speeding aircraft was very quick and never easy. These were followed up by airborne surveys over the Dongargarh system in Central India comprising large volumes of rhyolite and granite. Numerous anomalies were picked up and followed up by ground surveys and exploration including drilling. Small uranium shows were discovered but these could not be sustained into major deposits of uranium.

Paradigm shift in uranium exploration strategies in the 1970s and beyond

The early 1970s marked a tumultuous period in the history of AMD. AMD’s headquarters saw a shift from New Delhi to Hyderabad since the Department of Atomic Energy was locating several units which comprise the front end of the nuclear fuel cycle like AMD, UCIL, NFC, and the ECIL at this place. AMD was in the process of building its own complex at Begumpet to locate its headquarters, laboratory facilities besides its technical and administrative wings.

In the global uranium resource scenario, a new class of deposits with high grades (>1% U with pockets of high (10-20% U) grade, large tonnage, giant uranium deposits (> 50,000t of U\(_3\)O\(_8\)) termed as the unconformity-related uranium deposits between the Lower and Middle Proterozoic unconformity were discovered from Canada (Key Lake, Cigar lake and others) and Australia (Ranger, Jabiluka and others).

The early 1970s also saw India being outcast after its first peaceful nuclear explosion at Pokhran. India had to be more self-reliant both in raw materials as well as nuclear technology. In fact we had to take a loan of Nb-Ta minerals from Brazil. At this point of time, a large quantum of AMD’s men and material resources had also remained in the Singhbhum belt since 1950. Fresh mandate for Nb-Ta and REE resources from DAE ensued major recruitment of geologists, physicists, drilling engineers and deployment of new recruits in a number of thrust areas in central India, Himalaya and the NE India. Thus AMD expanded...
its exploration activities resulting in scores of new discoveries in a wide variety of geological domains and also different types of mineralisations such as the QPC, (Karnataka, Jharkhand, Odisha), shear controlled vein type (Bodal, Bhandariota in Madhya Pradesh), sandstone-type uranium deposits in the Cretaceous rocks of Meghalaya and the Miocene rocks in the Siwalik foot hills (Aстоtha, Kya and others) (Nagabhushana et.al., 1976 and others)

The creation of special exploration cells such as the rare metal and rare earth (RMRE) and beach and off-shore investigations (BSOI) led to significant production of columbite-tantalites and also proving substantial reserves of monazite and zircon besides ilmenite, garnet and others in the coastal tracts of Andhra Pradesh, Tamil Nadu and Kerala.

**Outsourcing Airborne Surveys, Drilling and Exploratory Mining Activities**

As a sequel to change in exploration policies and philosophies during 1980s and 1990s several activities as mentioned above were outsourced to varying degrees so as to expedite exploration and proving of resources. As I was given to understand that the quantum of exploratory drilling has tripled in the last decade especially in terrains where exploration activities are located in sedimentary terrain as in the case of Cuddapah basin. Exploratory mining at Gogi is being taken up jointly with UCIL. Airborne surveys including Heliborne systems with transient electro magnetic surveys for buried graphic and other conducting bodies in Lower Proterozoic terrains for unconformity-related deposits akin to those found in Australia and Canada are being attempted in collaboration with NGRI, IGCAR and others.

**Augmentation of training, HRD and publication facilities**

The 1970s and 1980s were significant years in AMD’s scientific contributions in the special field of nuclear raw materials and their search in India.

**Formulation of field programmes through discussions with young and experienced and accountability of work allotted**

It was during the mid 1970s that the unique experiment of visiting the different uranium and rare metal prospects in India by a team of young and experienced geologists began. The mandate was to evaluate the status of work, the mineral potential of the area and submit a report and also participate in the pre-field season discussions so as to choose the best possible area, optimum men and material especially the deployment of drilling rigs and other exploration inputs. Such interactions helped the new recruits in better understanding of the problems and also developed the concept of "e spirits de corpus" and skills to work as a team.

**Participation in national and international scientific collaboration programmes**

The 1970s saw a revolution in the induction of new analytical tools especially XRF, Optical Spectrograph and AAS in the laboratories. AMD had deployed these instruments and they were world class in providing analytical data to AMD and also to a number of universities and other research institute, a feature recognized by visiting UN teams.

**Holistic approach to uranium exploration and exploitation of uranium ores**

The post-1970s exploration strategies in AMD include a holistic approach involving the concepts of provenance-source rocks-uranium mobility and uranium fixation in suitable hosts and conducive structures. Granite rocks constitute the most potential source rocks for uranium. Thus terrains with late Archean granitoids and younger granites become the first order favourability as a good
provenance. Dating of granites becomes an important prerequisite. AMD’s geochronology laboratories have been effectively dating granites from diverse terrains of India by Rb-Sr and U-Pb methodologies and such data had been factored in to planning the exploration strategy in potential new terrains. Proterozoic and Phanerozoic sedimentary basins contiguous to such fertile granitoid-rich provinces become potential targets for exploration. Stratigraphic, structural and petrographic studies on the basinal sediments would provide further information on the evolution of the basin.

Airborne gamma-ray and magnetic survey inputs, with contoured maps of U, Th, K and their ratios enable narrowing down targets in the ground for radiometric checking of the anomalies and drawing samples for radiometric assay, equilibrium-disequilibrium studies and establishing the radioactive minerals from the samples.

Trenching and pitting along the strike and dip of the vein provides a measure of the continuity of the mineralization at shallow depths. Further continuity of the ore body, both along strike and dip, gets established through exploratory drilling initially, followed by evaluation drilling in a grid-wise pattern to estimate ore reserves based on the radiometric assay of the ore zone by gamma-ray logging for uranium.

