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Uranium production and raw materials for the nuclear fuel cycle – Supply and demand, economics, the environment and energy security

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URANIUM PRODUCTION AND RAW MATERIALS FOR THE NUCLEAR FUEL CYCLE — SUPPLY AND DEMAND, ECONOMICS, THE ENVIRONMENT AND ENERGY SECURITY

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FOREWORD

Uranium, the heaviest element occurring in nature, is the basic raw material for nuclear reactor fuels. The International Atomic Energy Agency (IAEA) has been periodically organizing technical meetings and international symposia on all areas of uranium production cycle covering uranium supply-demand scenarios, exploration, mining, milling, refining of uranium oxide concentrates and safety and regulatory aspects. The last IAEA Symposium on Uranium Raw Materials was in October 2000, in Vienna and the topic was "Uranium Production Cycle and the Environment". The environmental, safety and social impacts of uranium production cycle were mainly discussed in this symposium. In 2000, the natural uranium market was extremely depressed, characterized by low prices and closure of several mines. In recent years there has been "rising expectation" from nuclear power to meet energy needs for a large number of both developed and developing countries. From 2002 onwards, there has been dramatic improvement in the demand for uranium and a near tripling of the uranium price because of expected expansion of nuclear programmes all over the world. Several new exploration and mining activities have been initiated and the major uranium producers have increased their annual production in 2004.

The International Symposium on Uranium Production and Raw Materials for the Nuclear Fuel Cycle — Supply and Demand, Economics, the Environment and Energy Security at IAEA, Vienna, 20–24 June 2005, was thus organised at the most opportune time when the uranium industry is poised for a take-off after nearly two decades of slump. The symposium was organized by the IAEA in cooperation with OECD/Nuclear Energy Agency (NEA), the Nuclear Energy Institute (NEI), the World Nuclear Association (WNA) and United Nations-Economic Commission for Europe (UN-ECE). Some 175 delegates from 33 countries, the above 4 international organizations and the IAEA, participated in the symposium. Ninety four technical papers were presented in oral and poster sessions and an exhibition on uranium exploration, mining and production was organized. The symposium covered all areas of natural uranium resources and production cycle including: (i) Uranium Supply and Demand; (ii) Uranium Geology and Deposit; (iii) Uranium Exploration; (iv) Uranium Mining and Milling; (v) Waste Management; and (vi) Environment and Regulation.

The IAEA acknowledges the contributions of the experts who participated in the consultancy meetings, evaluated and selected the abstracts and outlined the programme of the symposium, particularly W. Mays and M. Cuney; K. Wenrich in the initial phase of the symposium, J. Slezak, for his assistance in organizing the symposium and in preparation of the proceedings; M. Tauchid, President of the Symposium; and J. Grandey, Keynote speaker.

The IAEA officer responsible for this publication was C. Ganguly of the Division of Nuclear Fuel Cycle and Waste Technology.

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SUMMARY

BACKGROUND – INAUGURAL SESSION

This session provides the background and objectives of the symposium based on 'rising expectations' from nuclear power in recent years and acknowledgement of the fact that nuclear power is environment-friendly and can make a major contribution to global energy needs in the 21st century in a large number of both developed and developing countries. Uranium is the key element and raw material to fuel nuclear reactors for sustainable utilization of nuclear energy. The uranium industry is, therefore, faced with the challenge to provide an adequate supply of nuclear fuel that can be delivered to the market place at competitive prices by environmentally sound production practices. Uranium supply is generally divided into two categories — 'primary supply' or newly mined and processed uranium and 'secondary supply', which includes highly enriched uranium (HEU) of weapon grade (>93% U-235) from dismantling of nuclear warheads, inventory drawdown, reprocessed uranium (Rep. U), tails re-enrichment and mixed uranium-plutonium oxide (MOX). Since the 'secondary supply' will be progressively decreasing in the coming years, the annual 'primary supply' from the mines must be increased significantly in order to meet the uranium demand.

Over the next decade, the additional supply of uranium is expected to come from expansions at major existing mines, namely McArthur River underground mine in Canada, In-Situ Leach (ISL) mines in the USA, Kazakhstan and Uzbekistan and Olympic Dam in Australia and handful of new mines to come on, namely, Cigar Lake in Canada, Inkai and Katco projects in Kazakhstan, Honeymoon and Jabiluka in Australia, co-product of uranium/vanadium mines of Colorado, the USA and Langer Heinrich in Namibia. The challenge is to find more uranium deposits through innovative exploration techniques based on airborne and ground geophysics and develop the mines and mills quickly to supply uranium. In the area of uranium mining, efficiency could be significantly improved by utilizing radiometric scanning and sorting, equipping mine workers with direct reading dosimeters for combined gamma and alpha radiation with area radon progeny detectors, carrying out underground crushing and milling of ores and, if needed, leaching and promoting sandstone type deposits amenable to ISL mining in order to have a potential win-win for the mine and the environment. The uranium fuel industry must satisfy the needs of increasingly diverse group of stakeholders including the residence near current or proposed operations. 'Social license' is a key issue to the future of the uranium industry. Another important issue is a reduction in skilled workers and loss of knowledge on uranium exploration mining and milling operations.

The IAEA has been collecting and disseminating up-to-date information on uranium production cycle through periodic conferences, technical meetings and technical documents. The uranium Red Book, published biennially by the joint effort of OECD/NEA (Nuclear Energy Agency) and IAEA, gives an update of worldwide data from governmental sources, on uranium reserves, resources, production and demand. The information and the supply — demand analysis in the Red Book are used by nearly all countries with uranium production and or nuclear power programmes for their planning and policy making. In addition, the IAEA maintains and updates the databases: (i) Uranium Deposits (UDEPO) worldwide, which provides information on more than 800 uranium deposits, having ≥ 500 tonnes uranium with average grade $\geq 0.03\%$ U, from some 50 countries and (ii) 'Integrated Nuclear Fuel Cycle Information System' (INFCIS), which gives information on the civilian nuclear fuel cycle facilities worldwide. The IAEA technical documents on environmental protection in the uranium production cycle have been providing guidance on best practices in the planning, operation and closure of uranium mines and production facilities, from the perspectives of changing regulations and growing environmental concerns in uranium mining and milling.

TOPIC 1 – URANIUM SUPPLY AND DEMAND

The three sessions on this topic provided a 'global view' on uranium demand, supply and market trend, information on 'specific resources' and the 'realities and challenges of resource development'.

The 20th edition of the document "Uranium: Resources, Production and Demand", Red Book 2003, was published in 2004 and Red Book 2005 is being prepared for 2006. In the 21st edition, uranium resources will be divided into cost categories (< 40 US$/kgU, 40 to 80 US$/kgU and 80 to 130 US$/kgU) and based on the decreasing of confidence in estimates into:

- Identified Resources (formerly Known Conventional resources)
    - Reasonably assured resources (RAR) – having the highest confidence level
    - Inferred resources (IR) [formerly Estimated Additional Resources – I (EAR-I)]
- Undiscovered Resources
    - Prognosticated resources (PR) [formerly Estimated Additional Resources – II (EAR-II)]
    - Speculative resources (SR) having the lowest confidence level

The resources of uranium in RAR, IR and PR in cost category <130 US$/kgU are 3.17 million ton, 1.42 million ton, 2.25 million tons and 4.44 million tons respectively. In addition, there are some 3.10 million tons in speculative category with unassigned cost category. Apart from conventional resources several million tons of unconventional uranium resources could be available. In fact, uranium resources are adequate to supply the expanding nuclear power programme till 2050 and beyond even for 1274 MWe high growth scenario from the 367 MWe present level. For the high growth scenario the annual uranium demand will be 225 000 tons in 2050, from the present level of 67 000 tons and cumulative uranium demand will be in the range of 5.7 million tons.

Looking at the history, the uranium production reached a peak during the period from 1950 to 1970, when world annual production exceeded 70 000 tons. The uranium raw material was used for military applications in the form of high enriched uranium (HEU: >20% U-235) of weapon's grade (>93 % U-235) and also to fuel civilian reactors in the form of natural uranium and low enriched uranium (LEU: <20% U-235) containing <5% U-235. Thereafter, till the mid 1980s, uranium suppliers continued to produce large quantities of uranium in anticipation of fuelling major new nuclear power plants. Unfortunately, the expected new constructions did not materialize and the industry was left with an oversupply of uranium. The large uranium inventory and dismantling of nuclear warheads containing HEU resulted in large amount of uranium accumulation in stockpiles. From the mid-1980s onwards, the 'primary supply' from the mines started to fall progressively below 40 000 t U/year and was deeply below the demand level. The gap was filled by 'secondary supply', which until 2003, the total demand of some 67 000 tons uranium was met from both 'primary' and 'secondary' supplies. The oversupply of uranium from 'secondary source' led to progressive reduction in uranium price from the mid-1980s onwards dropping to a spot price low of US$ 19/kg U in late 2000. As a result uranium exploration and mining activities slowed down and many mines were closed. Since 2002, the 'rising expectations' from nuclear power led to dramatic increase in uranium price and revival of uranium exploration, mining and milling activities. The availability of 'secondary supply' is expected to decrease to the level of 10–15 % by 2020. Hence, 'primary' supply will have to increase to ensure a balance between supply and demand. Simultaneously, efforts are underway to minimise demand by efficient use of mined uranium by increasing the fuel burn –up, lowering tails assay and increasing the use of MOX fuels. The challenge for the uranium industry will be to ensure that the path between the uranium resources in the ground and uranium yellow cake in can is laid on time by augmenting uranium exploration activities and building additional mining and production capacities.

The uranium resources are assigned on the basis of their geological settings to the following categories: unconformity–related deposits, sandstone deposits, hematite-breccia complex deposits, quartz-pebble conglomerate deposits, vein deposits, intrusive deposits and other types. The world uranium production prior to 1989 was mostly from vein deposits, sandstone and quartz-pebble conglomerate. However, in recent times unconformity has taken the lead followed by sandstone type. In the area of uranium mining, In Situ Leach (ISL) mining has gained popularity in Kazakhstan, Uzbekistan, USA, Russia, China and Australia, though most of the uranium mining is still carried out by underground followed by open-pit mining.

Apart from the major uranium producing countries like Canada, Australia, Kazakhstan, Niger, Russia, USA, Namibia, Uzbekistan and South Africa, uranium exploration, mining and milling activities have been significantly augmented in India and China which have very ambitious nuclear power programme. In India, the uranium exploration is focused in proterozoic basin and new underground and open-pit mines are being opened in vein type, sandstone and unconformity–related deposits. In China the focus is mainly on ISL amenable sandstone type deposits.

Life Cycle Management, Corporate Social Responsibility and Environmental Assessment have become a part and parcel of pre- mining and milling activities in uranium production cycle and the objective today is not just regulatory license but social license, too.

TOPIC 2 – URANIUM GEOLOGY AND DEPOSITS

This topic provided practical background for the future of uranium market development e.g. uranium geology, deposits and associated topics. It included 15 presentations from 7 countries — 5 from Canada, 5 from France, 1 from Australia, China, the Czech Republic, India and Russia. The topic was subdivided into two main parts: presentations related to UNCONFORMITY-RELATED URANIUM DEPOSITS represented by 11 papers and presentations related to SANDSTONE DEPOSITS which were represented by 4 papers. The presentations aimed at the deposit types, which are of the highest interest at present, unfortunately the other types like vein deposits etc. were not covered even if they will also be of a potential interest, especially with increased uranium market price in the future.

The starting papers described geological features of recently discovered deposit and exploration area (Millenium deposit, Maybelle river mineralization). The presentation on lead isotopes showed that the study of lead isotopic system can identify fluid flow pathways that are blind to other exploration techniques. Based on comprehensive (lithological, mineralogical and geochemical) studies in the Pasha Ladoga (Russia), Satakunta and Muhos (Finland) basins, there is no evidence of major diagenetic fluid flow and they seem to be an area with low potential of large uranium mineralization. Similar example of geochemical modelling of unconformity related uranium mineralization was given from Baskati area in Madhya Pradesh, India. No significant mineralization has been discovered there so far.

An interesting presentation on markers of paleoconditions in unconformity related uranium mineralization based on aluminium phosphate sulphate minerals (APS) showed that the same factors control creation of APS and uranium mineralization. Also precise isotopic studies of uranium oxides show that their alteration leads to a very strong increase of the lightest REE, but preserves the intermediate and heavy REE signature. Also sources of uranium for unconformity deposits were discussed and according to the results the source could be uraniferous monazite. Similar features of alteration to Athabasca basin were observed in Pasha-Ladoga basin in Russia.

EXTECH IV, a multidisciplinary field and laboratory project in Canada should enhance and preserve geoscience data and improve exploration methods for unconformity-related uranium deposits. The results show positive implications for uranium exploration.

It was recognised, that sandstone deposits are of the highest interest and fastest development in the world at present. This is also caused by a fast development of ISL mining technology, especially in Kazakhstan.

Sandstone uranium deposits in China are one of the main exploration targets in China, the geological settings of these deposits are compared with the known sandstone deposits worldwide and some of the explored areas are distinguished favourable for different uranium deposits. Some experience with sandstone-hosted uranium deposits in the Czech Republic was presented, there has been a long term experience with sandstone deposits there.

Dornot uranium ore field in Mongolia is one of several very prospective areas in Mongolia. This area is similar to one with rhyolitic melts of the Strelcovsk caldera in Russia.

Very interesting presentation was done on Australia´s uranium endowment: Metallogeny, exploration and potential. Some of the uranium deposits appear to have formed during the three main periods of igneous activities. This also includes the giant Olympic Dam deposit. Considerable potential exists for the further discoveries of various types of uranium deposits.

All the presented papers gave the comprehensive understanding on the various aspects of uranium deposits and exploration areas including: geology, lithology, metallogeny, mineralogy, petrography, alteration, geochemistry, geochronology, stratigraphy, ore genesis and isotopic studies. The deposits and exploration areas described in the papers are located in Canada, Australia, China, India, Russia, Finland, Czech Republic and Mongolia.

The presented results show that important recognition criteria are discovered for different type of uranium mineralization, which can be used for new exploration areas.

The discovery of the new uranium deposits requires much tighter international cooperation between exploration, mining and research organizations to develop the unified exploration models for uranium deposits of various types.

TOPIC 3 – URANIUM EXPLORATION

This topic provided an overview on the uranium oriented exploration techniques and strategies. They are of high importance in the present developing uranium market to identify new uranium resources. Not only up to date and advanced technologies have to be used, the situation proves that the adequate methods in the adequate environment could be the most successful tools in exploration. Interpretation of measured data can also influence the results very much.

A new strategy of uranium exploration in Russia has been defined recently to cover domestic consumption and export requirements. There are several major areas where exploration will be targeted: areas surrounding the operating or developing mines, re-evaluation of former active mining areas, specified prospective areas and basic evaluation in poorly explored areas.

Because of the growing market, also Argentina is looking for new uranium resources. A lot of work has been done so far, however with respect to reactor requirements there, it is essential to expand a national uranium exploration programme.

Canadian Cameco´s experience in new uranium discoveries in Athabasca basin area has remained very much a conductor-focussed exercise. Results proved the efficiency of airborne and ground geophysical methods for investigation underground deep-seated tectonic structures, conductors and lithological inhomogenities favourable for uranium accumulations.

A renewed interest in uranium exploration in Australia was driven by an increased demand for uranium production. Exploration is concentrated on potential deposits beneath the substantial cover. Uranium exploration is positively impacted by the changing attitude within legislative and public arenas towards nuclear energy.

In India a lot of efforts is aimed at exploration for unconformity related deposits. The integrated exploration strategies involve different airborne methods, followed by ground methods and by drilling in the most promising areas. Some uranium mineralization was found. Regional hydrochemical survey is also applied.

Not only locally focused exploration should be carried out. A global radioelement baseline for gamma-ray spectrometric data has been under preparation by the group of specialists. Benefits of the global baseline are in identification of uranium provinces, detection of uranium deposits, uranium resource evaluation, estimation of natural radiation background, contamination caused by uranium mining and milling activities etc. Globally standardized radioelement data would lead to an appraisal

of uranium potential on global scale and application of radiometric techniques for direct assessment of radiation in the uranium production cycle.

No entirely new exploration technique has been presented, however a substantial progress in application and data processing of basic geophysical methods was demonstrated.

Under recent uranium market situation and increased uranium prices, several countries (Argentina, Australia, Canada, India, Russia) demonstrated a renewed interest in U exploration.

Fixed governmentally supported future exploration programmes (as in the Russian Federation) are likely to lead to wider exploration activities, minimize their economic risk for small private companies, and can lead, ultimately, to an increase in uranium resources.

Geophysical methods of exploration will be successful in indicating new uranium accumulation only under proper selection with respect to their physical detection capability and expected geological setting of target bodies. Radiometric survey should be applied to extensive unsurveyed regions, while electromagnetic, electrical resistivity, seismic and magnetic surveys are oriented to U prospective structural geology. These indirect exploration methods should be applied in areas where subsurface U structures and their forms have been already identified (examples Canada, Australia).

Data processing and reporting should be performed using recommended and verified procedures, including 2D, 3D and multiparametric (GIS) visualization, enhancing interpretation and analyses possibilities.

The general trend in exploration is focussed on both high-grade U mineralization and low-grade extensive resources.

Globally standardized radioelement data (a global radioelement baseline) lead to:

(a) an appraisal of uranium potential on a global scale,

(b) identification of K/U/Th ratios indicative anomalies (need precise reliable data),

(c) control and assessment of radiation environment of industrial U production cycle objects and facilities (with respect to environmental regulations)

It is expected that the fundamental directions and programmes on a global scale will be supported by the IAEA, which should play a prominent role in evaluation of these programmes, even if those development programmes have no immediate and direct economic impacts and results.

TOPIC 4 – URANIUM PRODUCTION

The number of only five presented papers in this topic still reflected the limited development of mining activities after the long-term depression in mine development. However all presented papers were very interesting and induced long discussions. The industry will be quickly waking up after a long-term depression in the market.

In Canada the Key Lake mill is, after the end of the Key Lake production, now used for milling the ore from McArthur River mine. One obvious question is “will any of the new upsurge in uranium production taking place worldwide discover any deposits with similar grades to Saskatchewan?”

In Brazil, uranium production at Caetité is a heap leaching operation and has current capacity of 300 t U/year. Reserves in Brazil are extensive but the grades are not high enough by world standards. However, with hopes rising, that the Angra-3 reactor will be completed, Brazilian aims for self-sufficiency in uranium that requires over 500 t U/year by then. Brazil is also believed to be interested in export possibilities for its uranium.

Many of foreign companies have or plan to start joint ventures in Kazakhstan. Currently two interesting projects are ready for the commercial development. It is the Inkai project (60% Cameco, 40% KazAtomProm) and the KATCO joint venture (51% COGEMA and 49% KazAtomProm). These projects have some common issues. Working with joint venture partners from a different culture is clearly challenging but both companies are very confident of success — Inkai is aiming at 2 000 t U and KATCO at 1 500–2 000 t U of annual production. There are also technical challenges with deep ISL mines and issues of obtaining adequate labour and material inputs in the booming Kazakh economy. It is clear that there are other likely production increases coming from Kazakhstan – the Russians have a joint venture there, other foreign countries such as Korea, Japan and China are investigating deposits and KazAtomProm itself has big expansion plans. It is thus likely that the largest increment in world uranium production over the next 5-10 years will come from Kazakhstan, rather than Canada or elsewhere (Africa perhaps).

The past, present and future of the mines in Niger emphasised the long history of the mines, going back to the period of France's involvement in nuclear weapons testing. There are still adequate reserves for many more years of production and they explore for improved resources again. The efforts of the company are made to improve the lives of the local people, where the mines have a major economic impact in a poor country. Another issue is the extent to which the Niger mines (and also the KATCO project) give AREVA diversity in its uranium supply, which may be an attractive aspect for customers now that supply has become more heavily concentrated in the hands of a few major companies.

Questions regarding adequacy of worldwide uranium production capacity have contributed to the recent market price increase. Papers presented during this session provided perspective as to how the uranium production industry is responding to these questions. Expansion of capacity at McArthur River and development of Cigar Lake will ensure that the Athabasca Basin in Canada will continue to be the world's leading uranium production area for the foreseeable time. Kazakhstan, which is continuing to expand production capacity through joint venture projects and development of new wholly owned mines, will maintain its position as one of the world's leading producing countries. Similarly, Niger is well positioned to retain its position among the world's leading producers, with adequate resources to ensure current production capacity for several years. A recent revival of exploration in Niger has the potential to further expand the country's production capacity. Brazil's Caetité heap leach operation is sufficient to satisfy the country's goal of uranium self-sufficiency. As it increases its nuclear generating capacity, Brazil plans to proportionately increase uranium production capacity, either through expansion of Caetité or development of new mines.

TOPIC 5 – WASTE MANAGEMENT

The nuclear industry and the mining and milling aspect of the industry is coming under more and more regulation. There is a greater emphasis on the environmental impact of the mining and milling operations. The major concern with the operations is the waste which is generated during the construction, operations and closure of a mine or mill. The waste streams include; toxic chemicals, as well as mine water, overburden, tailings piles, radon releases, as well as other liquids, solids, and gases which are released during the life cycle of the mine and /or mill. This topic focuses on these and how they are being addressed. It is up to our industry to be good stewards of the environment in the area of the mines and mills. It is only through attention to the control and proper disposal of the wastes that the industry will avoid additional regulatory requirements.

The ICRP´s proposed changes to the current radiation protection programme is an indication of general additional requirements, which are not supported by the rationale. It appears to be the more popular thing to do, rather than the technically defensible thing to do. Support is needed in responding to the ICRP proposal.

There are many places in the world dealing with safety aspects of present and past waste from mining and milling activities. Very nice examples were done from Brazil, Russia, Kazakhstan, Canada, the Czech Republic, Hungary and Romania covering mine waste rock, mill tailings and mine and mill

waste water. A presented long-term behaviour of uranium containing waste rock piles from silver mining in the middle ages in Jachymov (Joachimsthal) could help in studies on future behaviour of the present uranium mining waste rock dumps.

The nuclear industry, especially the uranium production cycle is coming under more regulation with an emphasis on the environmental impact of the mining and milling operations. The waste which is generated during the construction, operations and closure of a mine or mill has to be treated.

The changes in regulation requirements could heavily influence the economics of uranium production activities, the requirements should be strict, but realistic. Any unrealistic requirements will negatively influence the future development. To support sustainability, the consensus between the industry and (local) communities has to be found to allow sustainable development of both parties. Of course safety aspects of the radioactive waste management, especially at old operations, has to be taken into account and proper measures have to be applied. Both industry and (local) communities are responsible for their future development. The results from the past and information gained have to be compared with each other and distributed for better application of those results in the future. The historical operations have to be explored to get comparative information on the future behaviour of presently solved problems. Water as the main transport media for contaminants is the important area of the industry activities in the waste management.

TOPIC 6 – ENVIRONMENT AND REGULATIONS

In the other sessions, they expressed, how exploration and mining and milling of uranium will likely undergo significant expansion in coming years to meet expected growth in demand for fuel as secondary sources dwindle.

The previous great expansion in uranium mining took place during the 1970's, a time when concerns other than environmental were paramount. Now, however, environmental regulations, reflecting the current concerns of the public, will play a much greater role in any future expansion.

The ability of the mining industry to meet future demand will be greatly enhanced, indeed literally permitted, by demonstration of the ability to meet and exceed more stringent requirements and that it can responsibly manage the remediation of legacy sites produced in the previous era.

Thus, it is important to report on the work that addresses the uranium industry's behaviour with respect to the environment and illustrate the innovative means being used to minimize the environmental impacts of past and present uranium mining.

The papers presented in this session, both orally and as posters, demonstrate that the uranium industry is conducting important work that improves its ability to meet these challenges and reflect the importance placed on meeting societal obligations vis-à-vis the public and the environment.

Knowledge of a mining site and its environs and the associated risks are key elements in the management of current and former mining sites. This knowledge benefits all stakeholders. Therefore, it is no surprise that the quest for and management of accurate information are the focus of work in the remediation sector and was a common theme of the papers presented in this session.

The papers presented in this session provided insights into innovative technologies and processes in use around the world to provide the information needed to permit informed decisions by regulators (and the various publics) on what are the real risks from uranium mines and how they can be effectively managed.

The open and transparent presentation of the facts and risks demonstrated by these papers will help dispel myth and misunderstanding and should work to increase the confidence of the public and regulators, as agents of the public, that mining can be accomplished with minimal environmental impact or long-term consequences. This increased confidence that the interests of the community are being protected and promoted not merely exploited can only help facilitate the forecasted expansion of uranium mining.

OPENING REMARKS

Y.A. Sokolov

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Ladies and Gentlemen,

I take great pleasure in welcoming you to this Symposium, which will address a broad range of topics related to the front end of the nuclear fuel cycle. And it is important to begin by putting the topic of this meeting into the broader context of global developments in nuclear power today.

After a number years of describing the nuclear power globally as 'on a plateau', the Director General has been speaking this year of 'rising expectations'. Among other places, he used this characterization in his opening speech at a March conference in Paris on the future of nuclear power, that was organized by the IAEA, hosted by the French government and attracted high level representation from 69 governments, including 25 at the ministerial level. The concluding statement of the conference noted, among other things, that: "a vast majority of participants affirmed that nuclear power can make a major contribution to meeting energy needs and sustaining the world's development in the 21st century, for a large number of both developed and developing countries". A "vast majority" out of 69, is particularly striking given that only 30 countries currently have nuclear power plants.

Why are expectations rising? There are many reasons. Nuclear power has a good and lengthening track record. New environmental constraints on greenhouse gas emissions favour low-emission energy sources like nuclear power. Concerns about energy supply security also increase interest in nuclear power. Key energy growth countries like China and India have announced substantial expansion plans. The experts here at the Agency and at the IEA have been steadily revising their forecasts upwards. Oil and particularly natural gas prices have been rising. And both the media and the polls in key countries have turned gradually more favourable on nuclear power.

None of this guarantees a nuclear renaissance, but it certainly raises the likelihood of a high nuclear growth future and the importance of knowing how to fuel that future if that is the route the world takes. That is your topic this week.

The International Atomic Energy Agency takes a great deal of pride in the role that it played in the early 1990s in bringing together the international uranium community to begin to develop a comprehensive database on uranium supply and to openly exchange ideas on uranium geology, production technology and economics and environmental issues associated with uranium production. One of the most valuable biannual publications jointly issued by OECD/NEA and the IAEA is URANIUM: Resources, Production and demand popularly know as Red Book. The Joint OECD/NEA – IAEA Uranium Group also supports the activities in the front-end of the nuclear fuel cycle. The Agency is committed to serve as a forum for discussion on all aspects of uranium supply and demand and hence this symposium.

The ultimate goal of the uranium industry can be stated rather simply – providing an adequate supply of uranium that can be delivered to the market place at competitive prices by environmentally sound production practices. Achieving that goal is, however, anything but simple. The industry faces a number of challenges that can best be met through exchanging ideas at meetings such as this Symposium. New exploration techniques may help to broaden the geographic diversity of the uranium resource base. Diversity of supply in turn can help offset the risk arising out of unforeseen delay in executing uranium mining projects in some areas. Sharing information on new production technology can potentially lead to improved project economics and an increase in the low-cost resource base. Case histories ranging from pre-production licensing to final site rehabilitation are invaluable guides to the time frames and costs associated with environmental planning and compliance.

An adequate supply of uranium is essential to the future of nuclear power. This Symposium is intended to bring together the broadly diverse expertise needed to assure that future. We are pleased to note that more than 200 participants from 30 countries and 4 international organizations are attending this symposium.

Once again, I welcome you to Vienna and the IAEA. I am optimistic about the success of the Symposium. Thank you.

ACTIVITIES IN FRONT-END OF URANIUM FUEL CYCLE IN IAEA

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Introduction

Natural uranium, the basic raw material for nuclear fuels, contains ~99.3% fertile ^{238}U and ~0.7% fissile ^{235}U isotopes. The present fleet of some 440 operating nuclear power reactors and some 270 non-power research reactors mostly use fissile ^{235}U as fuel. To a very limited extent, the fissile plutonium isotopes formed by the neutron capture of fertile ^{238}U in a reactor is recycled in the form of mixed uranium plutonium oxide (MOX) or other fuels. Uranium is, therefore, the key raw material for sustainable utilization of nuclear energy for peaceful purpose.

Table I. Status of Reasonably Assured Resources (RAR) of uranium at a cost of < US $130/kg U and nuclear power programme in some representative IAEA Member States [1]

Country	Uranium Resources (Tons 'U') RAR (< US $130/kg U)	Percentage of world resource (%)	No. of Nuclear Power Reactors (% Electricity)
Countries with major uranium resources but without nuclear power reactors			
Australia *(second largest producer of uranium)*	735 000	23	Nil
Kazakhstan	530 460	17	Nil
Namibia	170 532	5	Nil
Niger	102 227	3	Nil
Uzbekistan	79 620	2.5	Nil
Mongolia	46 200	1.5	Nil
Countries having uranium resources and nuclear power reactors			
USA	345 000	11	104 (20)
Canada *(largest producer of uranium)*	333 834	10.5	20 (~12)
South Africa	315 330	10	2 (5.9)
Russian Fed.	143 020	4.5	30 (16)
Brazil	86 190	3	2 (4)
China	35 060	1.1	9 (1.4)
India*	40 980	1.3	15 (~3)
Countries having many nuclear power reactors but not significant uranium resources			
France	100% from overseas sources		59 (78)
Germany	100% from overseas sources		18 (30)
Japan	100% from overseas sources		53 (39)
Republic of Korea	100% from overseas sources		19 (39)

* cost range > US $130/kg U

Australia has the largest reserve of uranium followed by Kazakhstan. However, Canada has the richest grades of uranium ores and is presently the largest producer of uranium, followed by Australia, Kazakhstan, Niger and Namibia. The world uranium production in 2003 and 2004 has been 35 349 t U and 39 311 t U respectively, more than 50% of which are produced in Canada and Australia. It is interesting to note that uranium is mostly produced in Member States without nuclear power programme and is consumed in Member States having no uranium production as shown in Table 1.

During the last two years, the primary uranium production from the mines supplied approximately 55% of the world's demand of some 67 000 t U, with the remainder being met by secondary uranium

sources including civilian and military stockpiles, reprocessed uranium and MOX and re-enrichment of depleted and reprocessed uranium. However, secondary uranium sources are expected to reduce progressively, particularly after 2020, and reactor fuel demand will have to be increasingly met by primary uranium supplies by expansion of existing production capacity together with the development of additional production centres. Advanced and innovative fuel cycles, including closed fuel cycles and fast reactors with lower uranium demand may be introduced after 2025.

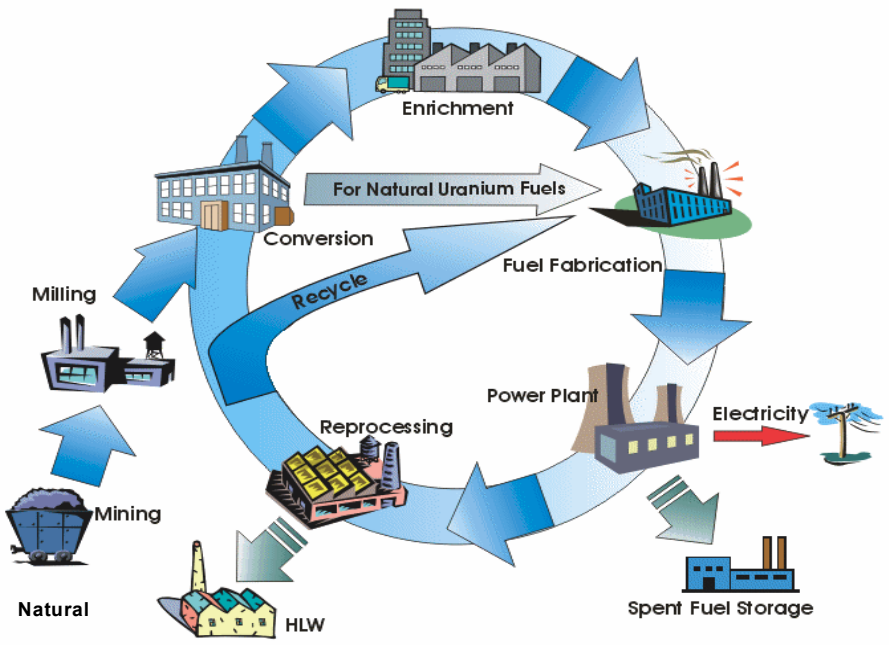


FIG. 1. Uranium fuel cycle.

Light Water-cooled and moderated reactors (LWR), consisting of Pressurized Water Reactor (PWR and WWER) and Boiling Water Reactors (BWR) are the most popular reactors all over the world, followed by the Pressurized Heavy Water-cooled and moderated Reactors (PHWR). The LWRs use Low Enriched Uranium (LEU: <20%^{235}U), with up to 5%^{235}U, as fuel in the form of high density uranium oxide pellets. The PHWRs are fuelled with high density natural uranium oxide pellets. The uranium fuel cycle, shown in Fig. 1, encompasses various processes and technologies related to fabrication of uranium oxide fuel from uranium ores, using this fuel in reactors, storage of spent fuel, reprocessing and recycling of spent fuel and management and treatment of radioactive wastes. The front-end of the uranium fuel cycle, include exploration and mining of uranium, leaching, purification and concentration in the form of yellowcake (ammonium diuranate, magnesium diuranate or uranium peroxide), conversion to uranium hexafluoride followed by enrichment in the range of 1-5%^{235}U for use in LWRs, preparation of sinterable grade uranium oxide powder of nuclear purity, pelletization and high temperature sintering to obtain uranium oxide fuel pellets. For natural uranium oxide fuel pellets, the steps involving conversion to uranium hexafluoride and enrichment are not required.

The Nuclear Fuel Cycle and Materials Section (NFC&MS) in the Division of Nuclear Fuel Cycle and Waste Technology (NEFW) under the Department of Nuclear Energy (NE) of IAEA implements Major Programme 1.B. of the Agency. NFC&MS fosters development of nuclear fuel cycle options that are safe, environment-friendly, economically viable and proliferation-resistant. It promotes information exchange on exploration, mining and processing of uranium and thorium, design, manufacturing, and performance of nuclear fuels, management of spent fuel, including storage & treatment of spent fuel & recycling of plutonium & uranium fuels, and development of advanced and innovative nuclear fuels and fuel cycles through Technical Co-operation, preparation of state-of-the-art technical documents, technical meetings, symposia and Coordinated Research Projects (CRP) and databases on nuclear fuels and fuel cycles. Figure 2 summarizes the activities of NFC&MS relevant to uranium exploration, mining, milling and concentration.

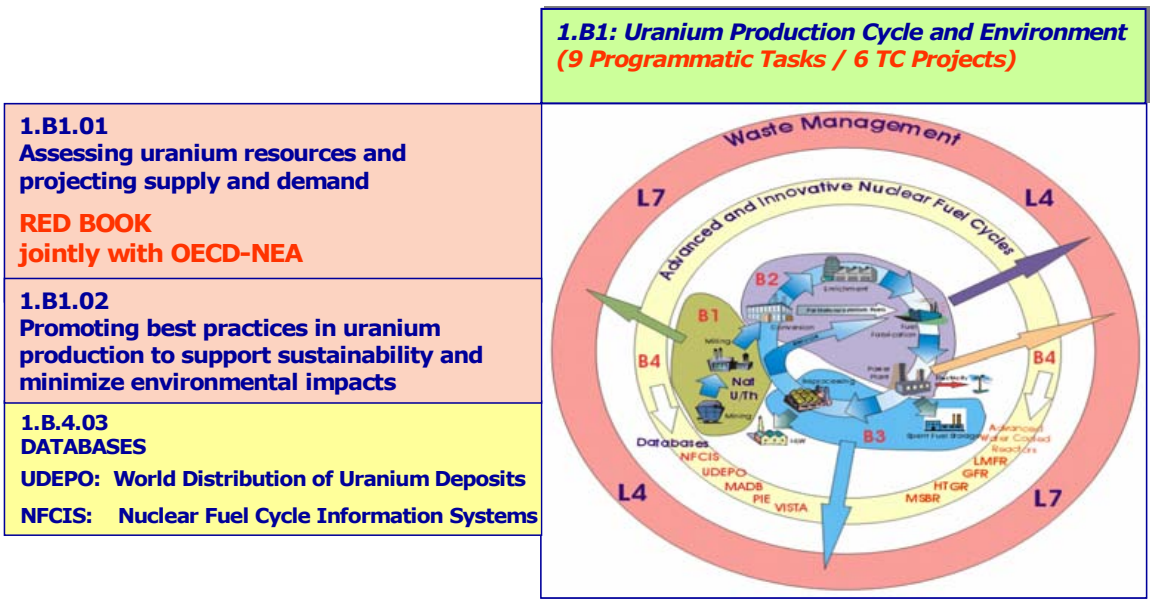


FIG. 2. IAEA activities under Major Programme 1.B – in Nuclear Fuel Cycle & Materials Section (NFC&MS) relevant to uranium, mining, milling and concentration.

The last International Symposium on Uranium was organized by the Agency, in cooperation with OECD/Nuclear Energy Agency (NEA), the Nuclear Energy Institute (NEI), the World Nuclear Association (WNA) and the Office of Supervising Scientists-Environment, Australia, in October 2000. The theme of the Symposium was "Uranium Production Cycle and the Environment"[2].

During the last five years, there has been significant changes in favour of nuclear power and a nuclear revival is expected. Several nuclear power reactors are either under construction or in the planning stage in China, India, Japan, Republic of Korea, Russia and CIS countries and Western Europe. In the U.S.A., several nuclear power plants have got their license renewed and quite a few are working with extended capacity. Nuclear power is emerging as one of the inevitable and viable options for generation of clean electricity. As a result, everywhere, stocks of natural uranium are being slowly but surely depleted. After nearly two decades of extremely depressed market for natural uranium, characterized by low price (< US $10/pound) and mine closures all over the world, the uranium industry appears to be at the dawn of new era. The uranium price has significantly increased during the last one and half years and is in the range of US $30/pound today. Thus, the present IAEA International Symposium on "Uranium Production & Raw Materials for the Nuclear Fuel Cycle - Supply and Demand, Economics, the Environment and Energy Security" is taking place at the most opportune time.

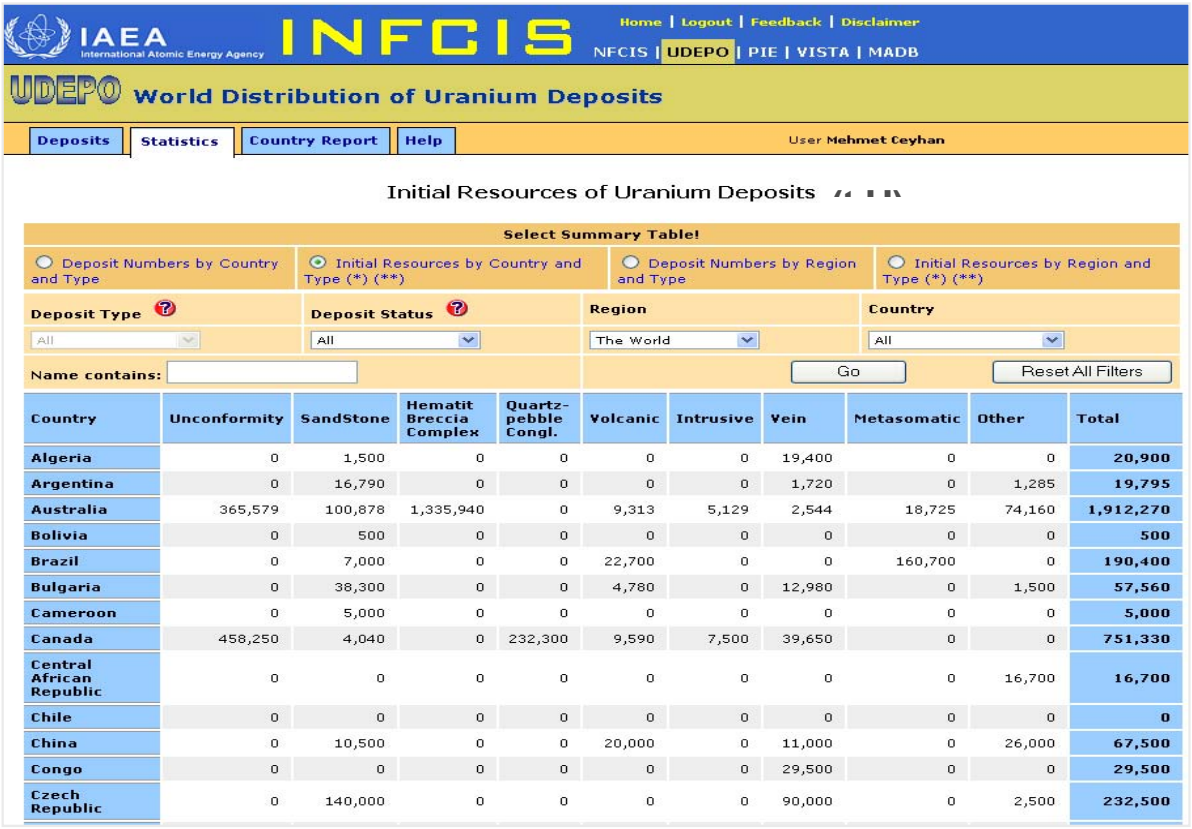
The present paper summarizes the portions of the Major Programme 1.B. of IAEA, related to the front-end of uranium fuel cycle, highlighting the activities on uranium supply and demand, exploration, production cycle and environment, the databases, and the Technical Documents (IAEA/TECDOC) that have been published or under preparation in these areas during the last five years.

IAEA/OECD-NEA Uranium Red Book

The IAEA collaborates with OECD-NEA in the collection, analysis and publication of worldwide data on uranium resources, production and demand popularly known as Uranium Red Book. The IAEA is the only global authoritative forum to provide independent and reliable analysis and information on the status of world uranium production and the projections of uranium requirements in Member States with nuclear power programme. The Red Book is published biannually and reports status of worldwide uranium industry based on governmental report and statistics. The information in the Red Book is extensively used by Member States with uranium production and/or nuclear power for the

planning and policy making. The data for the Red Book are submitted by Member States through the Red Book questionnaire. The publication of the Red Book is in the year following Red Book date. For example, the Red Book 2005 will be published in the Spring of 2006. The Red Book 2003 containing data from 43 countries has been published in 2004 [1]. The Red Book 2005 is under preparation and would be finalized in the IAEA/OECD-NEA Uranium Group meeting in November 2005. For the first time, the data is being submitted electronically with an idea of having Red Book online hereafter. So far, some 41 countries have responded to the IAEA questionnaire. The following changes have been made in the resource category of the Red Book 2005:

- The Estimated Additional Resource-I (EAR-I) would be hereafter referred as "Inferred Resources"
- The EAR-II has been replaced by Prognosticated Resources
- The Reasonably Assured Resources (RAR) plus Inferred Resources are now referred to as Identify Resources.



Country	Unconformity	SandStone	Hematit Breccia Complex	Quartz-pebble Congl.	Volcanic	Intrusive	Vein	Metasomatic	Other	Total
Algeria	0	1,500	0	0	0	0	19,400	0	0	20,900
Argentina	0	16,790	0	0	0	0	1,720	0	1,285	19,795
Australia	365,579	100,878	1,335,940	0	9,313	5,129	2,544	18,725	74,160	1,912,270
Bolivia	0	500	0	0	0	0	0	0	0	500
Brazil	0	7,000	0	0	22,700	0	0	160,700	0	190,400
Bulgaria	0	38,300	0	0	4,780	0	12,980	0	1,500	57,560
Cameroon	0	5,000	0	0	0	0	0	0	0	5,000
Canada	458,250	4,040	0	232,300	9,590	7,500	39,650	0	0	751,330
Central African Republic	0	0	0	0	0	0	0	0	16,700	16,700
Chile	0	0	0	0	0	0	0	0	0	0
China	0	10,500	0	0	20,000	0	11,000	0	26,000	67,500
Congo	0	0	0	0	0	0	29,500	0	0	29,500
Czech Republic	0	140,000	0	0	0	0	90,000	0	2,500	232,500

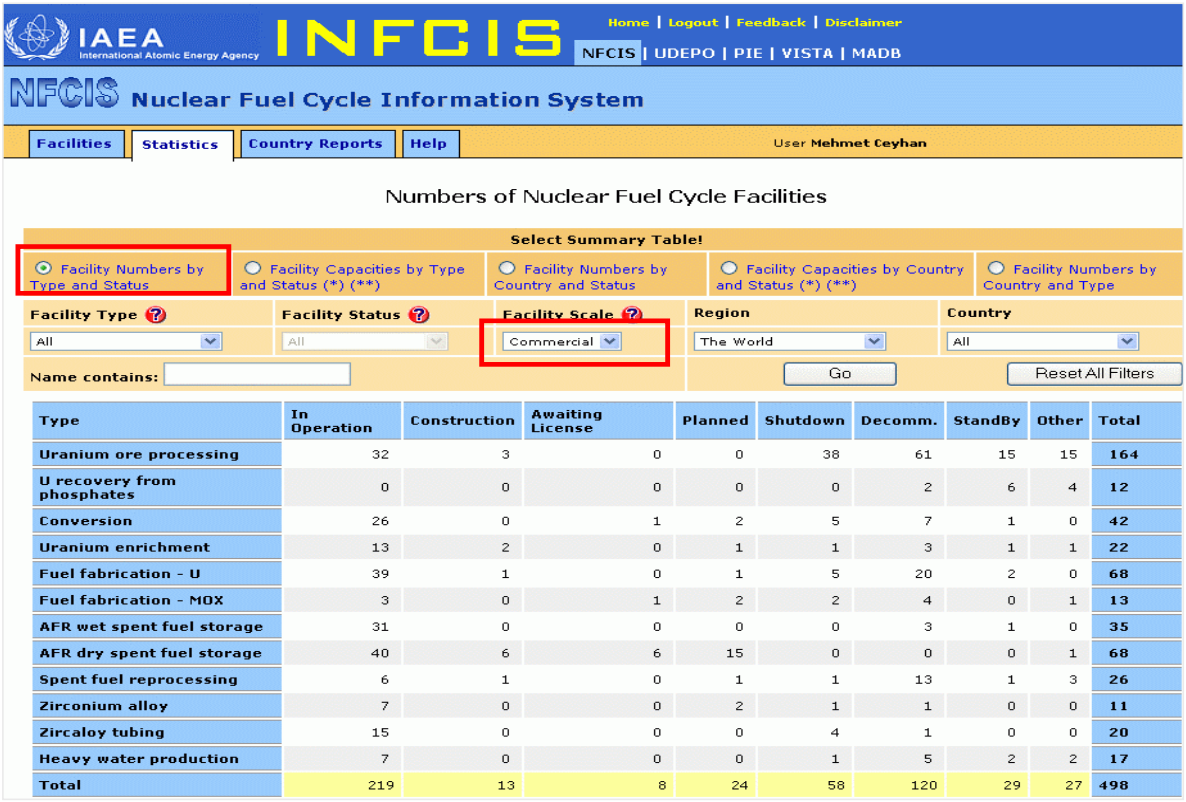
FIG. 3. Representative screen from new UDEPO web site.

IAEA Database on World Distribution of Uranium Deposits (UDEPO)

The UDEPO is a computerized, online technical and geological database on uranium deposits worldwide. It includes deposits with 500 tonnes or more uranium and with an average grade of 0.03%U_3O_8 and above. The uranium deposits are classified according to the Red Book terminology. Presently, UDEPO has the records of more than 800 deposits from some 50 countries. All types of deposits, namely, unconformity, sandstone, hematit breccia complex, quartz pebble conglomerate, volcanic, intrusive, vein, metasomatic, etc., are included. The database is being continuously updated and expanded and has been publicly made available since 2004. The web site would provide maps with location of deposits. Figure 3 shows a representative screen from the new UDEPO web site.

IAEA Database on Nuclear Fuel Cycle Information System (INFCIS)

INFCIS is an online database on civilian nuclear fuel cycle facilities worldwide. The web site is: http://www-nfcis.iaea.org. It covers commercial as well as pilot laboratory scale facilities. INFCIS is updated annually through questionnaires to nominated contact points in Member States. In addition, other authoritative information sources (e.g. publications in journals, symposium proceedings, etc) are also used when official data is not available. A typical screen from new INFCIS web site showing commercial nuclear fuel cycle facilities worldwide is described in Fig. 4.



Type	In Operation	Construction	Awaiting License	Planned	Shutdown	Decomm.	StandBy	Other	Total
Uranium ore processing	32	3	0	0	38	61	15	15	164
U recovery from phosphates	0	0	0	0	0	2	6	4	12
Conversion	26	0	1	2	5	7	1	0	42
Uranium enrichment	13	2	0	1	1	3	1	1	22
Fuel fabrication - U	39	1	0	1	5	20	2	0	68
Fuel fabrication - MOX	3	0	1	2	2	4	0	1	13
AFR wet spent fuel storage	31	0	0	0	0	3	1	0	35
AFR dry spent fuel storage	40	6	6	15	0	0	0	1	68
Spent fuel reprocessing	6	1	0	1	1	13	1	3	26
Zirconium alloy	7	0	0	2	1	1	0	0	11
Zircaloy tubing	15	0	0	0	4	1	0	0	20
Heavy water production	7	0	0	0	1	5	2	2	17
Total	219	13	8	24	58	120	29	27	498

FIG. 4. Representative screen from new INFCIS web site.
(showing commercial nuclear fuel cycle facilities worldwide – numbers and status)

Environmental Protection and Best Practices

Environmental issues in the front-end of the uranium production cycle including mining, milling, chemical purification and long-term management of mine tails, residual materials and radioactive wastes are of paramount importance to the uranium industry. The Agency provides guidance on best practices in the planning, operation and closure of uranium production facilities including mine reclamation, from the perspective of changing environmental regulations in mining facilities and growing environmental concerns in uranium mining. This is of great use to Member States which are developing uranium resources but do not have adequate regulatory and technological infrastructure. This will facilitate the Member States to take informed policy decisions and plan strategy associated with uranium production and to make use of preventive measures to reduce impacts from uranium mining and milling on the environment through guidance and transfer of information on current status and perspectives. In this connection, the Agency prepares state-of-the-art documents on the best practices in all types of uranium mining including open cast mining, deep underground mining, In-Situ Leaching (ISL) and purification operations involving solvent extraction and ion exchange processes for obtaining uranium concentrate (yellowcake) from uranium ores. Table II and III summarize the IAEA TECDOCs published during last five years and the ones that are under preparation respectively.

Table II. IAEA publications on uranium geology, exploration, mining, milling, environment protection in mines and mills since 2000 (already published: 13)

Year	Reference	Title of the TECDOC
2000	IAEA-TECDOC-1174	Methods of exploitation of different types of uranium deposits
2001	STI/PUB/1104	Analysis of Uranium Supply to 2050
	IAEA-TECDOC-1239	Manual of acid in situ leach uranium mining technology
	IAEA-TECDOC-1244	Impact of new environmental and safety regulations on uranium exploration, mining, milling and management of its waste (Proceedings of a TCM held in Vienna, 14-17 Sept.98)
	IAEA-TECDOC-1258	Assessment of uranium deposit types and resources - a worldwide perspective (Proceedings of a TCM organized by the IAEA and OECD/NEA, Vienna, June 1997)
2002	Working Material	In Situ Leach Uranium Mining, Proceedings of a Technical Committee Meeting held in Almaty, Kazakhstan, 9-12 Sept. 96
	C&S Papers Series 10/P	The Uranium Production Cycle and the Environment: Proceedings of the International Symposium held in Vienna, 2-6 October 2000
2003	IAEA-TECDOC-1296	Technologies for the treatment of effluents from uranium mines, mills and tailings, Proceedings of a Technical Committee Meeting held in Vienna, 1-4 November 1999
	IAEA-TECDOC-1363	Guidelines for radioelement mapping using gamma-ray spectrometry data
2004	IAEA-TECDOC-1396	Recent Developments in Uranium Resources, Production and Demand with Emphasis on In Situ Leach Mining, Proceedings of a Technical Meeting held in Beijing, China, September 2002
	IAEA-TECDOC-1419	Treatment of liquid effluent from uranium mines and mills (Report of a Coordinated Research Project)
2005	IAEA-TECDOC-1425	Recent developments of uranium resources, production, demand and the environment, Proceedings of a technical meeting in Vienna, June 1999
	IAEA-TECDOC-1428	Guidebook on environmental impact assessment for in situ leach (ISL) mining projects

Table III. IAEA publications on uranium geology, exploration, mining, milling, environment protection in mines and mills (under preparation/publication: 5)

Title of the TECDOC
• Recent Developments in uranium exploration, production and environmental issues (in press)
• Criteria for sustainable development of uranium mining & milling operations
• Radioelement mapping and status of the global radioelement baseline and maps
• Best practices in environmental management of uranium production facilities
• Natural background of uranium deposits including surface and Ground waters

Looking Forward

In recent years, there has been an expansion of nuclear power programme all over the world, and experts call it “A Nuclear Renaissance”. This has led to an increasing demand of uranium and, in turn, a revival of the uranium industry after a long slump of two decades. During the last three years, the uranium spot price has increased nearly three times. The secondary supplies of uranium, which meet nearly 45% of market demand today, are likely to be progressively diminished particularly after 2020. It is heartening to know that new exploration and mining activities have been initiated, major uranium producers have increased their annual production and there has been significant expansion in In-Situ Leaching (ISL) activities. New mines and mills are required to be opened during the next two decades in order to close or narrow the gap between uranium in the ground and the yellowcake (uranium

concentrate) in the can. The present Symposium has been organized at the most opportune time when the uranium industry is poised for a take-off. The response from the Member States have been overwhelming. The Symposium is being attended by nearly 200 participants from 30 countries and 4 international organizations, namely, OECD-NEA, NEI, WNA and UNECE as well as the IAEA. Some 100 technical papers have been received and compiled into the book of the extended synopsis. An exhibition on uranium exploration and mining and production has also been organized. The deliberations and discussions in the Symposium, in the panel and in the corridors will provide new guidances to the IAEA for planning their programme and budget activities in coming years.

REFERENCES

[1] OECD NUCLEAR ATOMIC ENERGY AGENCY, INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium 2003: Resources, Production and Demand, No. 5291, OECD, Paris (2004).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Uranium Production Cycle and the Environment (Proc. Int. Symp., IAEA, Vienna, 2000), C&S Papers Series No. 10/P, IAEA, Vienna (2002).

Keynote Address
THE NUCLEAR RENAISSANCE — OPPORTUNITIES AND CHALLENGES

G.W. Grandey
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Thank you to the IAEA for your kind invitation and a special expression of gratitude to my good friend Mr. Ganguly for devoting the energy to organize this symposium.

It's a pleasure to be here.

Vienna is one of my favorite cities in the world – steeped as it is in cultural, artistic, scientific and al history. Throughout the ages, innovation and talent have thrived in such an atmosphere.

One of Vienna's most famous residents, Ludwig Von Beethoven, once said:

"The barriers are not erected which can say to aspiring talents and industry, 'Thus far and no farther."

It seems fitting that you, some of our most talented scientists and technical experts, have gathered here to take a hard look at the opportunities and challenges our industry will face in the decades to come – opportunities and challenges that are born of the promise of a new day for the nuclear industry.

After a 20-year slump, we have seen uranium prices rise from a low of about US $7.00 to today's price of over US $29 per pound. We have witnessed icons of the environmental movement like James Lovelock – originator of the GAIA theory – and former Greenpeace CEO Patrick Moore, come out publicly in support of the industry.

Dozens of reactors are being built or planned in Asia, several in Europe and there is talk of new reactors being built in much of the rest of the world. In the United States, president Bush has publicly supported expansion of the nuclear industry as key to long-term energy security. Japan has released a strategy to double its nuclear capacity to meet its future energy needs and reduce carbon emissions from fossil fuels. And the list goes on.

People all over the world are rediscovering the environmental, security and cost benefits that nuclear energy delivers, and promises to deliver, to mankind.

And it is increasingly evident to consumers, legislators – and investors – that nuclear energy must be part of the solution to meet future electricity demand and do it cost effectively, without damaging our environment.

But are we, as representatives of the fuel supply industry, up to the challenges presented by the new prospects for nuclear energy? Can we, this time, deliver on the promise of our technology? That's a question each of you will be debating over this next week – as you discuss the technical papers and listen to the views from the distinguished presenters and delegates gathered here today.

The answer, I believe, will depend upon our collective ability to manage several issues:

first, closing the looming gap between uranium supply and demand;

second, overcoming the technical and political challenges in exploration and mine development; and

third, finding and developing innovations throughout the nuclear fuel cycle that make good economic and environmental sense.

* * * * *

Let's start with the most fundamental issue, uranium supply and demand.

Uranium Consumption

Forecasting uranium demand based on consumption in the world is fairly predictable.

Today, the world's 440 nuclear plants use 180 million lbs. of uranium annually. Conservative estimates, using World Nuclear Association (WNA) statistics for existing and identified reactor requirements show that annual consumption is expected to increase to about 206 million pounds within 10 years and rise to 215 million pounds by 2024.

Over the next two decades, cumulative uranium consumption will be in excess of 4 billion pounds.

If we get just a little more bullish and predict a high, but plausible scenario – with accelerated nuclear construction programs and reactor life extensions – the numbers become more daunting. In 10 years, annual consumption could reach 225 million pounds and by 2024, annual consumption would top 270 million pounds.

That would put cumulative uranium consumption at about 4. 6 billion pounds in the next 20 years.

These figures are, of course, sensitive to several risks and I would be remiss if I did not enumerate them. They are:

- plant closures
- tails assay adjustments
- operating performance and
- political uncertainty.

Assuming the projections are even close to realistic, the question for us is how will this demand be met?

Uranium Supply

Unfortunately, the future of uranium supply is more uncertain as evidenced by the rapid 165% rise in the price of uranium over the past two years.

Today, uranium is supplied from:

- primary mine production, which accounts for about 60% of annual consumption, and

- secondary sources, made up of surplus military materials (US or Russian), excess inventories, and recycled products.

As we all know, with the exception of recycled products, these secondary supplies are finite and will not be sufficient to bridge the shortfall between consumption and primary mine supply beyond a few more years.

Indeed, the gap between demand and existing supply begins to appear within the next 5 years and increases to a cumulative 2 billion pounds over the next 20 years, using the high case scenario, or 1. 4 billion pounds using the base case.

So, we face some near term supply challenges.

Where will the supply come from?

Identified Production Expansion

Over the next decade, additional supply will come from expansions at existing mines and development of new mines, offset by the depletion of a few existing mines.

Several examples of expansions are the McArthur River mine in Canada, US and Central Asian ISL operations, as well as Olympic Dam, in Australia.

The handful of identified new mines to come on over the next decade include Cigar Lake slated to start up in 2007; Inkai and Katco, also expected to hit commercial production in 2007; perhaps Honeymoon and Jabiluka; other US and Kazakh ISLs; co-product uranium/vanadium mines on the Colorado plateau, and possibly the Langer Heinrich property in Namibia.

With these new mines and expansions, additional production is expected to total about 900 million pounds over the 20-year period, still 500 million to one billion pounds short.

It is clear we need these current suite of "mines in the queue" to come on seamlessly… on time and at the expected rate…or there will be some near-term tightness.

Looking longer term, our challenge will be not only to find more uranium deposits, but to develop them quickly to supply an expanding nuclear power industry.

Exploration

The discovery and development of the new uranium resources, requires a robust and successful international exploration effort.

We are entering what appears to be the second cycle of world uranium exploration, fueled by the recent price recovery.

The first cycle occurred in the 1960s and 1970s and focused mainly on surface-based prospecting techniques. But this first phase only scratched the world's uranium potential. Since that time, some 80% of the uranium discovered in the world's most active exploration area, the Athabasca Basin, has been discovered using deep exploration techniques. This will likely be the trend in many other regions over the next 20 years.

Techniques to look deeper were made possible by many advances in the ways to image the earth and understand its geological processes. Although uranium exploration has been relatively quiet during the past 30 years, it has benefited from improved deposit models that allow explorationists to better select prospective areas.

Geophysical technology is key to success when exploring for blind deposits, those which do not have a surface expression. In this area, there have been advances in both airborne and ground geophysics. In particular:

- the availability of airborne gravity measurements within the past five years;

- the increasing depths of penetration of airborne electromagnetic (or EM) measurements, now capable of seeing conductive material one kilometre down;

- improvements in the use and understanding of EM inversions, which promise to better integrate geophysical methods with geological models; and

- reduced costs and improved resolution from seismic methods, including methods that can be used from drill holes.

All of these innovations, and many more, will be employed as we begin the second exploration cycle for uranium. With these advanced techniques, I am confident that the exploration sector will respond to the clear need for new sources of primary production in an efficient, environmentally-sound and cost-effective way.

But if we are to realize this discovery potential, much of the world's favourable terrain must be unlocked as it is currently not open to exploration at all, or, at least, not open to exploration by the private sector.

And several countries otherwise supportive of mining, generally, continue to allow policies that discriminate against uranium.

Countries that maintain full control of uranium exploration and mining by restricting foreign investment impede development and hurt their economies. These countries will fail to enjoy the full benefits of the rediscovery of nuclear technology.

It is important for such states to remember that crown jewels are only crown jewels if you know where they are. To find them, you need significant investment and people willing to take risks.

* * * * * * *

Assuming the next exploration cycle is productive, we will be confronted with the challenges of mining and milling.

We know there is a shortage of identified deposits that are ready for development. New discoveries are likely to be lower grade and, perhaps, not as large, so efficiencies will need to be found to insure uranium stays competitive.

One key advancement of the past 10-15 years, largely unrecognized, is the increase in productivity through the use of larger and better-performing equipment.

Whereas 100-tonne haulage trucks may have been the norm ten years ago, 240 tonne trucks are quickly becoming the standard. What this means for uranium mining is that a deposit such as Olympic Dam may now be economic to mine as an open pit despite the need to remove 350 metres of waste rock above the orebody. Indeed, if Olympic Dam had been discovered today, underground mining would likely not have been the chosen approach. Other deposits may be in a similar position and should be re-evaluated for their open-pit potential.

However, since it appears that many of the surface mineable uranium deposits are in production or already mined out, engineers must come up with ways to improve the economics of deeper deposits. Unfortunately, there have been fewer technological advancements in the underground area.

One of the difficulties with underground mining has been, unlike its open pit cousin, bigger equipment does not always result in improved workforce productivity. As equipment size increases so must the size of the tunnels and this often leads to false economies underground.

So the push in underground mining has been to get smaller equipment to perform better. Some examples include, the switch from pneumatic jumbo drills to higher penetration rate electric/hydraulic drills and the use of low profile mining equipment to replace less efficient jackleg drills and slushers.

One of the most costly aspects of constructing an underground mine is the need to sink shafts. Recent underground haul truck advances, however, have made it economic to haul ore to surface from depths greater than 800 metres thereby avoiding the need for a hoisting shaft. Project economics are consequently improved with the reduction in initial capital outlays.

Significant advances have also been made in characterizing the rock mass to come up with the most efficient mining method for a given set of circumstances.

Ground support methods are also becoming better understood and help avoid unnecessary costs. At Cameco's Eagle Point mine for instance, detailed mapping of the rock around a future production area provides vital information on expected ground stability. Only ten years ago, this type of geotechnical tool was not available to engineers and geologists.

But what additional things can we do specifically to improve uranium mining efficiency? Some tools in use at the few existing underground mines include:

Radiometric ore scanning and sorting, which allows the mine to extract lower grade ores while reducing the barren waste rock sent to the mill;

Mine workers equipped with direct reading dosimeters for gamma and alpha radiation in combination with area radon progeny detectors, all resulting in very low exposure levels and increased productivity.

I would be remiss if I did not mention advances in uranium milling technology. Basic mill flow sheets have changed little in the last half-century. But subtle changes in technology have greatly impacted the economics of some deposits.

For instance, 20 years ago, many surface calcrete deposits were considered uneconomic to mine due largely to the inability of existing filter technology to separate clay from the uranium-bearing solution during milling.

Advances in high pressure filter technology for solid/liquid separation, historically handled with thickeners or vacuum filters, have now made some uneconomic deposits economic.

The McArthur River mine was the first uranium mine in the world to move much of the milling process underground. High grade ore is ground, thickened and pumped to surface for delivery to the Key Lake mill. Engineers are now asking why not also conduct the uranium leaching underground, and send only the uranium bearing solution to a mill. Tailings would immediately be back-filled into the ground from where they came – a potential win-win for the mine and the environment.

At this conference, Cameco people will be discussing another key technological change at Key Lake. We have been assessing the potential to change from atmospheric and pressure leach to a full atmospheric leach circuit. Full atmospheric leaching would result in a less aggressive leach with less impurities being liberated. Additional benefits include reduced maintenance and radiation exposure associated with the current autoclave leaching circuit.

Even with such technological advances, the industry struggles with low equipment utilization and worker productivity. To address this, I believe we need to be vigilant in developing effective management systems. Equipment condition monitoring and better equipment reliability will be of great importance in ensuring the economics of future lower grade underground uranium mines and their mills.

Another issue is the loss of uranium mining and milling knowledge. The concentration of primary supply into the hands of a few suppliers over the past 30 years has meant that a great deal of industry knowledge has disappeared. This is particularly relevant for uranium milling where the subtleties of alkaline leaching, for instance, is only known to a small handful of individuals.

Across the mining industry, we are also facing a reduction in skilled workers. Underground mining has not been viewed as a profession of choice by young workers. Opportunities for rewarding work must be sufficient to attract and retain people. The shortage is especially acute in the numbers of tradespeople, as an aging workforce retires.

Increasingly stringent regulatory requirements make mine development difficult for all but a handful of established companies. Mine water discharge quality and tailings disposal requirements are two areas where standards continue to become more stringent. This leads to increased complexity, retrofitting at existing mines and higher capital costs for new mines.

Changes in the regulatory environment have also led to long project lead times and therefore greater risk for investors. Return on investment is generally highest when there is a short lead time from discovery to production. A long project lead time means guessing at what the uranium price may be 10-15 years into the future which, by necessity, leads to conservative assumptions and caution.

Lastly, the uranium fuel cycle industry must satisfy the needs of an increasingly diverse group of stakeholders. Our companies must be increasingly aware of the wants and needs of residents near current or proposed operations. These are the people who will give our operations their "social licence" to operate – one of the underpinnings for sustainable development, so key to the future of this industry.

So what can this international body, the IAEA, do to help us meet these challenges? Let me touch on a few possibilities:

There has been very little assessment work conducted on known uranium deposits since the early 1980s. Much of the work is contained in previous IAEA technical documents, various government reports, as well as recorded in numerous non-IAEA technical meetings. In order to promote further uranium mining the IAEA should play a role in gathering and organizing information needed to avoid a very costly re-education of the next generation of uranium miners.

The IAEA can also play an important role in collecting and disseminating up-to-date information concerning the latest technological advances – through periodic conferences and technical meetings such as this.

The organization can also gather and compile accurate uranium supply information. In its existing compilation that forms the IAEA Red Book, the Estimated Additional Resources (EAR) categories have long been inconsistently reported by member countries, reducing reliability and in some cases overstating or understating the supply potential of important regions. The usefulness of IAEA's supply estimates would be improved by the development of a single, consistent approach to the estimation of uranium potential, which member countries would then be encouraged to adopt.

Countries that have abundant resources should be encouraged by the agency to open up their lands to foreign investment for uranium exploration and development. The IAEA should present the case for improved investment climates, educating restrictive jurisdictions about current industry practices and standards, and lobbying for consistent and reasonable licencing processes that reflect science-based assessments of risk.

Most of all, though, I would encourage the IAEA to fill its role as an industry promoter both within the organization and to the world. Countries that enjoy the benefits of nuclear power have a large, but largely neglected, role in encouraging open, supportive, and consistent policies for the beneficial and peaceful use of nuclear technology.

If we fail to accelerate the use of this technology in the coming nuclear century, the world will be a dirtier and climate challenged place.

Austrian neurologist and the father of psychoanalysis, Sigmund Freud, once said:

"The voice of the intellect is a soft one, but it does not rest until it has gained a hearing. "

This conference – which celebrates the voice of the intellect – reflects our collective resolve to be heard.

Over the next few days, you will be letting the world know. This is our time, our renaissance. The message is that we're here, we're serious and we're ready to meet the challenges and advance nuclear energy's multiple benefits.

Thank you.

TOPIC 1 - URANIUM SUPPLY AND DEMAND

Worldwide uranium resources and production capacity – the future of the industry

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Abstract. The worldwide uranium resource base is distributed across a broad range of confidence levels and projected production costs. High confidence low-cost resources (RAR) are, however, not geographically well diversified, with up to 75% of the resources located in just four countries. Therefore, to minimize the risk of production being delayed by environmental opposition, exploration should be diversified to include additional areas where mining will likely be accepted. Though the total resource base is extensive, a large part of it requires additional exploration, development drilling and engineering studies to be elevated to the high confidence RAR classification. Exploration investment needs to be made available now to ensure that resources are adequate to satisfy future uranium demand. For this to happen, however, the uranium industry must be confident that the recent increase in the market price will be sustainable over a long enough time period for it to accept the risks inherent in uranium exploration. Among the known uranium deposits that have near-term development potential, relative few have projected production capacities in excess of 3 000 t U/year. Therefore, the industry may be facing the need to develop large numbers of relatively small projects with production capacities in the 400 to 1 000 t U/year range. This scenario could well over load government agencies responsible for project permitting and licensing, potentially leading to delays in the start of production for lack of required permits.

1. Introduction

Confidence in the adequacy of uranium resources to meet future reactor uranium requirements will be essential to the growth of nuclear power. During the past decade, the worldwide nuclear community has come together under the auspices of the OECD and IAEA in a concerted effort to establish a global uranium resource base. This worldwide uranium resource base is summarized in the OECD/IAEA 2003 Red Book [1], which includes information on uranium resources and production capacity submitted by 44 countries. This paper will examine various aspects of uranium resources and the capability of the uranium mining industry to deliver those resources to the marketplace in a timely and environmentally sound manner.

Uranium supply is generally divided into two broad categories – primary supply or newly mined and processed uranium and secondary supply, which includes highly enriched uranium from dismantling of nuclear weapons, inventory drawdown, reprocessed uranium, mixed oxide fuel and tails re-enrichment. Though this paper will emphasize primary supply, we must also consider availability of secondary supply to gain a more complete perspective on uranium requirements and the adequacy of the uranium resource base to ensure a balance between supply and demand. Figure 1 shows the historical relationship between uranium requirements and production between 1988 and 2003. As can be seen from this now familiar chart, uranium production exceeded demand until about 1990, when that relationship was reversed. The disparity between primary supply and demand grew rapidly until in 2003, total demand was satisfied about equally by primary and secondary supply.

Availability of secondary supply, the area between total demand and production in Fig. 1, is expected to decrease to about 15% by 2020; primary supply will have to increase in proportion to the decrease in availability of secondary supply to ensure a balance between supply and demand. The challenge for the uranium production industry will be to ensure that there is adequate production capacity to replace declining secondary supply and there are adequate resources to sustain production.

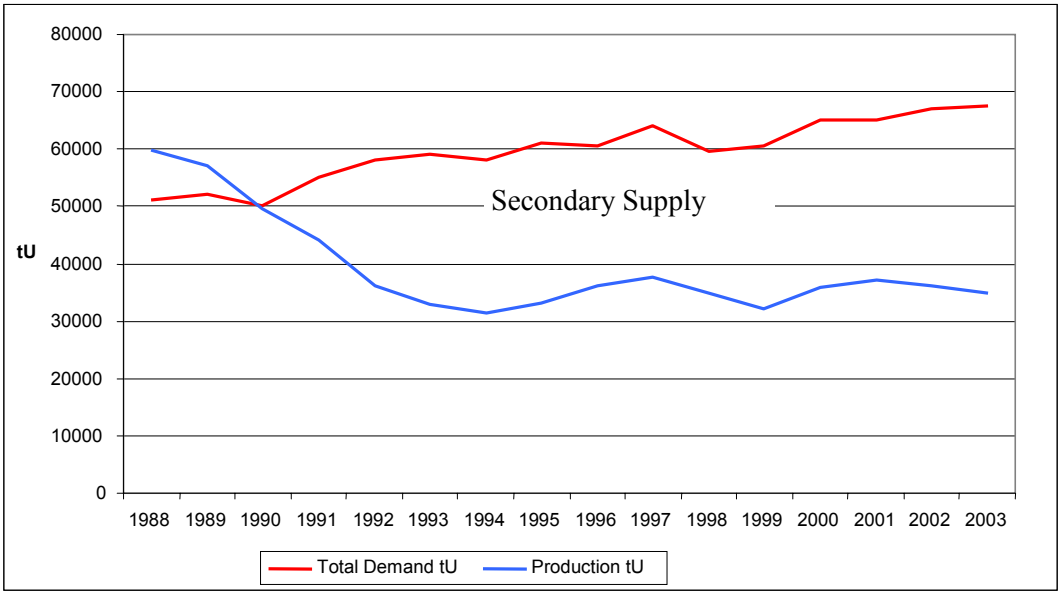

FIG. 1. Historical relationship between demand and production (primary supply).

2. Resource nomenclature

- Uranium resources are divided in the Red Book on the basis of confidence category:
- Reasonably assured resources (RAR) – highest confidence
- Inferred resources – formerly EAR-I
- Prognosticated resources – formerly EAR-II
- Speculative resources – lowest confidence
- Resources in each of the confidence categories are divided into production cost categories as follows:
- <US $40 per kilogram uranium (kg U)
- US $40 – 80/kg U
- US $80 – 130/kg U
- <US $130/kg U (used when more specific information is not available)

As a frame of reference for these production cost categories, the uranium spot market and long-term prices were about US $55 and 70/kg U, respectively when this paper was being prepared.

3. Resource credibility

Uranium resources are reported to the OECD/IAEA by government authorities on a bi-annual basis. The resources are not attributed to specific deposits, but are reported in aggregate on a country-by-country basis for each resource category. However, as part of a broader forum on the nuclear fuel cycle, in 2004, a group of IAEA consultants developed a uranium resource base that is related to specific deposits, which would be approximately equivalent to RAR. That resource base includes more than 150 individual deposits with resources totaling 3.96 million tonnes of uranium (t U) compared to 3.169 million t U listed as RAR in the 2003 Red Book. The difference in the two numbers cannot be entirely explained. However, the IAEA consultants were assessing uranium resource availability through 2050, and given the expanded timeframe they included remaining resources in abandoned mining districts not considered viable by government geologists. It is also possible that some of the deposit-specific RAR were categorized as inferred resources in the Red Book tabulation.

Though the difference in the two data bases cannot be completely explained, the fact that experienced geologists could attribute RAR to specific deposits on which they have considerable information that exceed Red Book RAR, lends a great deal of credibility to the Red Book information. This credibility should not, however, lead to complacency as to the adequacy of uranium resources to meet future

demand. Many of the deposits included in the RAR data base were discovered decades ago. The data on which the resource estimates and production cost information were based need to be re-evaluated in light of more advanced technology, market dynamics and environmental regulations.The discussion of resource credibility has to this point focused mainly on RAR, the highest confidence resource category, because RAR are the key to assuring a balance between near-term supply and demand. There are, however, also substantial lower confidence resources including those in the inferred, prognosticated and speculative categories that, with additional exploration, have the potential to be elevated to RAR and to become available for future development. Table II, which provides a summary of resources in all confidence ranges, shows the magnitude of worldwide resource potential. To put the numbers in Table I into perspective, consider that historical uranium production has totaled about 2.05 million t U; therefore, indicated resources (RAR + inferred resources), the two highest confidence categories exceed historical production. The resources listed in Table I, while impressive, are only the beginning, and the path between resources in the ground and "yellowcake in the can" is unpredictable.

Table I. Worldwide uranium resources by confidence and cost category [1]

Confidence Category	<US $40 (t U)	<US $80 (t U)	<US $130 (t U)	Cost Range Unassigned (t U)
RAR	1 730 475	2 458 152	3 169 238	
Inferred Resources*	792 782	1 078 762	1 419 450	
Prognosticated Resources		1 474 600	2 254 500	
Speculative Resources			4 437 300	3 102 000
Total	2 523 257	5 011 514	11 280 488	3 102 000

* formerly Estimated Additional Resources Category I (EAR I)

By their very name, inferred resources carry a great deal more uncertainty than RAR. They are based on geologic extensions of well-defined deposits, but more exploration needs to be completed to elevate inferred resources to the confidence placed in RAR. Even more geological and engineering work remains before prognosticated and speculative resources are elevated to the point where they can be relied upon to satisfy future demand. Having said this, however, even lower confidence resources in the prognosticated and speculative resource categories have as their foundations geologic interpretations based on more that 60 years of worldwide exploration.

In addition to the resources listed in Table I, there are also significant resources associated with what have historically been referred to as "unconventional resources". As market prices continue to increase, "unconventional" production methods could once again become economically viable. For example, prices will not have to increase much beyond the current long-term price before interest in recovery of uranium as a by-product of phosphoric acid production could be renewed. Recovery of uranium from marine phosphorite deposits uses well established technology, having been used in Belgium and the United States as recently as 1997 and 1999, respectively. Estimates of uranium resources associated with marine and organic phosphorite deposits total approximately 9 million t U, with four countries – Jordan, Mexico, Morocco and the U.S. – accounting for about 90% of these estimated resources [2]. A potential resource of this magnitude clearly cannot be ignored as we look to the future.

According to Red Book estimates historical uranium exploration expenditures totaled nearly US $10 billion through 2002. This investment led to discovery of the deposits from which more that 2 million t U have already been produced and discovery of the deposits that are currently in production or are under development. This investment also resulted in development of a geologic framework that has identified favorable areas that could host new uranium districts and deposits. What is needed now is a sustainable market price and demand projection that will justify the hundreds of millions of dollars needed for exploration and development to add further credibility to the uranium resource base.

Resource Totals and Production Costs

Uranium resources have no real meaning unless they are put into an economic context. For example, the resource potential of seawater is estimated to be about 4 x 10^9 t U [2]. Even with the recent price increase, however, the estimated cost of extraction of uranium from seawater of US $300/kgU is still more than 10 times the current long-term market price. Therefore, the potential of seawater should be considered as a very long-term, high-cost resource and should clearly not be a distraction in the evaluation of the adequacy of uranium resources to meet future supply requirements. Figure 2 provides juxtaposition between RAR, the highest confidence resource category, and production costs. It is indeed encouraging to note that 72% of high confidence resources are projected to be recoverable at less than US $80/kgU, particularly given the fact that the current long-term market price of US $70/kg U is within striking distance of that production cost. A similar percentage distribution exists among inferred resources: 55% in the <US $40/kgU category, 19% US $ 40-80 and 23% US $80-130.

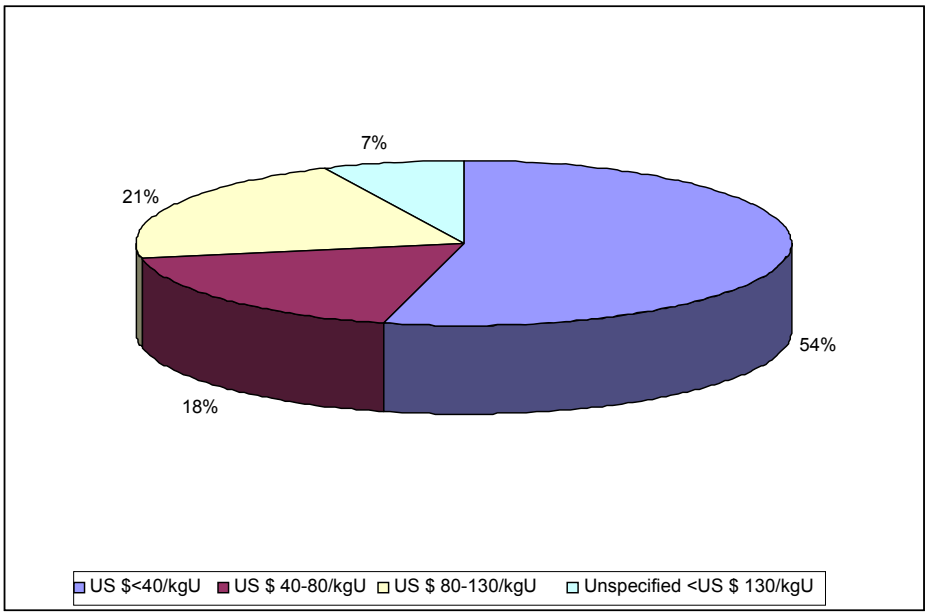

FIG. 2. Percentage cost distribution of RAR.

4. Diversity of supply

Diversity of supply is critical to the long-term viability of any industry. Concentration of too many resources in too few hands has the potential for market disruption and manipulation. Diversity of supply is particularly important to the uranium industry where public acceptance of uranium mining continues to lag increasing approval ratings for nuclear power. A large resource base in a given country does not necessarily translate into that country being or becoming a major uranium producer.

To assess diversity of supply we again turn to high confidence resources. Figure 3 shows the percentage of RAR recoverable at <US $80/kg U that are controlled by the world's leaders in uranium resources. As noted in Fig. 3, the top four and top 8 ranking countries control nearly 70 and 90% of worldwide relatively low-cost resources, respectively. The remaining 10% of low-cost RAR are distributed among 35 different countries.

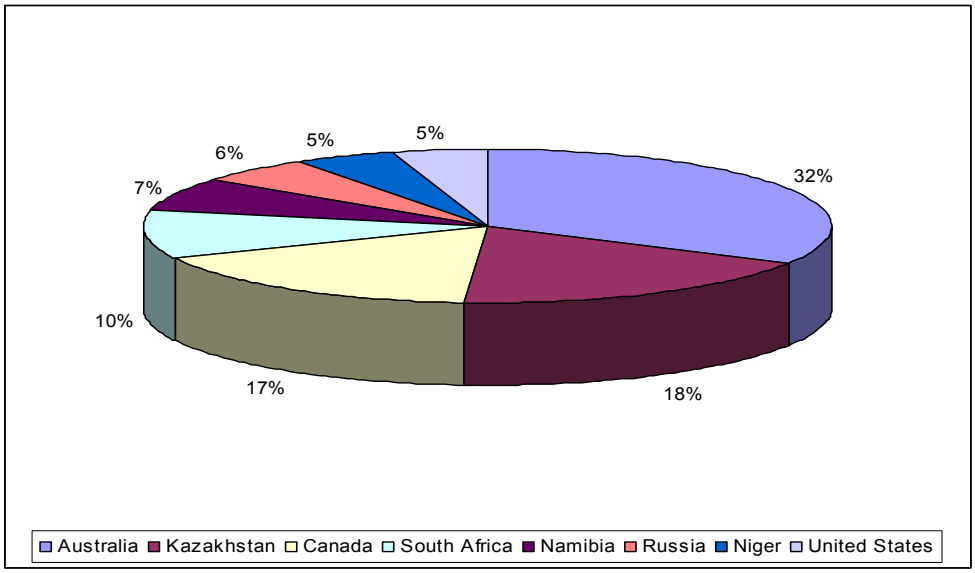

FIG. 3. Geographic Distribution of RAR Recoverable at <US $80

The distribution of uranium resources is a combination of geology and exploration effort. How much each of these factors is responsible for four countries controlling 70% of the world's low-cost, high confidence resources is a matter of conjecture. Not only is there limited resource diversity based on geography, but depressed prices during the past two decades have also resulted in an industry consolidation that has placed a majority of worldwide low-cost resources under the control of relatively few companies. Six companies control approximately 1.83 million t U of resources, most of which would be classified as RAR and would be recoverable at <US $80/kg U. Since the Red Book reports resources by country and not by deposit, there is no certainty as to how the resources controlled by these six companies are accounted for in the Red Book. However, while the numbers may be imprecise, a case can be made for saying that six companies control about 75% of RAR recoverable at less than US $80/kg U.

The lack of diversity of low-cost resources has several implications for future supply and market price. There is the obvious concern that limited diversity could lead to price manipulation. This is probably not an important concern, however, because of the close scrutiny focused on the uranium industry and the availability of secondary supply that partly offsets near-term demand for primary production. Of more concern is the fact that no matter how large a company is it has limited capital resources and must prioritize allocation of its capital. Therefore, it may elect to delay development of one or more projects because of limited capital and experienced personnel, even though the projects can be justified economically.

The lack of geographic diversity is of particular concern because of opposition to uranium mining in some parts of the world. For example, projects in Australia, such as Jabiluka, Kintyre, Koongarra andYeelirrie, with combined resources totaling 206 000 t U have uncertain futures because of environmental/political opposition to uranium mining. Similarly, in New Mexico in the United States, development of relatively low-cost resources totaling 40 300 t U that are amenable to in situ leach (ISL) extraction has been delayed by the actions of well financed environmental activists and Native American tribes. This same opposition that has delayed mine development also discouraged exploration in Australia and New Mexico, both of which are considered to have potential for discovery of new deposits. There can be no certainty as to how populations will respond to uranium mining in the future, but clearly a geographically well diversified resource base reduces the risks of a supply shortfall resulting from environmental opposition.

5. Production capacity, the other side of the supply equation

Determining the magnitude of worldwide uranium resources and classifying them by confidence and cost categories is only the first step in characterizing the worldwide uranium industry. Evaluating the adequacy of resources to meet reactor uranium requirements is the next step in assuring that supply is adequate to meet long-term demand. Though a comprehensive analysis of uranium supply and demand is beyond the scope of this paper, there are aspects of uranium resources that have a direct bearing on the ability of the industry to deliver resources to the marketplace in a timely manner.

The ability of the uranium industry to develop and deliver resources to the marketplace, as measured in terms of annual production capacity (t U), is equally as important as resources in the ground. There is no direct relationship between uranium resources and production capacity, either globally or on a deposit-by-deposit basis. Production capacity is determined by a combination of factors including mining method, ore grade, geology and environmental constraints. Total resources of a deposit also play a part in determining its production capacity, with a large resource base typically justifying a larger capacity than would be appropriate for a small resource base.

All things being equal, open pit mines typically have the highest capacity potential, followed by underground mines and ISL operations in that order. Ore grade is also an important factor in determining capacity that can readily upset this relationship. Miners typically think in terms of tonnes of ore mined. The higher the ore grade, the higher the uranium content per tonne of ore. For example, a tonne of ore at McArthur River, an underground mine with an average grade of 15% U, contains 127 kg U, while a tonne of ore at the open pit Rössing mine, which has an average grade of 0.03% U contains about 1.7 kg U.

In 2003, 40 production centres in 16 countries accounted for worldwide output totaling 35 385 tU. The production centres operating in 2003 ranged from McArthur River with a capacity of 7 200 t U to small operations in developing countries that produced between 40 and 200 t U. The combined nameplate capacities of all production centres operating in 2003 totaled approximately 47 260 t U. Figure 4 compares projected capacities of existing and committed production centres through 2020 with all production centres that could be developed between 2005 and 2020, based on known deposits.

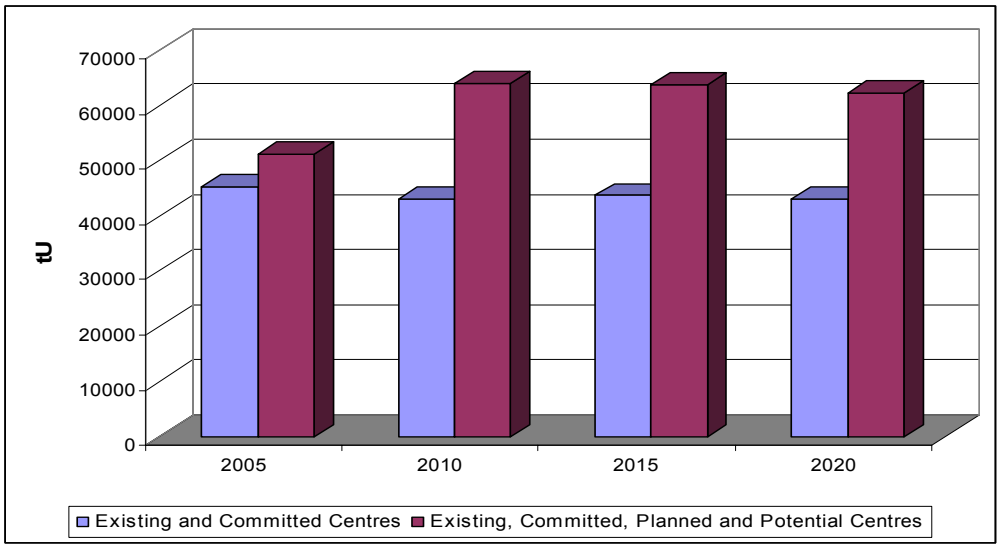

FIG. 4. Projected worldwide uranium production capacities through 2020 [1].

As shown in Fig. 4, output from existing and committed or firmly planned facilities is expected to remain about flat between 2005 and 2020. Exactly how the proposed expansion of capacity from new facilities will be achieved will depend in part on the nature of the resources that are available for development. As a way to more completely characterize the worldwide resource base, the OECD and

IAEA have begun collecting data that relates resources to deposit type, with the data to be released as part of the 2005 Red Book. This characterization is important, because some deposit types inherently have the potential to support higher production capacities. This information will not, however, be available until 2006. Therefore, in preparing this analysis, 2003 production has been classified by deposit type and projections from that classification are used to project future trends in uranium production capacity.

Figure 5 tells us a great deal about the current makeup of the uranium production industry. If we look inside the numbers we can also project the character of the industry into the future. Unconformity-related and ISL-amenable sandstone deposits made up 42 and 20% of 2003 production, respectively. Four deposits accounted for the unconformity-related output, while 17 production centres contributed to the ISL total. McArthur River, the largest unconformity-related deposit has an annual production capacity of 7 200 t U, while the largest ISL operations, Stepnoye and Centralnoye in Kazakhstan, each have capacities of 1 000 t U.

These relationships are not likely to change in the near future. Cigar Lake, an unconformity-related deposit with a production capacity of 6 900 t U, is expected to come on line in 2007. There are a number of ISL projects under development including Inkai and KATCO in Kazakhstan, with proposed capacities (including expansion potential) of between 1 000 and 1 300 t U. We can only generalize as to the future makeup of the industry. To begin with, there are wide ranges of resource potential and average grade within in the deposit types. For example, the ore grades and resources of Cigar Lake and McArthur River are exceptional, even among known unconformity-related deposits in the Athabasca Basin. Table II**,** which compares resources and average ore grades for unconformity-related deposits in Australia and Canada, clearly shows the influence that resources and ore grade have on production capacity.

Though we can only generalize as to the future makeup of the industry there is sufficient information to forecast trends in the kinds of deposits that will be developed in the near term. Cigar Lake is the only new unconformity-related deposit that is likely to be built in the next 10 (or more) years because of permitting and construction timetables and environmental opposition. After Cigar Lake, there are no very high-grade deposits in the pipeline for development. Instead, the most likely candidates for development are ISL-amenable sandstone deposits with annual production capacities in the range of 400 to 1 200 t U.

The types of deposits that will be available for near-term development will have far reaching implications. Cigar Lake is the only new project in the pipeline with potential for very high production capacity. In addition, Olympic Dam is scheduled to increase its annual output to double or even eventually triple its existing capacity (3 930 t U). No other project on the horizon is likely to have even half the capacity of Cigar Lake or the expanded Olympic Dam, and some of the deposits with the highest capacity potential such as Jabiluka have uncertain futures because of environmental opposition. In a worse case scenario, we may be faced with relying on development of a large number of relatively small capacity operations to ensure an adequate supply of uranium.

Every new project will require extensive environmental and safety reviews prior to the start of development. These reviews can take between 3 and 10 (or more) years. Careful planning by the industry will be needed to ensure that projects being considered for development are submitted to regulatory agencies well in advance of when they will be needed to balance supply and demand. Ideally there should be industry wide coordination of licensing activities to avoid overloading licensing entities. Uranium development will be competing with other natural resources including other metal mining, oil and gas and coal for limited permitting capability, so planning will be the key to gaining a priority position in the permitting queue.

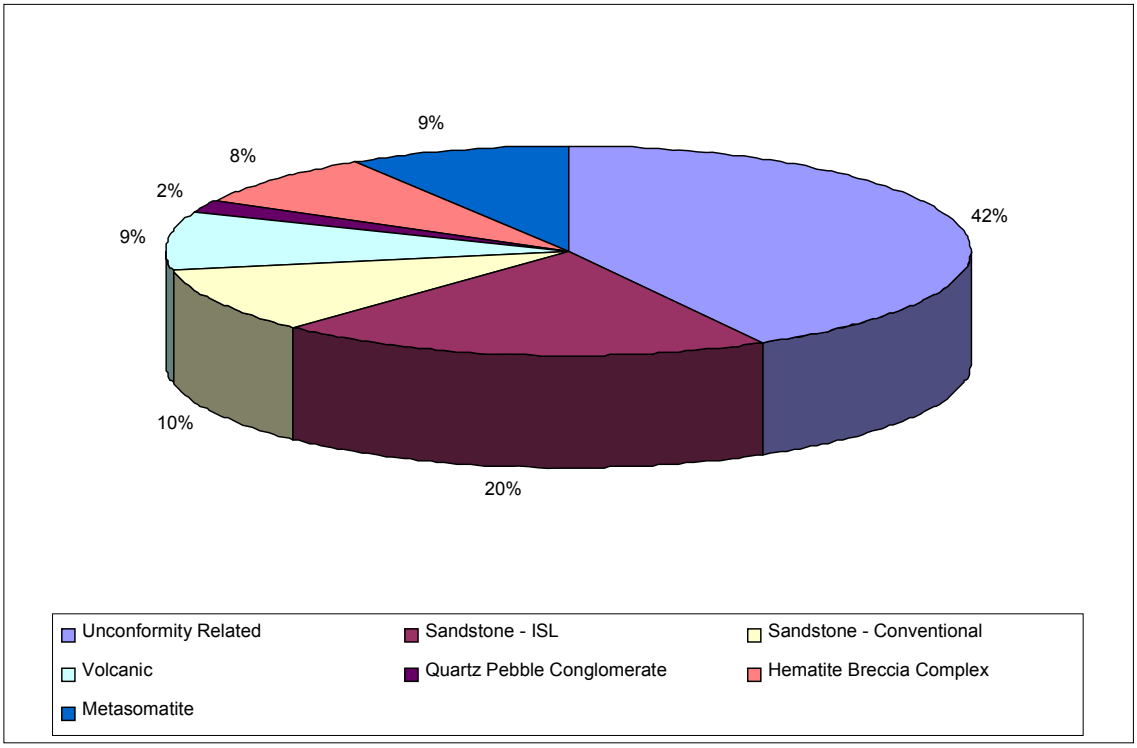

FIG. 5. Percentage distribution of 2003 production by deposit type.

Table II. Characteristics of unconformity-related deposits in Australia and Canada

Mine/Deposit	Country	Resources (tU)	Average Ore Grade (%U)	Production Capacity (tU)
McArthur River	Canada	215 360	15.5	7 200
Cigar Lake	Canada	134 510	15.5	6 900
Midwest Lake	Canada	13 846	3.7	2 500
Jabiluka	Australia	132 360	0.45	2 290
Kintyre	Australia	24 700	0.25	1 300
Koongarra	Australia	10 500	0.68	1 000

6. Exploration – Have we found it all

Historically, increases in the price of uranium have been accompanied by increased investment in uranium exploration. These bursts of exploration investment have led to new discoveries that are the basis for current resources. There is no reason to believe that this current round of uranium price increases will be any different, if exploration companies become convinced that the price increase is sustainable. For many countries, particularly those with already large resource bases, exploration will likely be concentrated on increasing the confidence level of existing resources – what may be termed development drilling. Exploration will likely continue in areas such as the Athabasca Basin in Canada where there remains excellent potential for discovery of additional unconformity-related deposits or for new deposit models such as the recently announced Millennium discovery. There is also renewed exploration interest in South Australia for hematite breccia complexes similar to Olympic Dam. Despite historical exploration expenditures totaling US $10 billion, there remain large areas around the world that are only sparsely explored. The answer to the question "have we found it all" is an emphatic no. The list of potential exploration targets is long – what is needed is exploration investment and experienced people to use it wisely to establish a geographically diverse resource base.

7. Conclusions

Historical exploration expenditures totaling US $10 billion, have defined a large worldwide uranium resource base, with resources covering a range of confidence levels and production costs. Though the total resource base is reasonably well diversified geographically, 75% of low-cost, high confidence resources are concentrated in only four countries. The development potential of a portion of these resources is, however, questionable because of opposition to uranium mining and broader diversification of the global low-cost resource base is called for to minimize the risk of production delays resulting from environmental opposition.

In 2003, 40 production centres in 16 countries accounted for worldwide uranium output. Approximately 40% of 2003 output came from four unconformity-related deposits with average production capacities of 4 890 t U/year. The largest of these mines, McArthur River has an annual capacity of 7200 t U. By contrast, 14 ISL-amenable sandstone deposits with average production capacities of 550 t U/year contributed 20% of 2003 production. Cigar Lake, with a projected capacity of 6 900 t U, is the only operation under development with capability to produce more than about 1 200 t U/year. Most of the other mines being developed are ISL operations with capacities ranging between 200 and 1 000 t U. This trend will likely characterize the expansion of the uranium production industry that will be needed to ensure a balance between future supply and demand. The likelihood that large numbers of relatively small-capacity mines will need to be developed in the future could put a strain on the regulatory agencies charged with project permitting and licensing, potentially leading to delays in the startup of new mines.

As we look to the future, approximately 70% of RAR are projected to be recoverable at <US $80, which is encouraging given the fact that this cost level is only about 15% higher than the current long-term market price. While the availability of low-cost resources is encouraging, though they are classified as RAR, many of these resources still require additional exploration and development drilling before they are ready to be subjected to rigorous economic feasibility studies. Similarly, all of the lower confidence resources, starting with those in the inferred resources category, will need extensive exploration before they can be reclassified as RAR. Therefore, the industry must find the capital resources and experienced personnel to undertake the exploration needed to ensure a well diversified uranium resource base for the future.

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The future of uranium: Filling the gap

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Abstract. The supply of uranium from new production has fallen short of nuclear power plant demand since 1985. However, this has not been a problem because uranium suppliers produced a large quantity of uranium in prior years, in anticipation of major new plant construction. When the expected new construction did not materialize, the industry was left with an over-supply of uranium.

1. The future of uranium: filling the gap

The large disparity between supply and demand hit uranium producers hard. Uranium mines closed. Some companies sold assets, stopped exploring for new sources of uranium or went out of business altogether. During this period, the shortfall between new production and reactor demand was filled by inventory and, more recently, by surplus weapons material.

Surplus weapons material involves high enriched uranium, down-blended to low enriched uranium and limited amounts of plutonium fabricated into mixed oxide fuel. By the end of this decade, these sources of non-production uranium will be almost exhausted. Because mining exploration largely ceased in the 1990s, there most likely will not be sufficient new production on line to fill the demand. The industry faces a big question: How is the gap between new supply and demand going to be filled?

This paper looks at the possible sources of uranium to fill the gap. The approaches include, higher burnup fuel, greater use of mixed-oxide fuel, use of enrichment versus uranium tails assay, and mining of enrichment tailings piles.

There is no one answer. The amount of supply from any one source will be dependent on the prices of uranium, enrichment and reprocessing service. The mixture of these alternatives also will be a function of the energy policy of various countries. National energy policy will impact where and how material is produced as well as how it is consumed. It will include restrictions on access to material and facilities. This paper will not address national policy.

2. High burnup fuel

Filling the gap begins with higher burnup fuel. It requires getting more energy out of the current fuel used in the reactors. Average discharge burnup for boiling water reactor (BWR) fuel is in the 40 000 to 45 000 MW d/Mt U, while pressurized water reactors (PWR) are experiencing burnup in the 45 000 to 50 000 MW d/Mt U. It has been demonstrated that burnup levels above 60 000 MW d/Mt U for BWRs and 70 000 MW d/Mt U for PWRs are achievable. Attaining these levels would reduce uranium demand between 6 percent and 9 percent. The impact of burnup on uranium demand can be seen in Fig. 1. The combined BWR/PWR increase in burnup would provide uranium saving of between 10 and 15 million pounds per year (Fig. 2). The issue is how to achieve these levels of burnup on a batch average basis in lieu of having them on a peak assembly. To reach this by the end of the decade, programs must be launched now.

In the United States, the Electric Power Research Institute has been considering the issue [1-3]. However, concern about fuel failure has taken higher priority. High burnup fuel requires better fuel

rod performance than the industry currently is experiencing. Until the industry reduces the fuel-failure rate and learns more about the cause of fuel failure, high burnup fuel will remain a future technology.

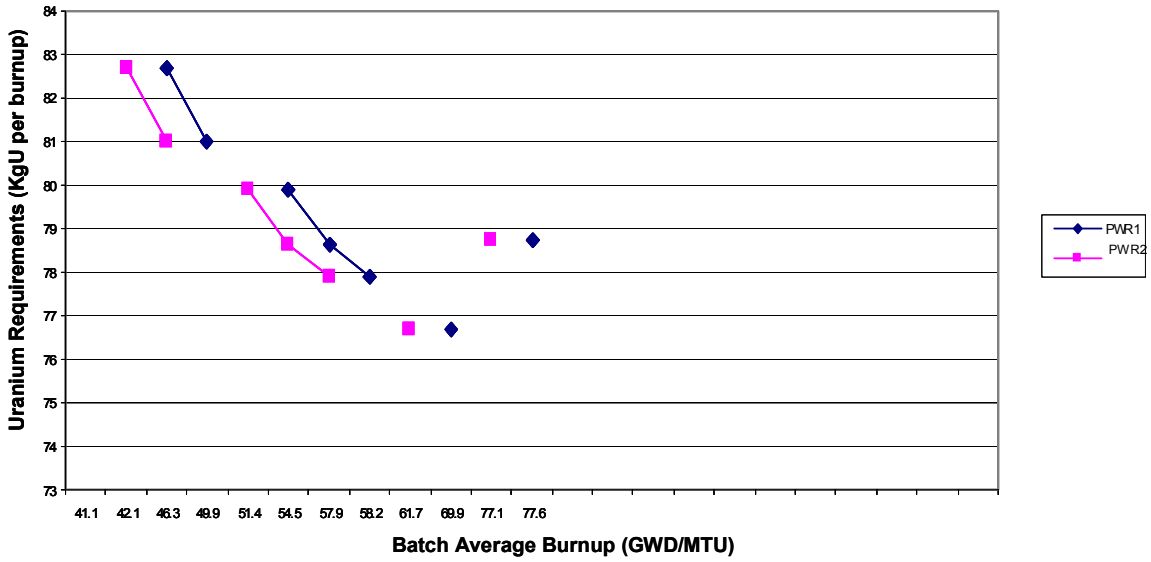

FIG. 1. Uranium requirements as a function of burnup.

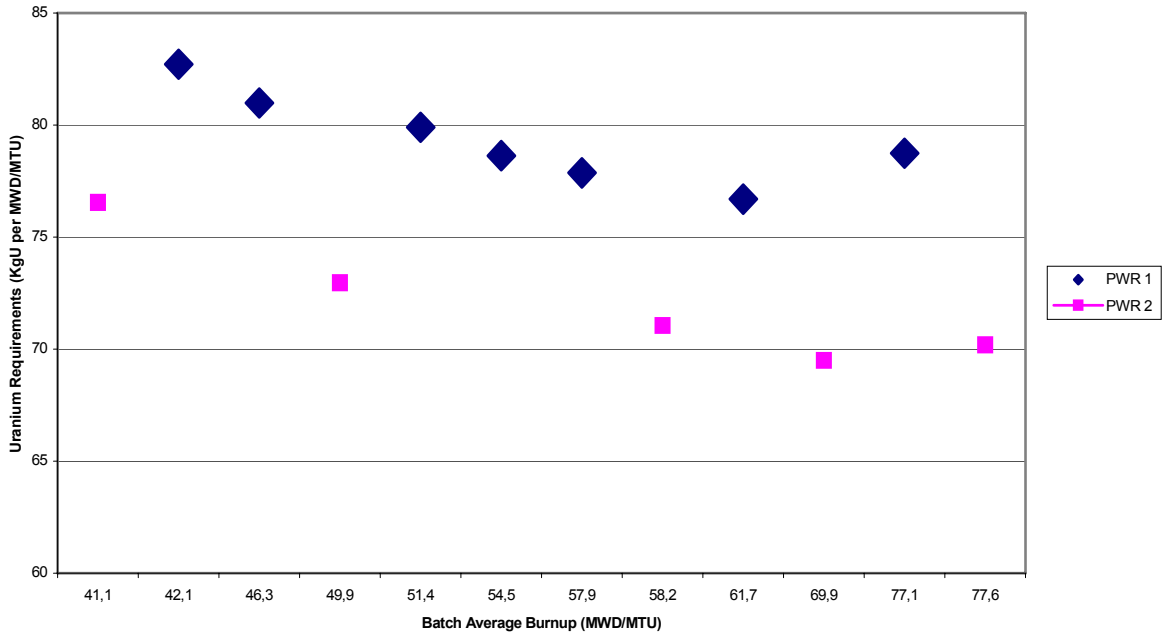

FIG. 2. Uranium requirements vs. burnup.

3. Mixed oxide fuel

The second step in filling the gap is expanding the use of mixed oxide fuel (MOX) to reduce uranium demand. Currently, a little more than 8 percent of the light water reactors in the world operate with MOX fuel. However, even this small sample is sufficient to demonstrate the safety and operability of MOX fuel. If the number of reactors using MOX fuel were doubled, it would reduce uranium demand considerably. The estimated savings in uranium would be 10 million to 15 million pounds per year. This impact is similar to that of high burnup fuel.

However, as with high burnup fuel, there are several steps to putting this into action. First, plants must be licensed to use MOX fuel. Depending on the country, this could be a simple process or one that is very complex and difficult. Second, some reactor designs can use MOX fuel with minimal, if any changes, while other reactors would require significant modifications in order to operate with a full MOX core. This would need to be assessed to establish the feasibility. The third and fourth steps would be expanding the infrastructure to provide the additional reprocessing to provide (1) the plutonium and (2) fabrication facilities to produce the MOX fuel. Neither of these will be simple tasks. If this is to be part of the solution by the end of the decade all of these issues need to be addressed starting today.

4. Lowering tails assay

The third approach to reducing the pressure on uranium to fill the supply gap is the use of lower-tails assay in the enrichment process. Variable-tails assay is nothing new. In the days of fixed commitment enrichment contracts, it was routine practice to use variable tails to provide additional product or change the amount of feed requirements. For example, with a fixed 1 000 swus and a final assay of 4.5 percent U-235, the amount of feed could be varied from a high of 1 640.0 kg U of natural feed to produce 160.5 kg U of product at 0.30 percent tails to a low of 1 094 kg U of natural uranium to produce 130.0 kg U of product at 0.20 percent tails. Therefore, by increasing the feed amount and using the higher tails assay, 30.5 kg U of additional product could be produced with the addition of 546 kg U of natural feed.

Today, utilities routinely vary the tails assay to achieve the lowest-cost final product. For example, if 1 000 kg U at 4.3 percent U-235 is required, it can be produced through several combinations of swus and feed and tails assay. At 0.30 percent tails, assuming 9 732 kg U of natural feed and 5 847 swus, it would create 1 000 kg U at 4.3 percent. Or at 0.20 percent tails, it would take 8 023 kg U of feed and 7 230 swus to produce the same product. In this case, adding 1 383 swus would yield a savings of 1 709 kg U of natural uranium feed. At US $110.00/SWU, the uranium price would be US $89.02/kg U for the transaction to break even. Therefore, if the utilities' uranium value is greater then US $89.02/kg U the lower tails assay would be used, however, if the value was less then US $89.02/kg U the higher tails assay should be used.

Based on today's uranium price, it is practical to substitute enrichment service for uranium in this tails range. As the price of uranium increases in relation to the cost of enrichment service it would be more practical to substitute enrichment service for uranium. With today's low-cost uranium, it is being substituted for enrichment. Recently, as the price of uranium has gone up the tails assay has gone down. Tails assay were well into the 0.35% range. Today they are falling into the 0.30 % and below. It is expected that tails assay will continue to decline as the uranium price goes up. This may be buffered by increased enrichment prices.

Due to the rising cost of uranium, a utility may want to determine its fuel cost over several cycles to arrive at a lower average cost. In this case, the utility would consider the uranium escalation cost, as well as the enrichment escalation cost in their respective contracts. By considering the future cost, a utility today may want to use lower-tails assay in order to conserve uranium, which over three or four refueling outages would result in a net present value lower then the alternative of business as usual. This approach is only practical with known costs of each of the commodities. It can be done on speculation as well, but the downside risks are very large. If this approach is taken, it also will reduce the pressure on future uranium requirements. It is difficult to predict the outcome of this arrangement.

It is important to note that a reduction in tails assay would have a large impact on uranium demand. For example, a small reduction of tails assay at 4.5 percent U-235 enrichment from 0.30 percent tails to 0.28 percent tails would be more than a 4 percent reduction in uranium demand. At 1.5 percent U-235 enrichment, uranium demand would decline 3.0 percent. Therefore, the change in tails assay could reduce the pressure on uranium demand between 5 million and 7 million pounds of uranium annually. As can be seen, the high-enriched end product has a greater impact. With the industry moving toward

higher enrichments, and uranium prices rising, using lower-grade tails assay would help to reduce the pressure on uranium.

5. Mining the tails

For decades the enrichment plants have operated at various tails levels. The tails assay was dictated, at the time of enrichment, by demand from customers and cost of energy supply. As a result, tails assay vary from as low as 0.1 percent to above 0.35 percent. With the new centrifuge enrichment technology, the tails material now can be enriched to the level of natural or enriched uranium. Doing so would greatly reduce the demand for new uranium. This is currently being done in Russia. This goes hand in hand with mining the tailings piles of enrichment facilities. Tails that have the higher assay would be used first and, as long as capacity was available and the marginal cost was being covered, it would be a profitable business. This would focus on starting with tails material which is at least 0.25 percent and leaving tailings of less then 0.2 percent.

Centrifuge enrichment plants have a high initial capital cost and much lower operating cost then gaseous diffusion plants. Therefore, once a centrifuge goes into operation, any excess capacity would be ripe for enriching tails material. With projected increases in the cost of uranium, this could be a very attractive opportunity for the enrichment complex. However, there will be countering forces. As the price of uranium increases, the substitution of uranium for enrichment service will decrease. This would increase demand for swus for providing enriched product for customers and, therefore, greater utilization of the capacity of the plants. This would reduce the amount of capacity available for tails enriching.

6. Conclusion

In summary, while it is expected that new production will not meet the demand for uranium, for some period of time; there are alternative forms of supply. If these were summed up, but not including the mining of the tailings piles, it would account for between 25 and 37 million pounds of uranium per year. These opportunities include:

- improving fuel performance,
- increasing the use of MOX fuel,
- reducing tails assay.

This indicates that uranium is available to supply gap and meet demand. It remains to be determined which alternative will be used to meet this demand. The answer to this question will be a function of the cost of uranium, enrichment service, reprocessing, ability to improve fuel performance, and national energy policies on the mining and use of nuclear energy.

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Recent activities of the joint Nuclear Eenergy Agency (NEA) / International Atomic Energy Agency (IAEA) Uranium Group

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Abstract. In the early 1960s, a group of experts from national atomic energy organizations was organized by the Organisation for Economic Co-operation and Development (OECD) to evaluate uranium resources in an economic perspective, under the auspices of the then European Nuclear Energy Agency. Reports prepared by these experts, known as the Uranium Group, are based on data submitted by national authorities and published biennially under the title "Uranium: Resources, Production and Demand", more commonly known as the "Red Book". Since its inception more than 40 years ago, the activities of the Uranium Group have grown beyond the original mandate. Although the focus of the Red Book remains uranium resources, production and demand, Uranium Group members have also produced volumes in recent years on environmental activities and remediation of uranium mining facilities. The most recently published Red Book noted that the current uranium resource base is adequate to meet future projected requirements, regardless of the role that nuclear plays in the future. However, questions remain as to whether these resources can be developed within the timeframe required to meet future demand. While uranium geologists and miners have demonstrated an ability to locate and develop economically attractive uranium deposits to meet market requirements in a timely fashion in the past, the difference today is the length of time that it takes to permit and develop uranium mines in many jurisdictions.

1. Introduction

In the early 1960s, when commercial applications of nuclear energy to generate electricity were just beginning, a group of experts from national atomic energy organizations was convened by the Organisation for Economic Co-operation and Development (OECD) to evaluate uranium resources in an economic perspective, under the auspices of the European Nuclear Energy Agency. This group of experts, geologists, mining engineers, economists, nuclear engineers and other professionals became known as the Uranium Group.

Reports prepared by the Uranium Group, which are based on data submitted by national authorities, are published roughly biennially under the title "Uranium: Resources, Production and Demand", more commonly known as the **"**Red Book.**"** The first Red Book was published 1965 as a thin booklet. Since then, it has steadily grown as the number of countries interested in participating has grown. The 20th edition published in 2004, reflected this growth in interest and scope as it spanned 288 pages [1].

Until the end of the 1980s, the Uranium Group was comprised mainly of experts from the Western World and did not include representation from the former Soviet Union and "Eastern Block" countries. Hence the information compiled was somewhat limited in geographic coverage. However, in 1991, the Uranium Group moved toward a truly global assessment when a number of experts from the former Eastern Block countries joined the Group and began to contribute data on uranium resources, production and demand. In 1996, coverage was further broadened when International Atomic Energy Agency (IAEA) member states became full participating members and the Uranium Group was reorganized as the Joint NEA-IAEA Uranium Group.

All Uranium Group members are formerly appointed by their government following an established protocol. The Group meets roughly three times every two years to facilitate the biennial publication of the Red Book and exchange information on global developments. In a publication year like 2005, two meetings, one each in Vienna and Paris, are held to compile, review and edit the contents of the upcoming publication. A single meeting, typically hosted by a member country, is often held every second year to update Group members on recent developments and to provide the opportunity for members to view first-hand uranium production facilities in the host country. Recent meetings in these non-publication years have been held in Brazil (2000), China (2002) and the Czech Republic (2004).

The Red Book not only contains information on the worldwide status of uranium resources and production, but also compiles and summarizes information on secondary sources of supply as well as demand for uranium to generate electricity. Since information collected from government-authorized organisations provides the basis for the publication, the content reflects a view of uranium supply and demand that is not directly influenced by commercial interests. As a result, the Red Book is utilized as an authoritative reference in libraries and government organizations around the world. It is also used as a reference by industry-sponsored publications for the mining industry and/or other private nuclear companies [2].

The purpose of this paper is to provide an update of recent activities of the Uranium Group, highlight some points emerging from the ongoing review of information contained in the 20 editions of the Red Book published to date and review the most recently published Red Book information on uranium supply and demand.

2. Recent activities

In addition to publishing the Red Book every two years, subgroups of the Uranium Group have produced two volumes in recent years. Published in 1999, "Environmental Activities in Uranium Mining and Milling" [3] reports information from 29 countries on a variety of topics, including environmental impact assessment, emissions to air and water, work environment, radiation safety, waste handling and disposal, mine and mill decommissioning and site restoration, and the regulation of these activities. Published in 2002, "Environmental Remediation of World Uranium Production Facilities" [4] summarizes issues and practices in the remediation of uranium production facilities and provides an overview of activities and plans in 22 countries. These two publications demonstrate the ability of the Uranium Group to draw upon member's expertise to produce volumes of topical interest.

Presently, the Uranium Group is engaged in a project called the "Red Book Retrospective," which is designed to retrieve and analyze historical data from the 20 editions of the Red Book published between 1965 and 2004. The analysis is designed to review a variety of subjects including; exploration activities and expenditures, resource estimates, production (including production centre ownership and employment), short-term production capability, installed capacity and uranium requirements, supply and demand relationships, price, environmental aspects, thorium resources and uranium stocks. It is anticipated that the final report generated from this exercise will provide insights into past experience and allow an assessment of a number of areas, including; the accuracy of supply and demand forecasts, the level of investment required to discover additional resources, the time required to bring resources into production, the accuracy of resource definition compared to mine production, and other analyses. It will also provide a complete and consise set of data encompassing all of the 20 publications.

3. Resources and production

Based on existing international systems for the classification of mineral resources, the Uranium Group established in 1965 a classification scheme for conventional uranium resources according to their degree of confidence in the resource estimates and on their costs of recovery [5]. Conventional uranium resources (i.e., those that have an established history of production where uranium is a primary product, co-product, or an important by-product), were the original focus of the resource

assessment and remain so today, although details of the classification system have been modified a number of times over the decades.

Conventional resources were subsequently divided into three categories, according to the degree of confidence of the estimates:

Reasonably Assured Resources (RAR)
Estimated Additional Resources (EAR)
Speculative Resources (SR)

The category SR refers to conventional resources not yet discovered or inferred from preliminary data, but are estimated to a low degree of confidence or are believed to exist, based on geological evidence. Under special circumstances, the Uranium Group has also compiled estimates of unconventional resources, for example those contained as by-products or occurrences of very low grade. In cases where uranium is an economically important co-product, such as quartz pebble deposits with gold, or hematite breccia complex deposits with copper and gold, these occurrences have traditionally been classified as conventional deposits.

The classification of uranium resources according to their cost of extraction is unique in the practice of mineral resource evaluation. For all other minerals, reserves comprise that part of the overall resources that are currently economically competitive, whereas for uranium, costs of extraction are fully embodied in the resource estimate. The continuous refinement of resource evaluation by the Uranium Group means that resource estimates published in the Red Book constitute the best estimate at the time of publication.

These resource categories have been well established in the literature and are familiar to experts in the field. By including cost as a fundamental component of the categorization scheme, uranium resource estimates tend to be among the best mineral commodity evaluations available. The Uranium Group has not only facilitated the consistent application of these terms and the methods used to categorize resources in a number of countries, but has been active in evaluating the categorization scheme in light of efforts by other organizations to develop other classification schemes, such as the proposed United Nations Framework Classification (UNFC).

For the 2005 edition of the Red Book the Uranium Group has revised the title of several of the resource categories to bring them more in line with common usage in many member countries and to make it easier to align the Uranium Group classification system with the UNFC. EAR category I is now called Inferred Resources and EAR category II is now labelled Prognosticated Resources.

During the period from 1965 to the early 1990s, Red Book resource assessments by the Uranium Group, which did not include data from the former Soviet Union and Eastern Block countries, estimated RAR at <US $80/kg U in the range between 1.1 and 1.8 million U (an average of about 1.6 million t U). Since 1993, when a complete assessment of resources from almost all countries worldwide became possible, RAR at <US $80/kg has averaged about 2.2 million t U and has displayed a remarkably low variation of some 0.1 million t U. A more complete picture of uranium availability that includes resources in categories beyond RAR recoverable < US $80/kg U increases the total conventional resource base (i.e. RAR, EAR I, EAR II and SR) to around 15 million t U [1].

Peak uranium production years occurred in the period from 1950 to 1970 when world annual production exceeded 70 000 t U. Production remained well above civil requirements until the late 1980s, but has since declined to less than about 60% of civil requirements. The large amount of uranium accumulated in these early years of over-production resulted in stockpiles of uranium in various forms (natural uranium, enriched uranium, depleted uranium tails and reprocessed uranium). As a consequence of these stockpiles and other pressures, uranium prices have remained at low levels, dropping to a spot price low of US $7.10/lb U_3O_8 in late 2000. This lengthy period of low prices (from the early 1980s to 2000) resulted in a decline of annual uranium production to less than 40 000 t U since about 1990. However, given that since the mid 1960s resource levels have remained relatively

constant, despite the mining of over 2 million t U, it can be concluded that depletion of economically attractive resources by production has essentially been balanced by the discovery of new resources [6].

4. Exploration

The availability of low to medium cost resources has been maintained through considerable uranium exploration efforts, with an emphasis on the exploration of extensions of known deposits and nearby areas with comparable geology, supplemented by the exploration of virgin areas and the application of new geological concepts. Global exploration expenditures have been compiled by the Uranium Group since early in the history of the Red Book, and an analysis of exploration efforts documented in previous Red Books is a component of the ongoing Red Book Retrospective project [7]. Up to 2003, total expenditures of more than US $8 billion (dollars in the year of assessment) have been reported, even though expenditures from the former Soviet Union and Eastern Block countries have only been reported since 1990.

From 1970 through 1974 exploration expenditures (Fig. 1) were low as a result of soft market. Beginning in 1975, expenditures rose rapidly to a historical high of US $756 million in 1979 in response to rapidly increasing uranium prices.

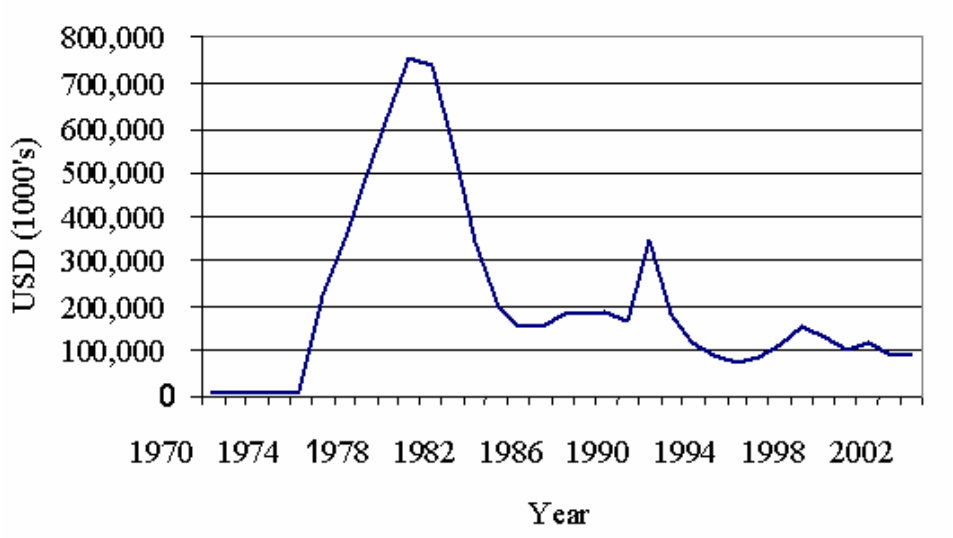

FIG. 1. Uranium exploration expenditures.

With the price for uranium declining thereafter, uranium exploration expenditures began a downward trend that began in 1980 and continued through 2000. The brief spike around 1990 is simply the result of the inclusion of data from the former Soviet Union and Eastern Block countries for the first time.

With the end of the Cold War in 1989, large stocks of uranium began to be made available in the commercial market and projections of nuclear capacity changed dramatically due to the world economic slowdown and heightened public concern about nuclear power. These factors maintained downward pressure on uranium prices, that in turn limited uranium exploration activity. As a result, no new discoveries have been made in virgin territory since unconformity-related deposits in the Athabasca Basin were identified in the early 1980s. Since 2002 there has been a dramatic increase in uranium price (on 30 May 2005, the spot price was listed as US $29.00/lb U_3O_8) and exploration expenditures are on the rise. This increased exploration can be expected to lead to the discovery of additional uranium deposits of economic interest.

5. Supply and demand

The Red Book in recent years has typically included a high and low case forecast for world uranium requirements based on country reports of nuclear development plans. This is compared to forecast mine production figures based on low-cost resource availability along with data on secondary sources

of uranium provided in country reports. Together, this information is used to develop a summary of the anticipated supply – demand relationship some 20 years into the future.

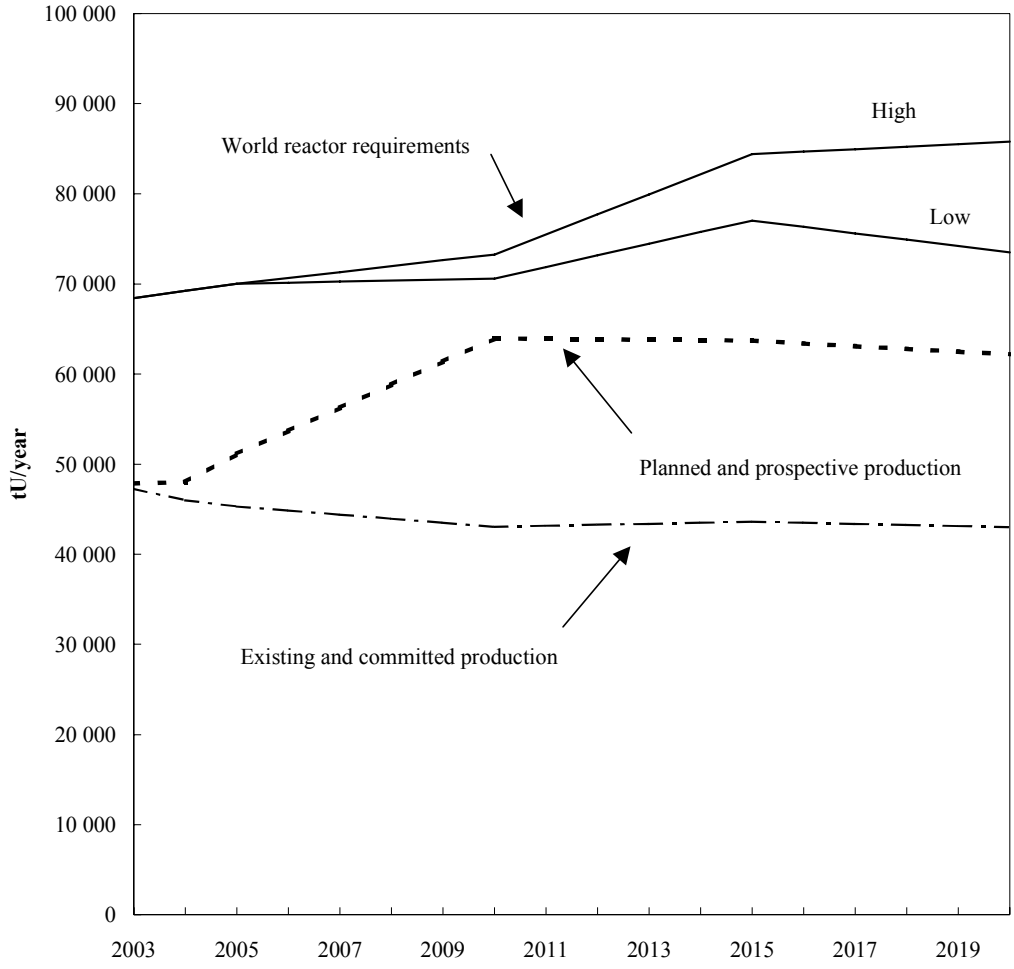

*FIG. 2. Annual world uranium production capability through 2020 compared with projected world reactor requirements.**

*Includes all Existing, Committed, Planned and Prospective production centres supported by RAR and EAR-I recoverable at a cost of <US $80/kg U.

In 2003 edition of the Red Book [1], world reactor-related uranium requirements by the year 2020 were projected to increase to 73 495 t U in the low case and to 85 780 t U in the high case, representing about 10% and 28% increases respectively, compared to the 60 725 t U required in 2002. In contrast to other regions, requirements in North America and Western Europe/Scandinavia were expected to either remain fairly constant or to decline slightly through the year 2020. Uranium requirement increases were anticipated to be largest in Eastern Asia, where increases in nuclear capacity were expected to almost double the 2002 uranium needs in that region by the year 2020.

Low-cost (US $ < 40/kg U) total uranium production capability (considering all existing, committed, planned and prospective production centres) was expected to be adequate to cover between 52% and 58% of the high and low case requirements between 2010 and 2020, respectively. If resources recoverable at between US $40-80/kg U are included, total production capability in 2020 will still only satisfy between 73% and 85% of the high and low case requirements, respectively (Fig. 2). Considering that production rarely attains 100% of capacity, this indicates that significant additional production capability and/or additional secondary supply would be needed to fill the potential production shortfall indicated in these projections. After 2020, when secondary sources of uranium are expected to decline in availability, reactor requirements will have to be increasingly met by primary

production. Therefore, primary production capability will need to be increased by expanding existing production centres, opening new production centres, or both.

Table I. Key dates in the development of selected mines

Country	Deposit/Mine	Exploration begins	Discovery of deposit	Beginning of production
Australia	Beverley	1968	1970	2000
Australia	Honeymoon	1968	1972	not yet announced
Australia	Jabiluka	l968	1971	not yet announced
Australia	Olympic Dam	early-1970's	1976	1988
Australia	Ranger	1968	1969	1981
Brazil	Lagoa Real	1974	1976	2000
Canada	Cigar Lake	1969	1981	2007
Canada	Key Lake	1968	Gaertner: 1975 Deilmann: 1976	Gaertner: 1983 Deilmann: 1989
Canada	McArthur River	1981	1988	1999
Canada	McClean Lake	1974	1979	1995
Kazakhstan	Inkay	1976	1979	2001
Kazakhstan	Kanzhugan	1972	1974	1982
Kazakhstan	Mynkuduk	1973	1975	1987
Kazakhstan	Uvanas	1963	1969	1977
Niger	Akouta	1956	1972	1978
Niger	Arlit	1956	1965	1970

An important consideration in evaluating future supply and demand is the time required to discover and develop new uranium production capability. The lead-time for the discovery and development of new uranium production facilities has historically been on the order of one to two decades, as indicated in Table I.

A variety of factors have contributed to these time lags, including investment decisions and technical difficulties. However, increasingly stringent regulatory requirements, combined with increasing attention to environmental concerns, have lengthened uranium mine development times in many jurisdictions. Lead times in the order of 10 –20 yrs or more have become commonplace in many countries since the 1980s. Notwithstanding the variety of causes, these long lead times underscore the importance of making decisions to pursue new production capabilities well in advance of any supply shortfall.

As demonstrated in the past, mining companies supported by government organizations have been able to cover increasing requirements when necessary. Meeting future requirements, in light of mine development times now typical of many jurisdictions, will likely require a combination of timely investment, vigorous exploration efforts, favourable political and economic conditions, and continued efforts to develop and implement environmentally sustainable mining practices.

6. Conclusion

Although efforts to meet the increasing regulatory burden with respect to health, safety and the environment have added to the cost of production, a review of availability of low-cost resources documented in the Red Book shows that the industry has been capable of maintaining a very large low-cost resource base despite the production of over 2 million t U and the development of more stringent and time consuming regulatory requirements.

In terms of current and future production centres, however, there remain concerns about the global uranium supply and demand relationship. A lengthy regime of low prices has resulted in the closure of higher cost production facilities and the ability to rapidly increase production is limited. With the decline of global inventories, there is an emerging understanding that new uranium production centres

will need to be brought on-line in a timely fashion. However, lead times for bringing resources into production are significant. The challenge to the industry is therefore to continue to meet demanding regulatory requirements and, at the same time, future market demand. Although sufficient uranium resources exist to meet energy requirements at current and increased demand levels well into the future, developing the full potential of these resources will require timely decisions and considerable resources.

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Emerging trend of uranium mining
The Indian scenario

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Abstract. From the modest beginning in 1948, the atomic energy programme of India has grown to vast dimensions with mosaic of many interrelated programmes. The uranium ore mining and processing industry of the country began at Jaduguda in 1968. It has made a very impressive growth during these years with four operating mines and meeting the entire fuel requirement of the country. The country now has a definite plan for multi-phase expansion of the nuclear power programme, self-reliance of raw materials being the basic drive. The uranium mining industry is fully geared up to meet the challenge of uranium fuel demand by undertaking uranium mining and processing activity progressively in line with the requirement of fuel. Several new uranium ore mining projects are in pipeline for execution. The technology of mining, processing and tailings disposal has also undergone improvement absorbing global advancements in these fields.

1. Introduction

Soon after independence, with the formation of Atomic Energy Commission in 1948 India made a humble beginning of its inspiring atomic energy programme. Consequent to this development, it was felt that the country must have indigenous resources of basic raw materials such as uranium, thorium etc. A group called Rare Metal Survey Unit (later on renamed as Atomic Minerals Directorate for Exploration and Research) was formed by the Government of India to locate good uranium deposits in the country. During that period, the emphasis of search was laid on the existing mineral belts and geologically favourable areas of the sub-continent. Association of uranium with copper and gold was already known in some parts of the world. On this analogy, known copper and gold provinces of the country were extensively investigated. The pioneering work of the first group of geologists, brought to light many uranium occurrences in Singhbhum Thrust belt in the eastern part of the country and soon it became evident that this belt holds the potential for commercial uranium mining operations.

2. Uranium deposits of India

Jaduguda in Singhbhum Thrust Belt (in the state of Jharkhand, formerly part of Bihar) is the first uranium deposit to be discovered in the country in 1951. The Singhbhum Thrust Belt (also known as Singhbhum Copper belt or Singhbhum shear Zone) is a zone of intense shearing and deep tectonization with less than 1km width and known for a number of copper deposits with associated nickel, molybdenum, bismuth, gold, silver etc. It extends in the shape of an arc for a length of about 160 km.

This discovery of uranium at Jaduguda in this belt paved the way for intensive exploration work and soon a few more deposits were brought to light in this area. Some of these deposits like Bhatin, Narwapahar and Turamdih are well known uranium mines of the country. other deposits like Bagjata, Banduhurang and Mohuldih are being taken up for commercial mining operations. Some of the other areas like Garadih, Kanyaluka, Nimdih and Nandup in this belt are also known to contain limited reserves with poor grades [1].

Apart from discoveries in the Singhbhum Thrust Belt, several uranium occurrences have also been found in Cuddapah basin of Andhra Pradesh. These include Lambapur-Peddagattu, Chitrial, Kuppunuru, Tumallapalle, Rachakuntapalle which have significantly contributed towards the uranium

reserve base of India. In the Mahadek basin of Meghalaya in North-Eastern part of the country, sandsyone type uranium deposits like Domiasiat, Wahkhyn, Mawsynram provide near-surface flat orebodies amenable to commercial operations. Other areas in Rajsthan, Karnataka and Chattishgarh hold promise for developing into some major deposits (Fig.1).

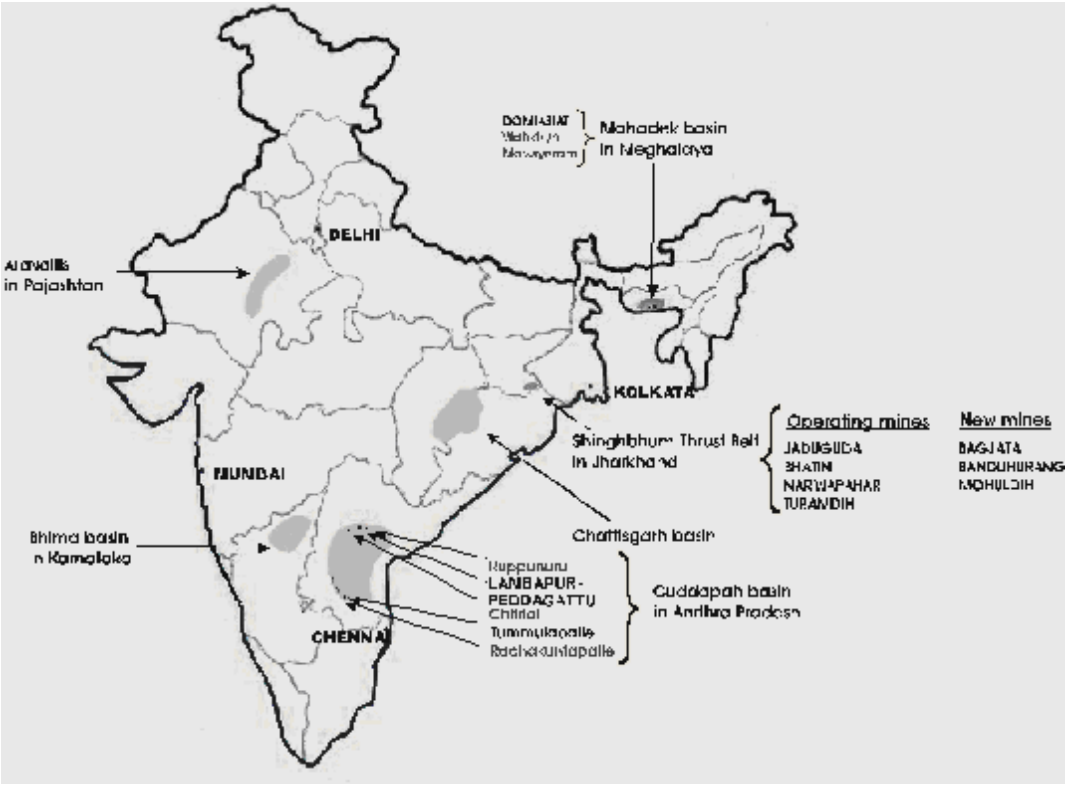

FIG. 1. Major uranium provinces of India.

3. Uranium mining in India

The uranium mining in India made an exciting beginning with the formation of Uranium Corporation of India Ltd. (UCIL) in 1967 under the Department of Atomic Energy. Since then, the uranium industry of the country has recorded phenomenal growth in production and up-gradation of technology. The corporation launched its operation with the commissioning of an underground mine and ore processing plant at Jaduguda (1968). Subsequently, underground mines at Bhatin (1987), Narwapahar (1995) and Turamdih (2003) were commissioned. All these units are within 25 km from Jaduguda in the state of Jharkhand. The process plant at Jaduguda was progressively expanded embracing newer technologies to treat additional ore generated from the new mines.

Keeping in view the nation's endeavour to expand nuclear energy infrastructure (20 000 MWe by 2020 AD from the present capacity of 2 770 MWe), new uranium mines are being opened by UCIL not only in the Singhbhum Thrust Belt of Jharkhand but also in other parts of the country.

3.1. Operating mines

Jaduguda Mine: Jaduguda is the first mine in the country to produce uranium ore in a commercial scale. In this deposit, two parallel lodes extend from surface up to a depth of 905 m, which may also persist deeper. The mineralization is structurally controlled being confined to shears. The entry into the mine is through a vertical shaft of 640 m deep, which was sunk in two stages - from surface to 315 m and then from 315 m to 640 m. The mine has been further deepened by sinking an underground vertical shaft from a depth of 555 m to 905 m. Both the shafts are equipped with two tower mounted multi-rope friction winders - the Cage winder and the Skip winder. Double deck cages are used for movement of men and material and for hoisting of waste rock. Skips with a payload of 5 tonne are

used for hoisting of ore. Levels are generally developed at vertical intervals of 65 meters. The principal stoping method adopted in Jaduguda Mine is horizontal cut-and-fill using de-slimed mill tailing as the fill. Jaduguda mine is presently the deepest operating mine of the country [2].

Bhatin Mine: Bhatin is a small uranium deposit situated 3 km west of Jaduguda. Geological settings, mineral assemblages and other host rock characteristics in this deposit are similar to those of Jadugdua deposit. The mine is now 215 m deep. The entry into the mine is through adits. The lower levels are accessed by two principal winzes and are equipped with double drum winders with provision for man winding. The levels are developed at 50 m interval. The stoping method is similar to that of Jaduguda. As the ore body is narrow, only pneumatic equipment are used for stoping and development work. Ore from Bhatin mine is transported by road to Jaduguda for processing and the de-slimed tailings of Jaduguda mill is sent back for mine back-filling. Mine deepening at Bhatin has now been taken up to create additional production levels.

Narwapahar Mine: It is a large deposit located 12 km west of Jaduguda. This mine was commissioned in 1995. A 7^0 decline has been developed as entry to the mine in the footwall side of the ore body through which large machinery move underground. From the decline, ramps are developed as entry to the stopes at different elevations, which facilitates the movement of twin-boom drill jumbo, low-profile-dump-truck, service truck, passenger carrier, low profile grader, scissor-lift etc. This system of mining has effected early commissioning of the mine with high productivity and low mining cost. It has also provided the flexibility to adopt different stoping methods that becomes suitable due to the variations in width and inclination of the ore lenses. Movement of men and hoisting of ore from deeper levels is done through a vertical shaft sunk up to a depth of 355 m. Cut-and-fill is the principal stoping method adopted in Narwapahar mine. Ore from this mine is sent to Jaduguda by road for processing. The de-slimed mill tailings of Jauguda mill and the waste generated from the mine are used as the filling material. The split ventilation system, micro-processor based bulk ore assaying system with automatic grade estimation and subsequent computation are some distinctive features in this mine [3].

Turamdih Mine: Turamdih uranium deposit is located about 24 km west of Jaduguda. The entry into the mine has been established through a 8^0 decline which provides facilities for using trackless mining equipment like passenger carrier, drill jumbo, low-profile dump truck etc. At a depth of 70 m (first level), the ore body has been accessed from the decline by a cross-cut. Drives are being developed following the contacts of ore body. Ventilation shafts have been sunk in line with the requirement of adequate fresh air. The development faces are ventilated by auxiliary ventilation system using auxiliary fans and flexible ducts. A vertical shaft of 5 m diameter is being sunk from surface up to a depth 250 m with facilities for ore hoisting and movement of men and material. The ore from this mine will be processed in the new plant, which is under construction near the mine site at Turamdih.

3.2. New mines in the state of Jharkhand

Banduhurang Mine: This deposit is the western extension of Turamdih mineralization, where part of the ore body outcrops at surface. It is a low-grade, large tonnage deposit. After the initial evaluation, the techniques of computerised ore body modeling and mine planning using SURPAC software was carried out. Open-pit mining method has been considered as the most favourable option. The pit limits were optimised using WHITTLE software and the layout of the mine as been finalized with all finer details. The pit will attain the ultimate depth of 160 m with ore to overburden ratio of 1:2.7. Ultimate pit slope has been designed for 47^0 up to a depth of 120 m and 44^0 below 120 m. The proposed mining at Banduhurang will be a conventional opencast mine using excavator-dumper combination. Careful selection of earth moving equipment has been done to maintain ore benches of 6m height and over burden/waste benches of 6 m/12 m height. A code of practice has been formulated for control of run-off-mine quality for this low-grade deposit with the introduction of bio-informatics. The pit will also undergo simultaneous back-filling with the over-burden (Fig. 2). The work on development of this deposit will start soon. The ore of Banduhurang mine will be processed in the new plant at Turamdih.

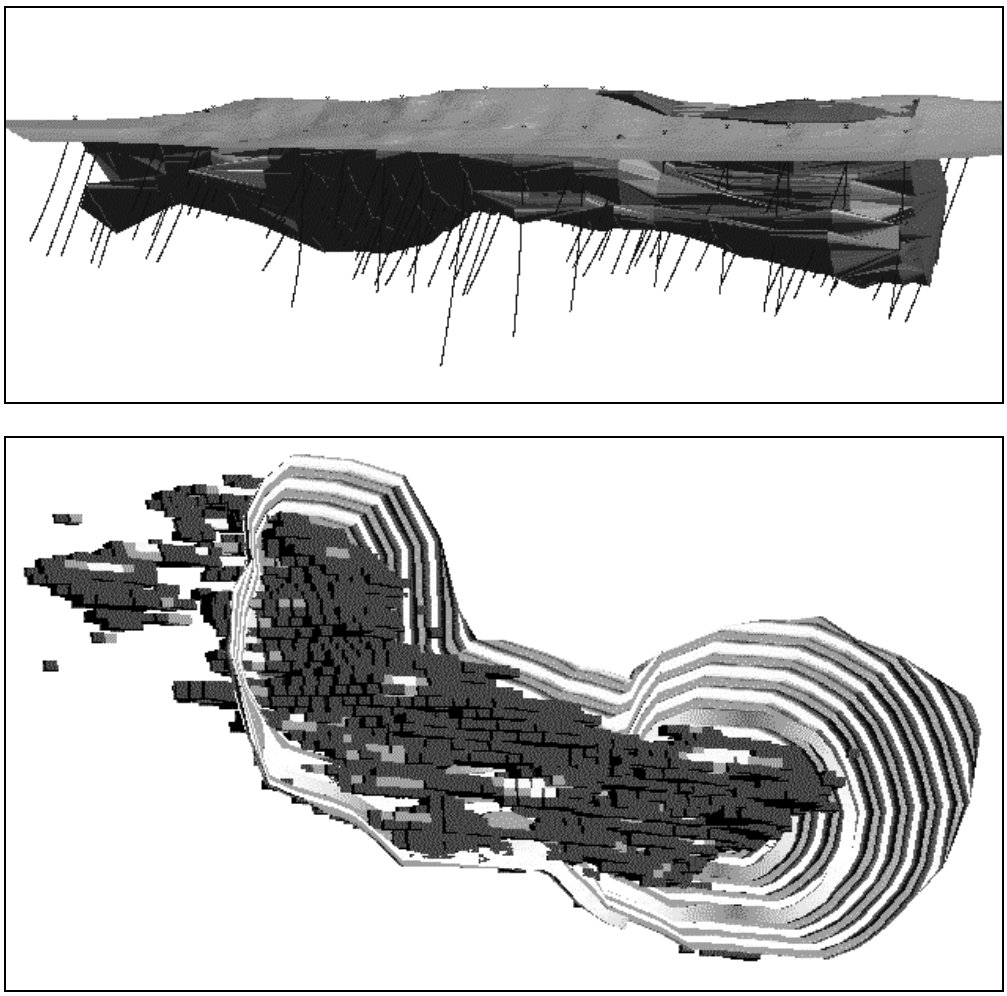

FIG. 2. Ore body model of Banduhurang using SURPAC software & Pit optimization at Banduhurang using WHITTLE software.

Bagjata Mine: This deposit is about 30 km south-east of Jaduguda, where the ore body extends like a thin vein up to a depth of 600 m. This mine is being developed in the first stage up to 300 m. It will become operational soon with a 7^0 decline as the access into the mine (Fig.3). The levels will be developed at 50 m interval. The method of stoping will be cut-and-fill with cross-cuts/ramps from decline as the entry to stopes. Moderate level of mechanisation with the deployment of single-boom drill jumbo, LHD, LPDT etc is proposed in this mine. A vertical shaft initially up to a depth of 375 m will be sunk to provide access of men and material to deeper levels. The ore of Bagjata will be processed in Jaduguda plant and the de-slimed mill tailings from Jaduguda will be sent to Bagjata for back-filling.

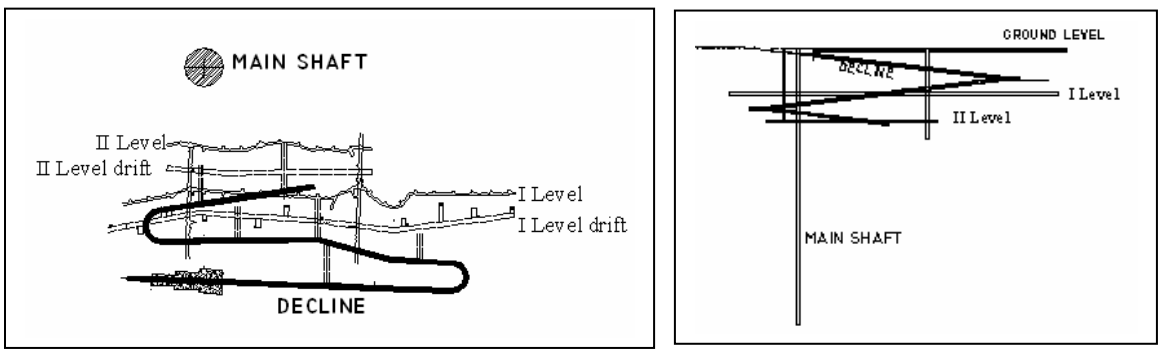

FIG. 3. Plan showing Bagjata mine layout & Section showing Bagjata mine layout.

Mohuldih Mine: This deposit is located about 27 km west of Jaduguda, about 3 km west of proposed Banduhurang open cast mine. The ore body extends like a thin vein up to a depth of 320 m. This deposit will also be opened with a decline as the access and a vertical shaft up to a depth of 355 m will be used for men and material transport. The levels will be developed at 50 m interval. Trackless equipment will be employed in this mine. The principal method of stoping will be cut-and-fill. The ore of Mohuldih will be treated in the Turamdih plant.

3.3. New mines in the state of Andhra Pradesh

Lambapur-Peddagattu Mine: The deposits in this region fall along the unconformity contacts of underlying granites and overlying quartzites. The flat orebody with varying thickness is spread over five distinct blocks and occurring within a depth of 15 m to 60 m. Considering the nature and depth of occurrence of ore lenses, one opencast mine and three underground mines have been planned in this region. The open pit mine will extend only up to a depth of 15 m with ore to overburden ratio of 1:4.2. The underground mines will be about 70 m deep accessed by declines. Room-and-pillar stoping method will be followed using low profile drilling machine, LHD and LPDT. Ore will be hoisted to the surface through central conveyor and transported by road to the plant.

3.4. New mines in the state of Meghalaya

Domiasiat Mine: This deposit with large and good grade uranium reserve is hosted in a thick pile of sandstone within a depth of about 40m with underlying granite. A small rivulet flowing in the area divides the deposit into two separate mining blocks. Both the blocks – Killung and Rangam will be mined by open pit mining method up to a depth of 45 m with ore to overburden ratio of 1:6.7. The pit will be concurrently backfilled with mill tailings and overburden (Fig. 4). Since the deposit falls in a very high rainfall area, special measures are planned for mine dewatering and the safe disposal of water to the aquatic environment.

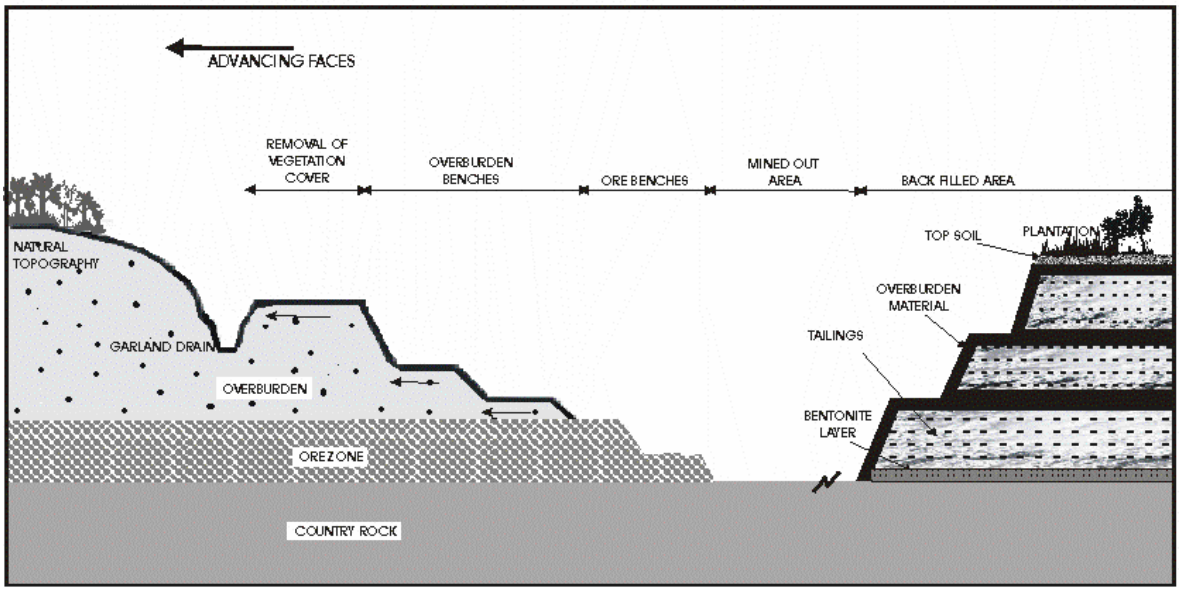

FIG. 4. Schematic section of Domiasiat pit.

3.5. Prospective mines

Pre mining activities are also set to begin in a few more deposits where the exploration is in an advanced stage and sufficient reserves have already been identified.

Tummalapalle uranium deposit: The large uranium reserve discovered in the Proterozoic Cuddapah basin in the state of Andhra Pradesh is hosted by carbonate rock formations. The strata bound ore body has been delineated up to a depth of 275 m extending like thin veins from surface. The orebody has

fairly uniform dip and width. Underground exploratory mining work in this deposit has been completed confirming the configuration of ore body. The ore recovered from the exploratory mine is being used for various laboratory and pilot plant studies.

Rohili uranium deposit: This area in the state of Rajsthan is under advanced stage of detailed exploration. The steeply dipping ore body in the albitite host rock already identified up to a depth of 100 m holds the promise of a deep underground mine. Pre-project activities in this area will start soon.

4. Uranium ore processing in India

The uranium ore processing facility is an integral part of uranium mining industry in India. The upsurge in mining activity has therefore necessitated the expansion of existing plant and construction of a few more new ore processing plants to treat the ore generated from different mines.

4.1. Operating plant

Jaduguda: The only operating plant of the country at Jaduguda in operation since 1968, is based on acid leaching technology. The process know-how has been indigenously developed and upgraded time-to-time keeping in pace with the global developments of uranium technology. Jaduguda plant has also been expanded twice, nearly doubling the original processing capacity to treat the ore of Bhatin and Narwapahar mines. In the coming years, ore of Bagjata mine will be fed to this plant.

The ore from different mines (upto 200 mm size) are crushed in two stages, primary jaw crusher and secondary cone crusher. The fine ore is wet ground in grinding mills in two stages for further size reduction. This ground ore in the form of slurry is thickened and leached in leaching pachucas for preferential solubilization of the uranium from solids under controlled pH and temperature conditions. The leached liquor is then filtered in which uranyl ions get absorbed in the resin. This is further eluted and treated with magnesia to get magnesium di-uranate or yellow cake. The magnesium di-uranate is then filtered in belt filter to remove soluble impurities, dried in a spray drier and finally packed in drums for onward dispatch for further processing. The plant has several automated process control mechanism and on-line monitoring system specially introduced during second phase of expansion. PLC based control system for ion exchange, DCS based on-line control system for control monitoring of pH in leaching pachucas, precipitation tanks and tailings plant, XRF based on-line analyzer for monitoring of uranium content in ion exchange, close circuit TV are some of the distinctive features in Jaduguda plant.

4.2. New plants

Turamdih: A new plant at Turamdih is being set-up to treat the ore planned to be produced from Turamdih and Banduhurang mines. The flowsheet of this plant is similar to that of Jaduguda. However, taking account of developments in hydrometallurgy/processing technology worldwide, some efficient equipment like apron feeders, particle size monitors, horizontal belt filter, pressure filter etc are being proposed in this plant. It has also been planned to encompass a very high degree of instrumentation minimizing human interference. PLC based control system shall be based on Man Machine Interface (MMI) with remote input-output and shall have facility to monitor process parameters, status of drives, control of relevant process variables and operate any equipment from plant graphics. Expansion of Turamdih plant to the higher level of processing capacity will be taken up with the progress of mine construction work at Mohuldih.

Seripalli: This plant has been planned in Andhra Pradesh to treat the ore of Lambapur-Peddagattu mines. The plant site is about 54 km away from Lambapur area as there are some environmentally sensitive places around the mine site. The design philosophy of this plant is similar to the processing practices proposed at Turamidh plant. Latest equipment and degree of instrumentation similar to the ones proposed at Turamdih, will also be adopted in Seripalli plant. However, the sizing of these equipment and provisions of flexibility to allow alternate processing technology to accommodate unexpected ore characteristics will be the vital aspects for Seripalli plant.

Domiasiat: This plant near the mine site at Domiasiat in Meghalya will be constructed with some modified process technology because of different ore characteristics. The host rock at Domiasiat is moderately friable sandstone, which will be crushed at the pit-head. Followed by conventional grinding in the plant, the thickened slurry of sandstone will undergo two stages of leaching – weak acid (WAL) and strong acid (SAL). Resulting filtrate will be clarified, concentrated in ion-exchange and precipitated along with magnesia as magnesium di-uranate or with hydrogen peroxide as uranium peroxide. The plant will also have PLC based central control system, on-line monitoring and XRF based on-line analysers etc.

4.3. Prospective plant

Tummalapalle: As the host rock of Tummalapalle uranium deposit is siliceous-dolomitic-phosphatic limestone, alkali leaching technology is being proposed to treat this ore. The ore produced during exploratory mining are being utilised for several laboratory and pilot plant studies in order to finalise the process flow-sheet and other parameters. The uranium values are found to be present as very fine to ultra-fine disseminations predominantly in carbonate matrix. In such case, pressure leaching with oxygen as oxidant has been found to be more attractive than conventional leaching with chemical and gaseous oxidants. The proposed flowsheet involves reagent regeneration and includes very fewer number of process steps from grinding to sodium di-uranate precipitation. The alkali-leaching plant at Tummalapalle, after construction, will be the first of its kind in the country.

5. Uranium tailings management in India

The uranium ore in India are generally of low grade, which necessitates production and processing of large quantity of ore. This results in generation of large volume of solid waste and effluent. With greater public awareness of health hazards and stringent environmental guidelines, the management of these tailings (solid and liquid waste) has become a crucial part of emergent uranium mining sector.

5.1. Tailings disposal in mines

The operating underground uranium mines of the country are carefully designed with suitable stoping method (cut-and-fill) to accommodate maximum tailings generated during the ore processing. As the mining work progresses, the void created are sequentially backfilled. In this process about 50% of the de-slimed neutralized tailings are safely disposed in underground. Similar underground disposal will also be followed in case of future underground mines in Singhbhum. The proposed opencast mine at Domiasiat is also being designed to sequentially store uranium tailings as backfill material after artificial lining at the pit bottom (Fig. 5).

5.2. Tailings management on surface

The finer fraction of the neutralized tailings is likely to contain some radio-nuclides and chemical toxins. It is therefore, necessary to make a sound impoundment arrangement of storing these materials on surface separating them from the public domain. In India, two such design criteria are chosen to effectively manage the tailings.

5.3. Wet tailings disposal system

The tailings pond at Jaduguda is designed for this system of impoundment. The tailings in the form of slurry is pumped through pipeline to the pond which has natural high hills on all three sides. The embankment constructed in the fourth side is designed to take the load of entire quantity of ore available in the deposits. The material used in construction of embankment consists of impervious clay towards the upstream, random fill material on the downstream side. The permanent drains have been constructed on all sides to prevent the flow of rain-water into the pond. The decantation wells are strategically placed at the inner periphery of the pond allowing the excess water only to flow out. This water is carried to the effluent treatment plant for necessary processing through a well-laid drainage

system. The tailings pond proposed at Turamdih will also be designed on this philosophy with some improved floor lining to prevent any downward movement of effluent.

5.4. Thickened tailings disposal system

In this method, the tailings which usually contain 20 – 30% solids is thickened in high rate / high density deep thickeners producing a highly viscous slurry (in the form of paste) which can be pumped and deposited in dry stacking area. The paste, because of its high yield stress value spreads all around at a gentle slope and forms a heap. As deposition continues, the heap grows in area and height. At the periphery small dykes are built to contain tailings within the disposal area. Once the desired height is attained, the deposition point is shifted to a nearby suitable location to form an adjacent heap (Fig 5). This kind of deposition technique helps to utilise the stacking area volume to the fullest possible extent. Land requirement is also less in this system than wet disposal method as the tails are deposited above ground level. The tailings pond at Seripalli in Andhra Pradesh will be designed following this method and this will be first such TTD for uranium tailings in the country. Very stringent design criteria are being proposed for this tailings pond with various laboratory inputs.

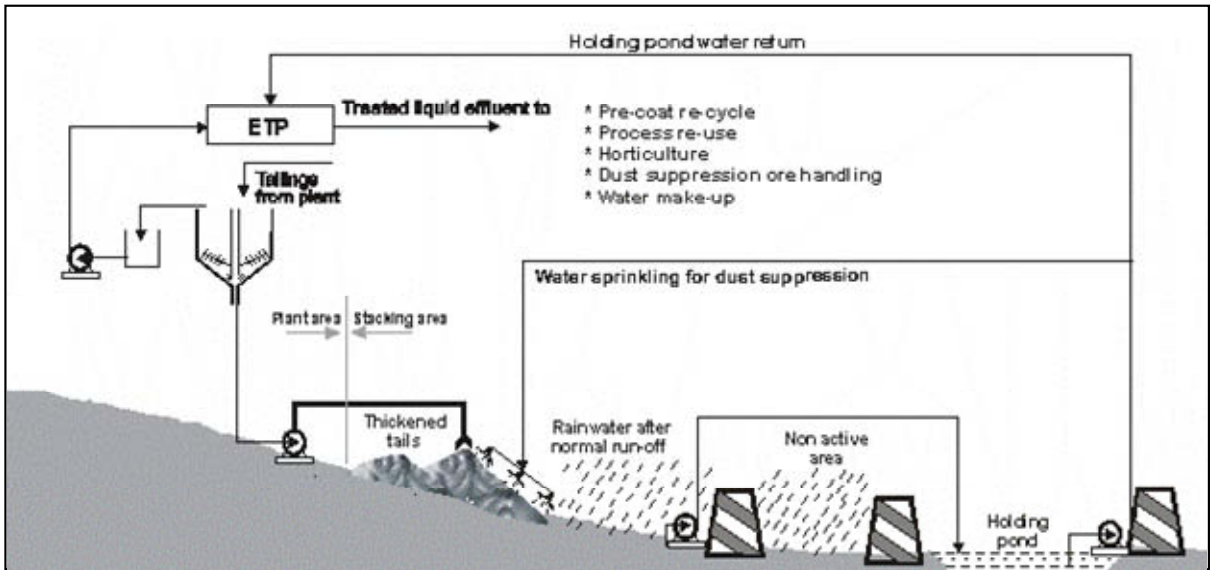

FIG. 5. Thickened tailings disposal system.

6. Challenges and emerging technology

Uranium deposits in India are generally small, lean in tenor and complex in nature of mineralization. With the globalization of Indian economy, it has become imperative to develop these deposits in cost effective and eco-friendly manner assimilating the worldwide developments in science and technology. In order to meet the timely requirement of uranium, the construction activities need to be accelerated. Rising ore production from forthcoming new mines calls for some innovative approach of physical beneficiation of valuable uranium bearing minerals, which will reduce the volume of ore transportation and processing. The available flow-sheet also needs modification for improvement in recovery under different mineralogical conditions. The plants, with a shorter processing route, need to incorporate measures to maximize the re-use of water, high recovery of the product and minimum discharge of effluents. In the field of tailings management, long-term stability of tailings restricting the movement of contaminants, strengthening of embankment system, maximum re-use of effluents and reclamation of the existing ponds are some of the challenging areas for continuous research and improvement. However, rapid progress has been made in some of these areas by absorbing technology through fundamental transformations.

Use of integrated software (survey-geology-mine planning) has helped to quickly establish the configuration of ore body and assess the potential of the deposit. Standard modules of mine layout and

method have been developed with minor variations to accommodate the site-specific geology. Similarly, standard modules and parameters for different processing activities are in place for implementation with site-specific modifications. This has considerably cut down time in planning, award of contracts for construction, drawing up specification for equipment and procurement. Uniformity in procedures for different studies like environmental assessment, feasibility, detailed project report etc has helped to reduce the pre-project period. Standardization of the layout and equipment has brought in significant cost advantage in the field of maintenance management and inventory control.

Mining in India has come a long way from conventional system to trackless mining, progressively emulating and absorbing global technology. In the existing mines, pneumatic equipment are systematically being phased out with the introduction of more energy efficient electro-hydraulic and diesel-hydraulic equipment. New mines are being planned with provision to automate all strenuous mining activities avoiding direct handling of radioactive ore at every stage of operation. Underground ventilation system, strata control measures etc are being simulated before field trial and implementation. The bulk ore assaying system with automatic grade estimation is undergoing continuous improvement. Country's dedicated mining research institutes have identified some of the thrust areas like cutting technology in place of conventional drilling & blasting, use of electronic detonators, environment friendly explosives etc for future development.

Keeping in view the worldwide technological progress in the field of ore processing, some major strides have been taken towards absorbing expertise and adapting cutting-edge technology through radical innovations. A great deal of efforts has already been made to implement precipitation of uranium peroxide ($UO_4.2H_2O$) using hydrogen peroxide in place of magnesium di-uranate. This will prevent co-precipitation of other metals, ensure higher purity in product and control many environment related problems. New plants with simpler and shorter processing route are being envisaged. Use of modern, energy saving and efficient equipment and concept of central control room are expected to be some of the distinctive features of new plants. Resolving the process know-how for alkaline leaching is now the emerging area for research and development, which can make the huge resource of Tummalapalle area exploitable. A dedicated state-of-art facility has been created at Jaduguda to pursue rigorous laboratory investigation/pilot plant studies in line with the above requirements. The research institutes of the country are also actively participating in time-specific projects for finding breakthrough in uranium mineral beneficiation, bio-leaching, bio- beneficiation etc.

Uranium tailings management has attracted enough interest of public and regulatory bodies in the country resulting in wide ranging research and development. The new tailings ponds are being envisaged with sound design features of embankment system and impermeable artificial liner to prevent any downward movement of effluent [4]. Various laboratory studies are being conducted to implement thickened tailings disposal (TTD) system at Seripalli. Remediation of existing tailings ponds at Jaduguda is being taken up on priority. Eco-restoration with suitable soil capping and vegetation are being addressed involving various premier research institutes. Efficacy of microbial leaching of tailings and microbial modifiers are also being looked into. Leachability characteristics of the tailings under different physico-chemical environment, studies pertaining to migration of contaminants into the adjoining environment, modification in tailings texture for minimizing dispersal of radon and its progeny are some of the critical areas for research in new tailings ponds of the country.

7. Future of uranium mining in India

During last five decades, with the increasing need of energy for the accelerated agricultural and industrial growth, the Atomic Energy Programme of our country has gained considerable momentum. The Government is committed to appreciable increase in contribution of nuclear power to the total power generation capacity and it has been felt that a balance mix of hydel, coal and nuclear power is a must for meeting the long-term power requirement. The Department of Atomic Energy accordingly,

has very strategically designed the nuclear power programme of our country and an immediate goal has been set to produce 20 000 MWe of nuclear power by 2020 AD.

Self-reliance in basic raw materials is the dominant paradigm of nuclear power programme of India. Therefore, the growth of uranium industry has shown an extraordinary up-trend during last one decade. The industry is expected to expand further matching with the phenomenal growth of nuclear power generation in the coming years. Apart from supplying the raw material for nuclear fuel, the uranium mining industry in India has a great potential to contribute towards development of infrastructure, mining technology and generate employment opportunity in the nation.

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The recent progress of uranium exploration in China

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Abstract. Since 1990's of last century, China has shifted its prospecting emphasis on in-situ leaching amenable sandstone-hosted uranium deposits instead of hard-rock hosted ones. Taking the newly discovered major sandstone-hosted deposits as examples, this paper gives a brief introduction to the exploration achievements of China in the past more than 10 years and the relevant geo-tectonics of mineralized basins, the lithologic-lithofacies of host formations, the development and distribution of interlayer oxidation zones as well as the basic characteristics of ore-bodies. Meanwhile, a uranium exploration programme for the coming years is simply discussed too according to the national demand.

1. Introduction

In 1980's of last century, China started its constructions of nuclear power plants. The first nuclear power unit was built in 1985 and put into operation in 1991. After that, another 10 units were constructed in succession. Up to now eight of them have been put into commercial operation respectively. The two left expect to be finished construction and put into generation in 2005 too. It means that uranium becomes mainly a raw material to meet the growing need of nuclear power generation and uranium reserves should be strictly evaluated from a commercial viewpoint. As a result, since 1990 China has shifted its prospecting emphasis from hard-rock hosted targets mostly located in south-eastern China, and has focused its exploration in sandstone-hosted uranium deposits in northern China, especially in north-western part. The sandstone targets expect to be amenable by low cost ISL mining. Such strategic shift in emphasis is based upon the regional metallogenetic consideration: the northern China, especially the north-western China, is possibly located within the range of a sandstone-type uranium super-province which extends from Trans-Ural eastwards, passing through Central Asia where Chu Saryssu-Syr Darya-Central Kyzylkum uranium province occurs, and Mongolia, Inner Mongolia into Trans-Baikal.

Since then, several ISL-amenable sandstone-type uranium deposits have been discovered and explored including Kujiltay, Wukulqi and Zajistan deposits in Yili Basin, Shihongtan ore deposit in Turfan-Hami Basin located in Xinjiang Autonomous Region and the newly discovered Zaohuohao deposit within Dongsheng uranium-mineralized area in the North of Ordos Basin located in Inner Mongolia Autonomous Region (Fig. 1). In the meantime, positive exploration results have been achieved in Erlian, Hailar and Junggar basins as well. A series of geological investigations with various scales and specific geophysical surveys have been implemented in other Mesozoic-Cenozoic sedimentary basins distributed in northern China.

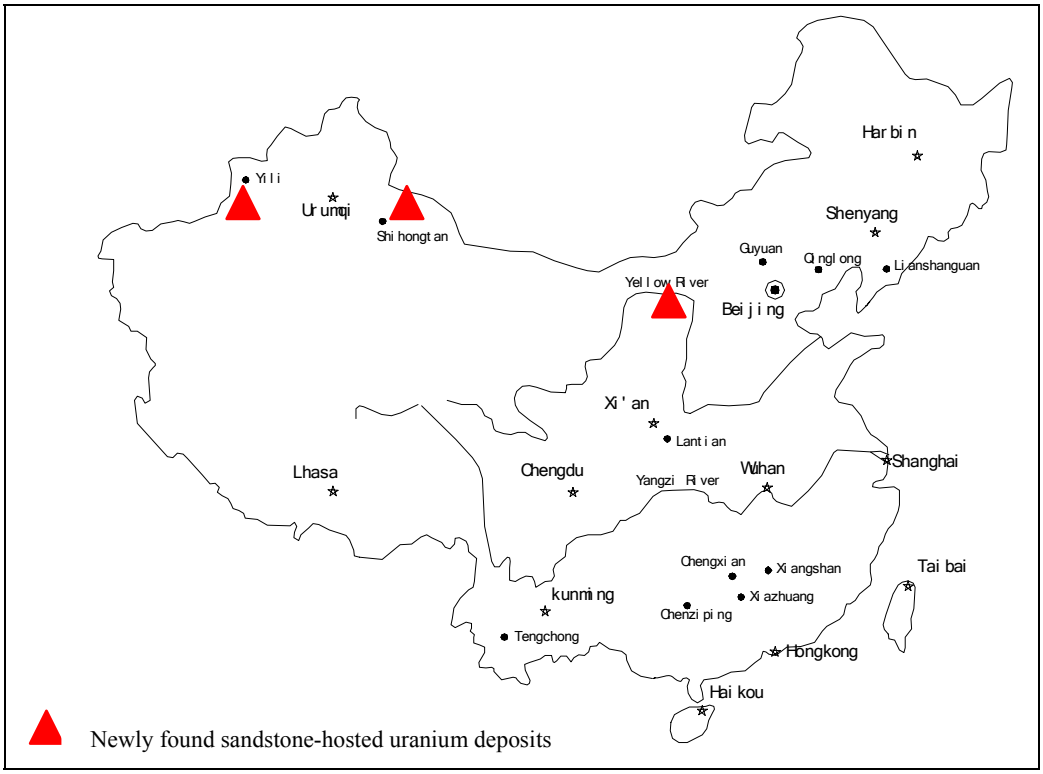

FIG. 1. Map showing the distribution of principal and newly discovered uranium deposits in China.

2. General geological features of the mineralized basins and the discovered ore deposits

2.1. Yili Basin

Yili Basin is a Meso-Cenozoic Intermountain basin situated in the Western Tianshan Fold Belt, belonging to a fault-controlled down-warped basin. And its northern and southern edges are bordered by fault belts. The tectonic movement displays a significant difference between the northern and southern part of the basin. Its northern part belongs to faulting uplift zone and has suffered strong faulting. At the edge of this part the Mesozoic sequences were uplifted to the surface with a big dip angle. The central part of the basin belongs to a depression zone and has received huge thickness of sediments. The southern part is situated in a relatively weak tectonic condition. A slightly tilting slope area exists along the southern margin of the basin. In this slope area, the Meso-Cenozoic sedimentary beds occur as monocline strata dipping at the angle of 6º to 9º. With regard to the southern slope area, it also shows some differences in structure: the western section experienced relatively weak tectonic disturbance, the eastern suffered a relatively strong tectonic influence, while the middle part displays some transitional features. From the west to the east, depressions and uplifting areas occur alternately along the southern margin of Yili Basin, and the ore deposits of Kujiltay, Wukulqi, Zajistan are occurred in the relatively uplifting areas. Apart from the 3 ISL interlayer oxidation type deposits, other two small-sized deposits, called Menqigul and Daladi were also found in this margin and belong to uranium-bearing lignite type (Fig. 2).

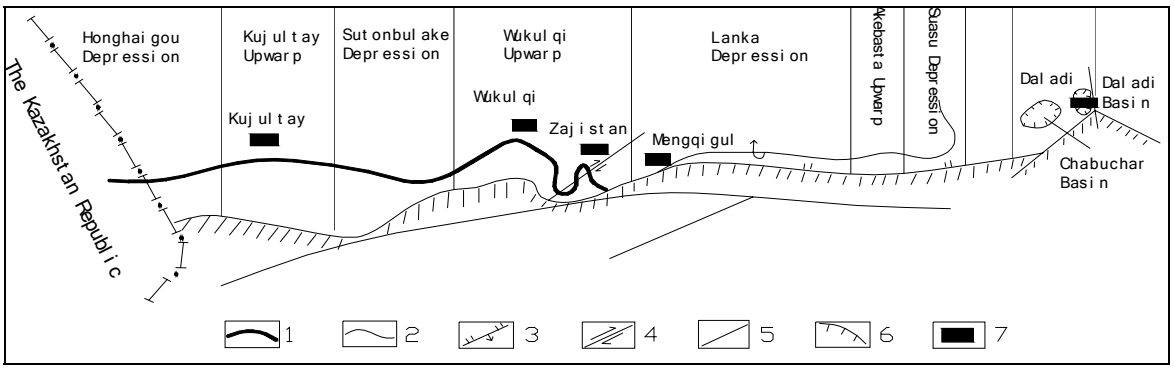

FIG. 2. Sketch structural map of southern margin of Yili Basin.
(1—Outcrop of VIII Coal Seam; 2—Geological Boundary; 3—Reverse Fault; 4--Compressive Strike-slip Fault; 5--Inferred Fault; 6--Eroded Area; 7--Uranium Deposit)

The ore-bearing sequence in Yili Basin is composed of coal-bearing clastic rocks of the Lower-Middle Jurassic Shuixigou Group. The Shuixigou Group sequence is stably distributed along the southern margin, consisting of eight sedimentary cycles and three sections: the lower section including cycle I to IV are formed in the condition of wet alluvial fan lithofacies controlled by braided rivers; the middle section including cycle V and VI belongs to lakeshore-delta lithofacies, and the upper including cycle VII and VIII is characterized by fluvial lithofacies. The oxygen-bearing underground water flows in the direction from the margin to the centre of the basin. Interlayer oxidized zones are found in sandstone beds occurring within all the eight sedimentary cycles and stretch out along the southern margin of the basin. Although all sandstone beds have suffered epigenetic oxidation, the oxidation intensity of sandstone beds within different sedimentary cycles and different locations present a significant difference because of the changes of lithology and underground water hydrodynamic conditions. The interlayer oxidized zones vary in width quite greatly and present in a complicated form. Uranium mineralization occurs within multiple cycles. Economic ore belts of Kujiltay Deposit occur in the sandstone beds of cycle V and cycle I-II of the Shuixigou Group, Wukulqi Deposit in cycle V and cycle VII, and Zajistan Deposit in cycle V.

Although all sandstone beds have suffered epigenetic oxidation, the oxidation intensity of sandstone beds within different sedimentary cycles and different locations present a significant difference because of the changes of lithology and underground water hydrodynamic conditions. The interlayer oxidized zones vary in width quite greatly and present in a complicated form. Uranium mineralization occurs within multiple cycles. Economic ore belts of Kujiltay Deposit occur in the sandstone beds of cycle V and cycle I -II of the Shuixigou Group, Wukulqi Deposit in cycle V and cycle VII, and Zajistan Deposit in cycle V. The ore-bearing rocks consist of pebbly sandstone, medium- and coarse-grained sandstones. Volcanic and granitic debris make up the most portions of fragments in sandstone rocks, and this indicates the proximal feature of sedimentary materials. The shape of ore bodies is commonly in form of roll, tabular and lens, and the roll-shaped is the most important one. Uranium exists in disseminated pitchblende and coffinite, and a small amount of uranium exists in adsorptive disseminated states by organic matters. These deposits display some different geological characteristics (Table I).

2.1.1. Kujiltay deposit

This deposit is located at the Kujiltay Upwarp area situated at the west part of the southern slope of Yili Basin. Stratigraphic sequence of the Shuixigou Group which consists of multi-rhythmic sedimentary beds is well developed in the deposit area, and 8 sedimentary cycles can be easily distinguished from the Shuixigou Group. Uranium ore bodies of the deposit occur in cycle V and cycle I -II in roll shape mainly. The major ore body in cycle I -II is 2.8 km long, 150m to 800 m wide, with the average thickness of 4.18 m, and the ore grade ranges from 0.01% to 0.08%; The major ore body in cycle V is 5.3km long, 250 m to 850 m wide, with the average thickness of 3.7 m, and ore grade varies between 0.01% and 0.06%.

2.1.2. Zajistan deposit

The deposit is located at Wukulqi Upwarp area, the uranium ore bodies occur in cycle Vof Shuixigou Group, also in roll shape. The ore belt is 3 km long, 50 m to 500 m wide, the average thickness is 5.3m, and the ore grade ranges form 0.01% to 0.07%.

2.1.3. Wukulqi deposit

Wukulqi deposit is also located at the Wukulqi Upwarp. The uranium ore belt which occurs in cycle V is distributed in the east part of the deposit, and it is 5km long, 20 m to 560 m wide. The average thickness is 3.18 m with a maximum thickness 7.45 m, and the ore grade varies between 0.013% and 0.075%. Another two ore belts are found in cycle VII in this deposit too. The belt occurring at the lower position is 2 km long, 75 m to 200 m wide, the average thickness is 6.6 m, and the ore grade varies between 0.01% and 0.09%. The belt at the upper position is 1 km long, 20 m to 100 m wide with an average thickness of 4.67 m, and its ore grade varies between 0.01% and 0.08%.

Table I. Comparison of geological characteristics among uranium deposits in the southern margin of Yili Basin

Deposit	Main Geological Features	Ore-bearing Sequence	
		Cycle V in Shuixigou Group	Cycle VII in Shuixigou Group
Kujiltay	Average thickness of sand bed	20 m	16 m
	Oxidized zone	The width of oxidized zone is less than 2 000 m, but at some location it can excess 3000 m.	The width of oxidized zone is about 800-1 000 m.
	Lithology of sandstone	Mainly composed of coarse-medium size sandstone, intermediate-loose cemented.	Mainly composed of coarse-medium size sandstone, intermediate-loose cemented.
	Reduction agent	Abundant.	Average.
	Uranium mineralization	Economic uranium ore bodies.	Mineralized sandstone.
Wukulqi	Average thickness of sand bed	18 m	14 m
	Oxidized zone	The width of oxidized zone is less than 2 000 m, but at some location it can excess 3 000 m.	The width of oxidized zone is about 800 m, rarely excess 1 000 m.
	Lithology of sandstone	Mainly composed of coarse-medium size sandstone, intermediate-loose cemented.	Mainly composed of coarse-medium size sandstone, intermediate-loose cemented.
	Reduction agent	Abundant.	Abundant.
	Uranium mineralization	Economic uranium ore bodies.	Economic uranium ore bodies.
Zajistan	Average thickness of sand bed	19 m	15 m
	Oxidized zone	The width of oxidized zone varies from 2 100 m to 3 100 m.	The width of oxidized zone varies from 800 m to 3 000 m.
	Lithology of sandstone	Mainly composed of pebbly coarse-medium size sandstone.	Coarse sandstone and medium-fine size sandstone.
	Reduction agent	Abundant.	Average.
	Uranium mineralization	Economic uranium ore bodies.	Mineralized sandstone.

2.2. Turpan-Hami basin

Turpan-Hami Basin is situated at the Junggar-Turpan Microplate consisting of the southeast part of the Kazakhstan Plate. It is a big size intracontinental faulting-depression basin. The Lake Aitin Structural Slope is located at the southwest margin of the basin, and the feeding, runoff, and drainage hydrodynamic system of underground water is well developed at the slope. Shihongtan uranium deposit is located at both sides of the Shihongtan nose anticline along the slope.

Similar to the deposits in Yili Basin, the ore-bearing sequence of Shihongtan deposit is also coal-bearing terrigenous clastic rocks of the Lower-Middle Jurassic series. Economic uranium mineralization is mainly discovered in Xishanyao Formation of the Middle Jurassic. The ore-bearing sandstone is formed in a big alluvial fan system and characterized by braided river and delta

lithofacies. There are several beds of sandstone in Xishanyao Formation, and the thickness of a single sandstone bed varies from 5 m to 30 m. These sandstone beds have suffered an extensive epigenetic interlayer oxidation. The oxidation front is distributed in a curved shape in plan, extending in the direction of west to east. Two sandstone beds have been found uranium mineralization within Xishanyao Formation and the ore bodies are proved near the oxidation front and mainly occur in a tabular or roll shape. The width of ore bodies varies from 50 m to 200 m, and the length of ore belts varies from 1 km to 5 km.

The ore-hosted lithology is mainly composed of loose-medium cemented medium to fine-grained sandstone. Uranium exists in an adsorptive form or uranium minerals. Associated elements, such as Mo, Se, Re, Ga and Sc have a significant enrichment in the ore zone. The ore grade varies from 0.01% to 0.3%. Multiple stages of uranium mineralization have been determined in this deposit. At the late of Early Cretaceous Period, extensively distributed low grade mineralization was formed, then the main ore-forming process took place at the end of Oligocene Epoch (30-20 Ma.), and since the end of Miocene Epoch (7 Ma.) a superimposition of uranium happened again.

2.3. Erdos basin

Erdos Basin, which was formed in Mesozoic period, is a huge platform basin in China. It suffered only slightly tectonic effects at the margin areas. Terrigenous coal-bearing clastic rocks of Lower-Middle Jurassic are well developed in this basin. The formation of Zhiluo within Lower-Middle Jurassic series is the most important prospecting target strata. Its upper section is composed of meandering stream sediments under the condition of an arid climate, and the lower section mainly composed of braided river sediments under a moist climate. The latter controls the found uranium mineralization mostly in this region. Within the braided river sandstone in the lower section of Zhiluo Formation a regional interlayer oxidation zone is discovered along the direction of east to west. The oxidation strength of the sandstone is gradually weakened from north to south, and uranium mineralization is exactly located in the transition of oxidation to reduction. However, the colour of oxidized sandstones mostly appears green, which reflects a reduction environment commonly. A preliminary research proves the green colour is caused by gas derived from deep oil or coal. Its original colour is still the common red. That means the interlayer oxidation zone in this area is a palaeo-oxidation zone.

The ore-hosted rocks are mainly medium to coarse-grained sandstone with a thickness of 20 to 50 m, which are well bounded by impermeable mudstone beds on both its top and bottom. According to the results from isotopic dating, uranium mineralization mostly took place in Middle Jurassic and Early Cretaceous, and major ore-bodies in this region were formed. Because of the influence of regional tectonic activities and gas reduction during Cenozoic, the dynamic condition of underground water was changed, and the oxidized sandstone was reduced again, the early formed ore-bodies were reworked as well. The upper limb of the ore-bodies becomes lenticular within the top of the host sandstone generally, and the lower limb becomes tabular at the bottom. Roll-front ore-bodies are very few.

At present, three sections have been found industrial mineralization along the interlayer oxidation zone which is more than 20 km. They are Sunjialiang, Shashagetai and Zaohuphao. The buried depth of the ore-bodies increases from east to west gradually. The ore grade varies from 0.018% to 0.36% with an average of 0.0463% in Sunjialiang, 0.016% to 0.157% with an average of 0.0363% in Shashagetai. And in Zaohuohao only 3 drill holes have been found industrial mineralization. The range of grade varies between 0.037% and 0.071%. A preliminary research shows that uranium exists in an adsorptive form or uranium minerals, but the former is the majority.

3. Exploration activities in near future

Last year, the government announced that the total generation capacity of nuclear power will be up to 36 000 Megawatts in the year of 2020. It means that 27 new nuclear power reactors with a capacity of 1 000 Megawatts per unit will be built in the next 15 years. This plan also makes a big demand for natural uranium. Therefore, the exploration for uranium in China must be strengthened from now on.

And the investment of footage should have a significant increase. The major exploration activities will be conducted in the next three fields: One is for ISL sandstone type of uranium deposits which is mainly carried out in North of China. The second is the surrounding and depth of existing uranium mines which are mostly distributed in South of China, and uranium deposits are granite-hosted or volcanic rock-hosted commonly. The third is the so called “blank” regions where fewer exploration projections have been made before.

Changing role of secondary supply in the global uranium market

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Abstract. The secondary supplies of uranium have acted as both a sword and a shield in the uranium industry. The present paper summarises how that process has worked and how it might continue to work between now and 2020.

1. Introduction

The RWE NUKEM is a subsidiary of the RWE Group, a Germany-based holding company with major utility holdings in Europe and elsewhere, having revenues of 42 billion euros (about US $50 billion at current exchange rates) in 2004, an appreciable sum in any currency. NUKEM stands among the world's largest suppliers of uranium to nuclear utilities. Figure 1 shows volumes of uranium delivered by NUKEM over several years. Acting as a market intermediary, NUKEM sources most of its product in the CIS countries, namely Uzbekistan and Kazakhstan under long term contracts of many years' duration and is also a partner in the so-called High Enriched Uranium (HEU) feed deal under which Russian warheads are being converted into reactor fuel. In total, the HEU feed would amount to more than 40% of the U.S. annual uranium requirement. This commercial background — as a marketer of CIS material, both primary and secondary — makes NUKEM particularly alert to the intersection of primary production and public policy.

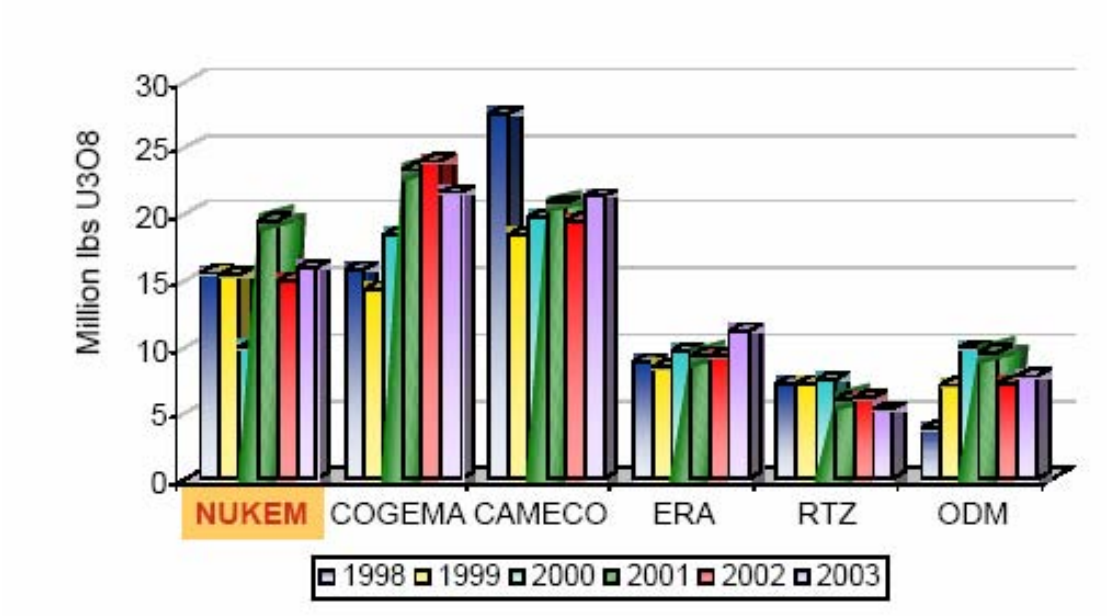

FIG. 1. RWE NUKEM delivery commitments vs. uranium production of the big producers.

2. Uranium supply and demand

Figure 2 shows the natural uranium production and demand in the Western world since 1945. The secondary supplies of uranium, in one form or another that was mined long ago, may be playing a continuing role in the nuclear fuel supply scenario for many years to come. Initially, up to the mid 1980s, secondary supply was composed of Western World commercial inventories built up when it was thought that nuclear power would completely dominate power generation. For several reasons, this did not turn out to be the case. However, in the last twenty years, the reactor demand has exceeded the primary uranium production. The secondary supplies, including inventories of different kinds, have filled in the gap, reducing the need for primary production. More often than not, these secondary supplies have come to market as though they had no cost that had to be recovered. The result is a crowding out of investment in primary production. These secondary supplies have acted as both a sword and a shield. They have acted to shield the industry from any prospect of a fuel shortage for many years. By the same token, their mere existence -- in such large volumes -- have acted like a Sword of Damocles hanging over the market. In a nutshell, investment in new primary uranium production can be (and historically, has been) chased off by the entry into the market of secondary uranium supplies. Over the years, however, the composition of secondary supply changed. Even as commercial inventories were being worked down, new inventories appeared in the market. Commercial inventories have continued to play an important role in the market, whether as a source of material that was being sold into the market or just being slowly consumed, forestalling demand that would otherwise have been there. The present paper discusses how that process has worked and how it might continue to work between now and 2020.

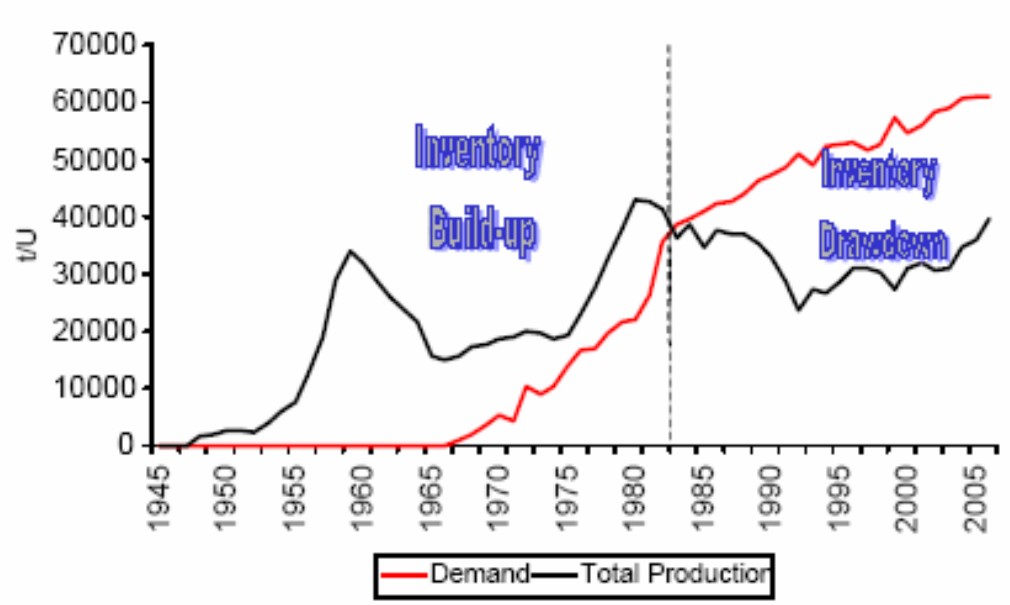

FIG. 2. Natural uranium production available to the West -vs- reactor demand.

3. Market impact of secondary supplies

What characterized the 1990s, though, was market entry of the following new sources of secondary supply:

- Material from the ex-Soviet stockpile,
- Material that once belonged to the U.S. Department of Energy, and was transferred to USEC and
- Material from Russian nuclear warheads.

None of these did the primary producers any good. The average spot price of uranium had fallen below US $20 per pound, and was hovering in the high teens, when the first wave of new secondary

supply hit the market, as shown in Fig. 3. This was the first onslaught of Russian stockpile liquidation -- "perestroika" coming to the West. Due partly to trade restraints and partly to the bankruptcy of a major intermediary, the market recovered in 1995-1996. It was already in retreat, however, when USEC was privatized along with its uranium "dowry" of about 70 million pounds. Large slugs of this inventory were dumped on the spot market in 1998-1999 to meet the company's short-term cash needs. The High Enriched Uranium (HEU) feed deal, inked in 1999, allowed for a more controlled release of this large quantity. Little went into the spot market, however most went to supply long-term commitments of primary producers.

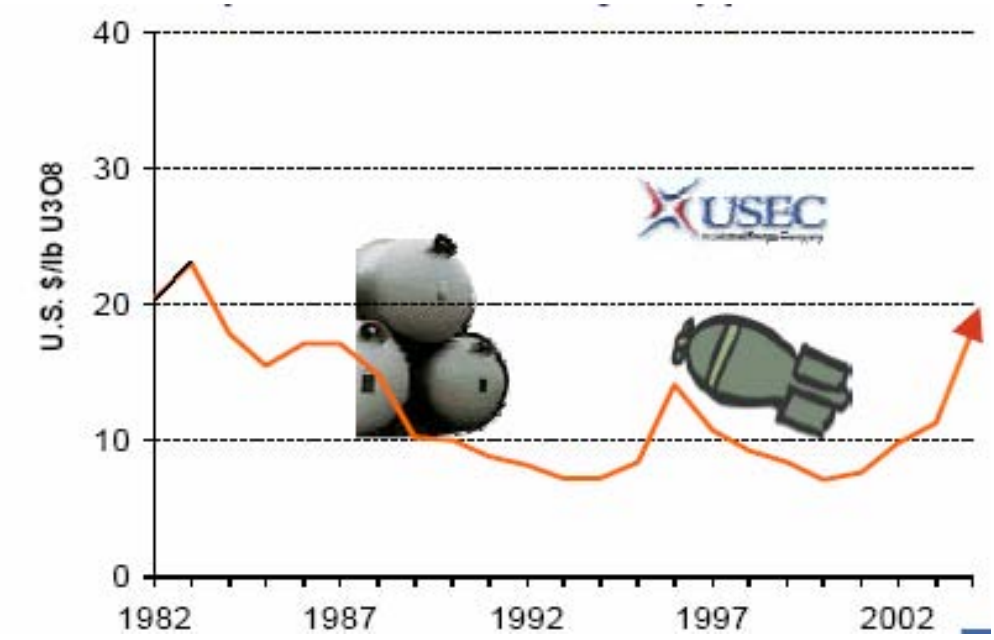

FIG. 3. 1982-2004: Market impact of secondary supplies.

The impact of these secondary supplies was a painful one for producers at the margins. Uranium production in Western Europe (France and Spain in particular) was all but eliminated. Gabon, a major producer for decades, was forced out. The U.S. industry, once the world leader, was all but obliterated and major producers like IUC/NFS, IMC-Agrico, RioAlgom: et al closed their operation. Consolidation became the order of the day, and virtually all new projects that were planned in 1995 (eg Cigar Lake in Canada and planned Australian projects) were postponed for at least a decade.

The turn around of the uranium market during 2000 – 2005, as shown in Figure 4, have been because of a series of unforeseen and unfortunate events like mill fire, mine flood, safety shutdowns, strike and contract dispute. There was a fire that destroyed the mill at Australia's Olympic Dam, a major producer. A flood then stopped production at McArthur River, the world's richest mine, in Canada. A regulatory shutdown impacted supply from one of the world's last remaining converters, ConverDyn A strike hit Port Hope, Canada, another converter. Then there was a contract dispute between the Russian marketers of HEU feed. These unplanned disruptions somewhere along the supply chain caused people to jump into the spot market in search of uncommitted supplies.

The bottom line impact of these events -- the market changing message -- was that, "uncommitted inventories were no longer available to meet any unexpected demand that cropped up". In other words, for years and years and years, there was always excess uranium available at low prices, ready to meet any short-term need. Its existence kept long term prices in check. Starting in 2003, and continuing into 2004, buyers were finding that material they had always counted on was just no longer there. Requests for proposals (RFP) -- for supply bids -- were simply going unanswered or were answered only at much higher prices. The surplus inventory era was over, at least for now. Importantly, these higher prices, as shown in Fig. 4, triggered a major resurgence in planned and prospective production.

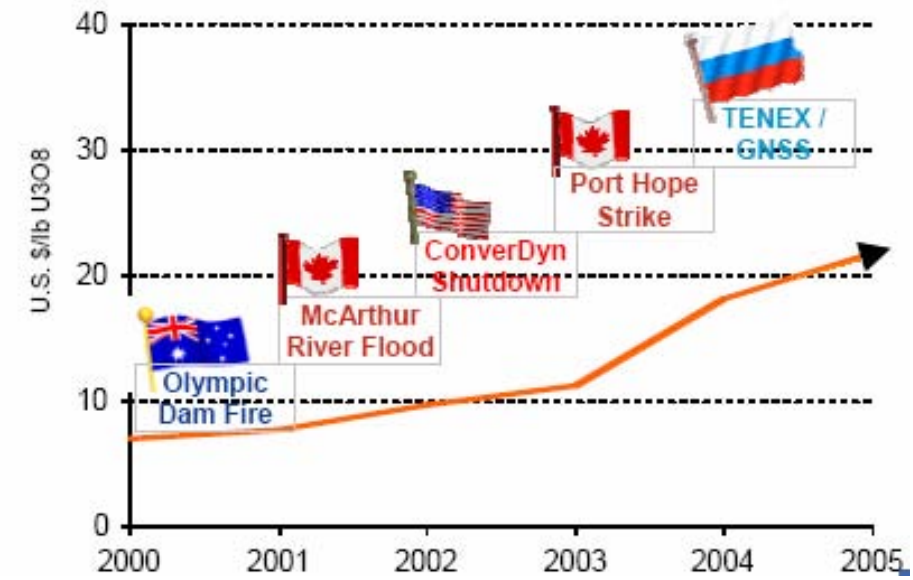

FIG.4. Turnaround 2000 – 2005: A Series of unfortunate events.

4. Western world supply-demand

Figure 5 shows a forecast of supply and demand for non-Russian reactors up until 2020. RWE backs out the Russian-type reactors in Russia, Eastern Europe and elsewhere -- because they all have long-term fuel commitments from the Russian nuclear enterprise. Two demand estimates, one from the World Nuclear Association from September 2004 and the other from consultant Energy Resources International in Washington, D.C., have been considered. Obviously, even among experts, there's room for debate. New reactor construction will be driving demand up. At the same time, fuel-saving strategies such as lowered tails assays and higher burn-up fuel, would drive demand down. The net result would be modest but not scorching growth. In the near term, up to around 2009, the supply-demand gap would be met with commercial inventories. That's the gray swatch on the left beneath the demand line in Fig. 5. This is largely composed of utility inventories plus some contribution from what remains of USEC's uranium dowry. It may be noted, though, that higher prices are also attracting additional supply. It takes a while to bring it on. As a result, the market is balanced under a moderate growth scenario.

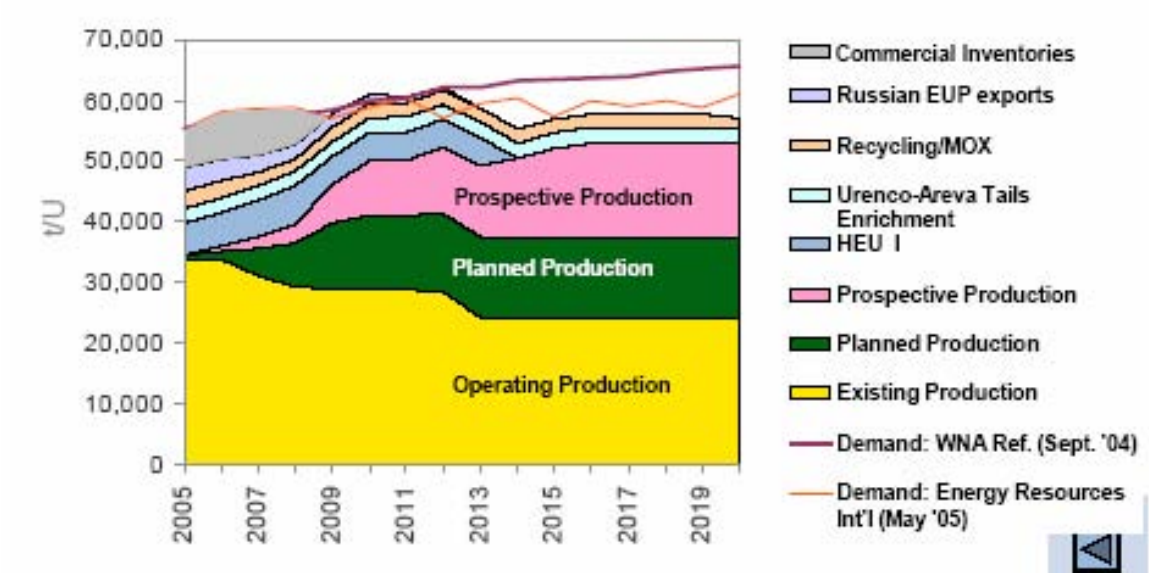

FIG.5. Western world supply-demand: Lowered tails assay, boosted production.

RWE's production forecast is neither optimistic nor pessimistic. There is a high degree of probability that these quantities would be available in this time frame -- possibly more -- under current pricing conditions. However, there could be complications.

5. Impact of DOE inventory, re-enriched tails

In just the last few months, it has been proposed that the U.S. Department of Energy should liquidate its stockpile of uranium. In the House-passed version of the proposed Energy Bill, there was a rather liberal schedule for its disposition. The impact is shown in Fig. 6. The amount involved is on the order of 23 000 t, comparable to the USEC inventory that rocked the market from 1998 to 2000. This could be yet another example of government inventories being recklessly liquidated. Moreover, this is not the only source of new secondary supply that could play a role in the years ahead.

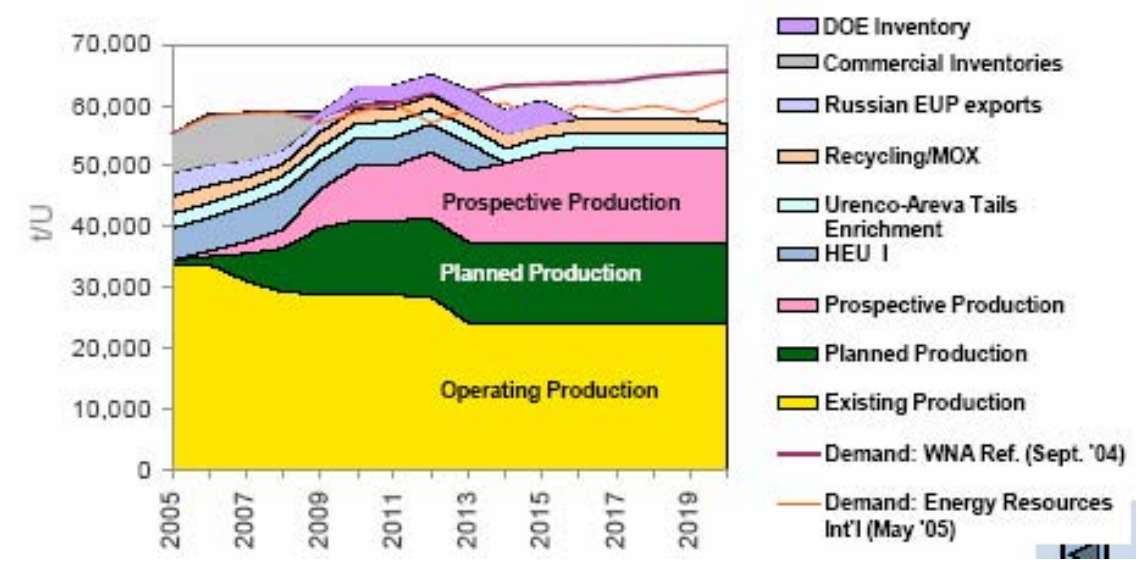

FIG. 6. Western world supply-demand: Impact of DOE inventory sales.

Starting around the year 2000, Western enrichment companies, notably EuroDif and Urenco, began sending tails material -- the left-over from the enrichment process -- to Russia for further enrichment. For Russia, with surplus enrichment capacity, it makes economic sense to "re-squeeze" this material to produce more natural uranium equivalent. A rising uranium price makes this business even more economic, and both Russian tails and Western-source tails could continue to play a significant supply role for the next 20 years. In the U.S., it is estimated that the DOE has tails material that could produce up to 23 000 t (50 million pounds) of natural uranium equivalent. It is a fair question to ask whether this material will in fact be produced and how and when it will be marketed.

The rising uranium price may make this previously uneconomic source potentially economic to "produce" even in the West. Meanwhile, there are code restrictions on the re-enrichment of U.S., Canadian and Australian-origin tails in Russia, but these restrictions could be re-visited in the near future.

6. More Russian stockpile exports

A substantial stockpile of uranium has supplemented Russia's "uranium budget" for many years. Depending on how the math is done, some portion of this stockpile could be supporting Russia's currently substantial exports of enriched uranium product to Western customers. RWE's supply-demand chart assumes that these exports will taper down over the next few years, but this is not a certainty. Depending on Russia's success in opening new mining areas and adding to the re-enrichment of tails, stockpile liquidation could play a continuing role in the years ahead, albeit at reduced level**.**

7. More warhead HEU?

RWE is not making any allowance on their supply-demand scenario for additional warhead HEU, either Russian or American ICBMs. As it is, U.S. DOE is currently kicking around plans for disposing of 100 tonnes of HEU that it wants to take out from under IAEA safeguards. Right now its potential commercial disposition is unclear. A number of Western pundits have assumed that the Russians will make a follow-on HEU deal. It is doubtful, but one never knows. A limited further blend-down of warhead HEU in Russia could free-up other stocks for export to the West.

These HEU blend-down programs are always couched in terms of national security and non-proliferation objectives. While those objectives are certainly legitimate and valuable, there seems to be serious misapprehension about the commercial "throw weight" of the civil nuclear fuel industry.

8. Impact of possible additional secondary sources

A combination of possible additional secondary sources, re-enriched tails, Russian stockpile liquidation, and additional HEU feed material (American or Russian), could combine to flood the market a few years down the road as shown in Fig. 7. Relative to potential supplies, these amounts are not that large and in the range of some 5 000 tonnes, composed of a thousand ton from the Russian stockpile, a couple of thousand from re-enriched tails, and a couple of thousand from DOE's warhead HEU. After 2017, another 2 000 tonnes could be added from warhead material, which could be either American or Russian. Even then, the warhead amounts are less than half of what the HEU-I deal produces today. Obviously, if this scenario is a probability, or even a strong possibility, it will curb investment in new exploration and new primary production. Some portion of that investment -- some of which is already being spent -- will have to be written off. Again, this start-stop approach to fuel cycle development adds needless risks and costs.

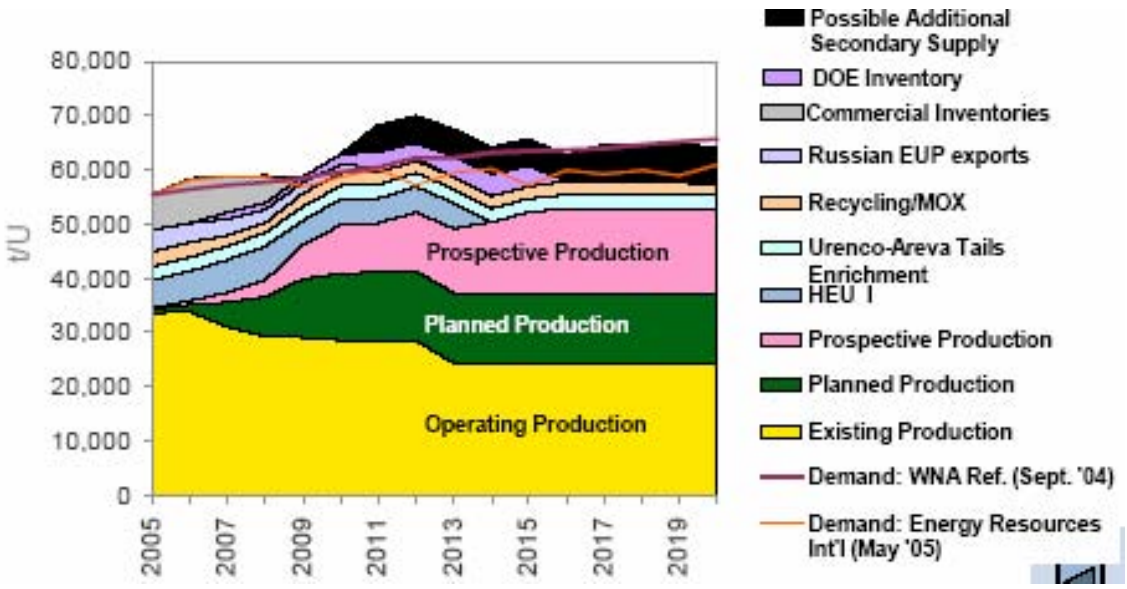

FIG. 7. Western world supply-demand: possible additional supply.

Many policy-makers seem to think that the uranium market can absorb any quantities that governments throw at it. This is assuredly not the case. The uranium market is miniscule next to the markets in other energy fuels. For example, the annual revenues of western nuclear fuel cycle, including the whole front –end of the nuclear fuel cycle -uranium (at current spot values), conversion, enrichment and fuel fabrication services, is only ~US $10 billion, compared to the annual revenue of just one oil company Exxon Mobil, which was ~US $298 billion in 2004.

9. Uranium vs. Competing Energy Fuels

Figure 8 shows an inter-comparison of uranium values (approximate delivered prices to utilities for 2004 primary production) compared to the approximate delivered prices for Next comes natural gas, weighing in at more that US $500 billion. Next comes coal, with global production of about 5 billion tons and an approximate value of US $127 billion (this is about half the current spot price). The uranium price is a virtually negligible US $1.5 billion for the entire world's 2004 primary production. Thus, the government's policy to raise money by liquidating uranium inventories will not lead to any meaningful result. On the contrary, such decisions will reduce the investment to primary uranium production.

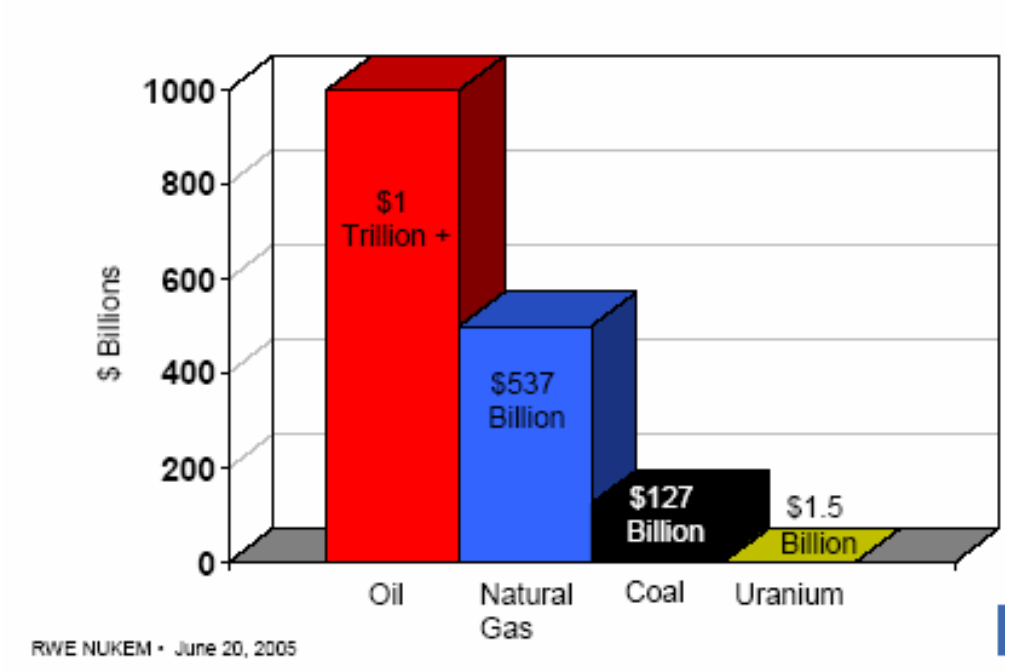

FIG.8. Uranium values vs. competing energy fuels.

10. Conclusions and recommendation

- Uranium supply is tight for next three to four years, but producers are responding favourably and inventories are sufficient for near term needs;

- It is foreseen that secondary supplies will be playing a continuing role. Even when the HEU-1 feed deal winds up in 2013 period, other sources of already mined uranium will continue to be there, including recycled spent fuel, re-enriched tails and quite possibly both government stockpile liquidations and more blended-down HEU fro warheads;

- Proposed/continued liquidation of government stockpiles could drive out investments needed for uranium exploration, mining, milling and production;

- Uranium market is much too tiny to be used as backstop for national security objectives;

- Uranium producers need more transparency/market sensitivity from both U.S. and Russian governments;

- Government inventories should be used as security –of – supply backstop and not for short-term money making.

Limitations to progress in developing uranium resources

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Abstract. The paper give a broad overview of where the limitations to the future progress in developing uranium production cycle are. It points out such aspects as historical overview, price, development of reservesand potential resources, social attitudes, political policies, legal constraints, environmental permitting and licensing, personnel, supplies and equipment manufacturing, financing, and technical limitations.

1. Introduction

There exists a gap between the supply of uranium to nuclear power plants and the current demand for uranium from nuclear power plants. Recently, spot and long term uranium prices have been rising rapidly, providing indications that the supply of previously mined uranium is nearing an irreduceable and unavailable inventory. The gap between supply and demand is quite large, around 45% of the demand. This gap has been filed over the past 20 years from inventory sales of previously mined uranium. Recently the price of uranium has increased, reaching levels last seen 20 years ago. This presentation examines the limitations on developing new uranium supply sources including secondary sources.

2. Historical perspective

It will be instructive to briefly review the history of developing the uranium supply sources. The history of uranium mining on a significant scale began dramatically with the Hiroshima Atomic Bomb on 6 August 1945. This beginning has had a profound impact on the development of Nuclear Power. The uranium for these weapons was purchased from mines previously developed in Africa and the Colorado Plateau of the United States for other minerals such as radium and vanadium. This was the secret “Manhattan Project”.

From that beginning the United States Government began a uranium ore buying program and contracted with companies to build uranium mills to process the ore purchased under this program. The primary purpose of this program was to develop uranium sources for Nuclear Weapons as part of the Defense of the United States in the Cold War. This provided the profit incentive to private industry to explore for and develop uranium mines. The buying was not limited to U.S. sources and provided impetus to the non-communist world to develop uranium mines and production facilities.

Similiarly, in 1946 Joseph Stalin founded the uranium geological expedition in the Soviet Union to explore for and develop uranium sources in the Soviet Union as part of the Defense of the Soviet Union in the Cold War. Thus the Cold War provided the political and financial impetus for developing the uranium sources. All promoted and controlled by these governments. Similar programs took place in other nuclear power states of Great Britain and France.

In 1954 the United States Government passed the Atomic Energy Act of 1954 establishing the Atomic Energy Agency. This Act of the U.S. Congress changed the U.S. Government emphasis from nuclear weapons to peaceful uses for atomic energy. This marked the start of the government sponsored development of uranium for nuclear power fuel. However, the Soviet Union did not change it’s emphasis completely until Perestroika during the late 1980’s under Gorbachov. In 1963 the U.S.

Government stopped buying uranium for nuclear weapons, however a tremendous inventory of uranium was already produced and in the weapons program of the U.S. Department of Defense. The U.S. Government continued to sponsor exploration programs well into the 1980's. These programs included extensive government funded airborne radiometric surveys gridding off huge sections of the United States and Ground Water sampling for radon (NURE programs). The Soviet Union did the same as did many other countries, all government funded regional reconaisance.

The Soviet Union continued to build up inventory even after the fall of the Soviet Union in 1991. The inflexibility of these production sources and systems to respond to commercial interests and changing government policies created a large overhang of inventory, both for weapons and for commercial nuclear power.

In 1963, with few nuclear power plants operating, the price of uranium collapsed when the U.S. Government stopping buying uranium. The U.S. Government had underestimated the strength of the Commercial Market. The famous so called "uranium cartel" started it's operations as the "Uranium Institute" as producers tried to continue operations by distributing a limited market demand. Most of the producers at this time were funded or subsidized by Governments or were subsidiaries of large mining companies, mining gold or other minerals or were oil companies. These companies included Homestake a U.S. gold mining publically traded company, Anaconda, a publically traded copper mining company, Union Carbide, a chemical company formerly producing vanadium in the Colorado Plateau and Continental Oil Company, Kerr-McGee, Getty Oil and Gulf Oil, publically traded oil companies, and as government subsidized companies, Rio Algom and the U.S. Government owned Tennessee Valley Authority. Some small private companies were quite active during this time; such as Charlie Steen's activities in Utah, Bob Adams's Western Mining in Wyoming These were funded by utilities production prepayment, investment or loans.

With the Suez Oil Crisis of 1973, there was a perceived need for nuclear power as it was perceived that nuclear power would provide much cheaper electricity. The price of oil rose rapidly as the Texas oil production capacity was no longer in excess of the market demand, allowing the formation of the OPEC oil cartel and resulting in prices of oil going from US $3 per barrel to US $10 and on to US $30 very quickly. Electric Power demand was growing at 7% in the U.S. and Texas no longer could match the oil market demand with excess production capacity. The western world began ordering nuclear power plants and uranium at a furious pace and it was perceived that we had entered the age of real commercial development of nuclear power. The price of uranum rose rapidly during the years from 1974 until 1978 when it peaked as it became apparent that the industry had overreacted to the oil crisis and the number of nuclear reactors on order was reduced by more than half. The Three Mile Island nuclear power plant event during early 1979 defined the extent of the problem of overreaction to the oil crisis, revealing the public and policy concerns of the time.

During that time the uranium producers responded rapidly to increase production to levels considerable above even the projected requirements. However, this was relatively easy as there was an inventory of resources already discovered by government sponsored programs and development. The expansion was facilitated by the existence of uranium mining companies that had survived as subsidiaries of Oil, Chemical or Mining companies and the entrance of Exxon, Atlantic Richfield, and Union Oil in the uranium mining as they wanted to be complete energy companies. It was perceived that uranium prices could be quite high as these companies thought that uranium would be sold at prices equivalent to the value of oil and coal based on the equivalent energy content. This development of production greatly in excess of market demand in anticipation of high growth rates for nuclear power, resulted in huge excess inventories and collapsing uranum prices. Changing U.S. Government policies increased the magnitude of the problem.

After the collapse of uranium prices beginning in 1979, the industry had to try to survive to any means possible, as first the commercial inventory and later the weapons inventory, began to be worked down. Some growth of nuclear power continued but at lower rate than expected previously.

So, where are we today. I suggest that we are now seeing the development of a mature industry where prices are driven by production costs, not overreaction to perceived market demand and inventory holding costs. This development will be difficult for the suppliers as the long depressed uranium market has depleted the industry's resources in all categories. We no longer have the industry subsidized by Governments, or by companies with other resources such as oil or gold mining. In fact, there is a clear understanding in these companies that uranium is a much smaller industry and has very special problems, so that there is an adversion to funding such production.

3. Limitations to development of supplies

Let us examine the limitations to developing the uranium sources needed to fill the gap between supply and demand. First, I would like to list the limitations and then discuss each. They are:

1. Price
2. Known proven and/or developed reserves
3. Known potential resources.
4. Financing
5. Social Attitudes
6. Political policies
7. Legal constraints
8. Environmental Permitting and Licensing
9. Personnel
10. Supplies and equipment manufacturing
11. Technical limititations.

4. Price

Price is probably the most important limitation. Prices have been below the level required to incentivize investors, producers, exploration activities and personnel to enter the industry or to even stay in the industry. So, many have exited the industry as it is not the best place to have a career. Uranium mining is too small and too narrow a field. Also, not supported by public opinion or public policy. Much of the industries capability has been lost due to 20 years of low prices. All the support systems need to be reenergized. New companies need to be formed and new personnel needed to manage exploration and production efforts need to be attracted to enter the supply side. While the price is adequate for the known low cost projects that are out there, it is still too low to develop a mature and health industry. Prices will continue to rise until there is a balance struck. However, I believe we will see again a very inefficient response as we reach higher prices. There will be some mitigation of higher prices from decreasing the tails assays for enrichment and utilizing the expanded enrichment capacity planned, but the development timing is critical for this impact on price. The prices must rise further and stay higher to provide for the exploration activities needed to develop new sources and to solve the other problems caused by such a long down time for the industry. There are sufficient known resources to meet the current demand, but at a much higher price than the current price, so substantial further price increases will occur.

However, as the demand is growing and in particular as public attitudes are changing, the industry will be challenged to meet the growth in demand. However, even much higher prices for uranium will not impact the competitiveness of nuclear power compared to other sources, since fuel is a small fraction of the cost of nuclear electricity. What impacts the competitiveness is public attitudes, government policy, and primarily how effectively and efficiently that nuclear power plant operators construct and operate their nuclear power plants reliably, safely and economically. This is because the price of fuel primarily affects only suppliers, and not the price of electricity.

5. Known reserves

The known reserves will probably fill the current gap, estimated at around 60 million pounds per year, assuming no growth of demand. This will require the following resources to be developed.

1. Cigar Lake estimated to add 6 million pounds per year to Canadian production on a net basis

2. Central Asian uranium large expansion as KazAtomProm projects to increase by 30 million pounds per year

3. Olympic Dam expansion to add 10 million pounds per year

4. Rossing must continue and possibly expand

5. Jabiluka needs to be developed to sustain Ranger production

6. South African Byproduct from Gold Production to add 8 million pounds per year

7. Sustaining or slight increase in U.S. Production from 3 million pounds to possible 7 or 8 million pounds

8. Russian production sustained or increased

9. Mongolian production to develop 3.5 million pounds per year of capacity

10. Chinese and Indian production is very limited

11. Niger expansion by 6 million pounds per year

If all of this happens, it will add about 68 million pounds. We will examine the limitations to this happening.

6. Exploration expansion

The exploration expenditures must be increased to provide for the growth and sustainability of nuclear power. This is a long term prospective and will need substantial increases in investment, which we have not seen in decades. Development of improved exploration technology will continue to have an impact, but the sustained exploration required can only be provided by large companies or national organizations with large cash flow from production to sustain the efforts. This is not a place for junior exploration companies. The most prospective areas are the Athabaska basin, Australia, Africa, Siberia and South America. There is a need for more advanced and sophisticated exploration methods, as the easily discovered uranium has been found. Fortunately, the surviving portions of this industry have learned a great deal about uranium geology,

Ore genesis, and improved exploration models. Many of these will be discussed in this conference.

7. Social and political restraints

There are severe limitations from the public concerns about the environment and the political opposition. Examples include the Marline deposit in Virginia which will probably not ever get developed due to it's proximity to developed countryside and concerned populations with environmental activists. The limitations on Australian development by political constraint also come to mind. The difficulties in dealing with the Navajo nation and Australian Aboriginal Tribal councils should be mentioned. The limitation to development of Tallahassee Creek project near Colorado Springs, due to real estate development concerns. The development in the Arab world will probably be limited due to concerns about proliferation of nuclear weapons.

The problem is different than the public acceptance of nuclear power. It is a prejudice against uranium mines that is due to public perception that uranium mines are radioactive and harmful to both people and the environment. While, this is not founded in truth, it has been a major discouragement to the development in certain sensitive areas and countries. The solution to this problem is active education

of the public about radiation and it's effects, the winning of lawsuits on this issue helps as does the demonstrated safe operation and successful restoration of uranium mines without damage to the environment. Non proliferation concerns must also be addressed and the public needs to be educated about the controls. Of course, this means that the IAEA non-proliferation section must demonstrate that it is in control of this problem to the satisfaction of the public, world wide.

8. Permitting and licensing constraints

While we usually are successful in overcoming resistance to licensing in most locations, this is a serious constraint as it may takes years to permit mines in some areas. Uranum Resources Inc,, for example, has taken US $10 million and 15 years to permit their New Mexico properties and still has not succeeded in placing a mine in production there. The costs and delays in permitting McClean Lake Mill come to mind. The 30 years of permitting Jabiluka are another demonstration of the problem. Permitting problems unnecessarily raise the cost of production as well as delay projects without any good benefit to society or the environment. Public perception must be changed as these uranium mines are not even unusually radioactive compared to the normal environment.

9. Legal constraints

In some cases laws must be adopted by the legislature to allow the resources to be developed or for the export of uranium. Past