Radioactive core assay, both physically and chemically, in the laboratories would establish the order of equilibrium between the parent and daughter, so as to correct the ore reserves accordingly. More detailed uranium mineralogical studies both by X-ray diffraction and electron microprobe studies would enable the leading minerals contributing to the radioactivity, their grain size, nature of alteration, paragenetic sequence and gangue minerals besides the presence of refractory minerals in the ore. Additional information on the presence of other valuable minerals or metal would also be known which may be a value adding co- or by-product. All these information would help in planning the bulk ore characters for chemical leaching in the pilot plant initially and later in the uranium mill. Thus, a well integrated and robust front end component in the nuclear fuel cycle is in place at AMD since the 1970s.

**Sedimentary-rock hosted uranium deposits**

In the first field season 1954-1955 of the Southern circle, a rapid radiometric survey by H.S. Sitarama Sharma in the Cretaceous sediments of Tiruchirapalli District, Tamil Nadu and adjoining Eocene Cuddalore sandstone reported radioactivity in the phosphatic nodules and ammonites in the Uttatur Stage of Ariyalur Group. Also the fossil wood logs at Turavekere embedded in Eocene sandstone was impregnated with placer sands of monazite, zircon etc. by wave action. Apparently this is the first discovery of radioactivity in the sedimentary formations of India. The late 1960s and early 1970s saw a major shift in uranium exploration in the sedimentary basins of India. Radioactive fossil bones from Siwaliks, carbonaceous matter in the Cretaceous sandstones of Meghalaya triggered such pursuits. Numerous smaller deposits were worked in the Siwalik sediments such as Aстоtha, Kya, Loharian and others during the late 1970s and early 1980s. The Cretaceous Sandstone type uranium deposit discovered and proved during the 1980s at Domiasiat in Meghalaya has been a major break though for this class of deposits in India. However, environmental aspects have been delaying its exploitation.

**PRESENT STATUS OF ATOMIC MINERAL RESOURCES**

Exploration for atomic minerals over the past 60 years by AMD has established substantial reserves of uranium hosted in the vein-type/stratiform deposits of Singhbhum belt and the dolomite-hosted, strata-bound deposits of Tummalapalle and others, together forming a reserve of over 1 lakh tones of $U_3O_8$. The grades in these deposits, however, are low (< 0.1%, and mostly in the range of 0.02-0.055 $U_3O_8$) (see Fig.2).

Unconformity-related deposits (sensu stricto) are yet to be discovered in India. All the unconformity-proximal, sensu lato...
types from the northern part of the Cuddapah basin (Lambapur, Peddagattu, Chitrial and others; see Fig. 2) are still low grade with moderate to low tonnage.

There are also numerous smaller tonnage deposits (c. 500t - 1500t) such as Bodal, Bhandaritola, Jajawal (in MP), Kasha, Kandi and others (Himalaya) in diverse terrains that have been proved. However, a strategy needs to be worked out to exploit them through innovative schemes.

The one and only, medium to high grade U-ore deposit discovery at Gogi, Karnataka is over 10 years old and we need to discover more of them to reduce the cost per tonne of \( U_3O_8 \). Thorium reserves, contained in the 3.5 million tonnes of monazite from the beach sands of Tamil Nadu, Kerala and Andhra Pradesh also very significant. Thus the energy security based on the projected utility of U and Th resources of India are substantial to sustain a nuclear power programme for over a century. The proven resources of Nb, Ta, REE, Y, Li and Be, however, are very modest. We need to seek them from non-traditional sources such as carbonatites, rare metal granites and other as yet unknown sources, and that is the challenge for the Indian nuclear geologists of the 21st century.

**EPILOGUE**

As I look back the decades of my tenure at AMD and also the decades gone by since my superannuation, I feel fully satisfied and happy the way AMD had progressed enormously under 15 committed and talented Directors. The Cuddapah basin emerged as a major uranium exploration success story with a uranium inventory, estimated to be over 1.5 lakh tonnes of \( U_3O_8 \). Thus uranium reserves of India improved substantially. I recall how as Dr. Gosh was predicting in the mid 1950s after inspecting the thorium anomalies at Gulcheru conglomerates at the base of the Cuddapah basin. He prophesized that we may have to go deeper in to the basin to get uranium since it would travel in the liquid form after oxidation and solution, which became true as we know now. Sharma’s Annual Report on the Cuddapah basin also had clues to pursue exploration in the basin more seriously (1956). AMD’s holistic approach to exploration had been highly rewarding. I hope and wish that in the coming decades we would discover more Gogi-type, medium-high grade deposits and economise on the cost/tonne of \( U_3O_8 \) and also strive to augment reserves of other atomic minerals.

Acknowledgement: Prof. M.R. Srinivasa Rao of the Geology Department Central College Bangalore, my Guru, reported in 1941 the presence of concentric Agala structure which was later confirmed by Dr. Birbal Shani. Perhaps this is the first discovery of life in the Proterozoic Era in India. I would like to dedicate this paper to Prof. L. Rama Rao and Prof. M R Srinivas Rao besides Dr. D N Wadia, F.R.S., Geological Adviser to Atomic Energy Commission from 1948; Dr. H J Baba F.R.S., first Chairman of Department of Atomic Energy from 1954; Dr. P.K. Ghosh, first Director of AMD from 1955 and Suri Subramayam, first Managing Director of UCIL, Jaduguda Mines from 1964. Lastly I would like to thank all my colleagues of AMD who were associated with me in various investigations in different part of India.

The author would also like to thank Dr. P. Krishnamurthy, my former colleague at AMD for taking notes on my thoughts and translating them in the text form. H.N. Varadaraju is thanked for obtaining some old reports of AMD and also in helping me with some old reports and references.

**References**


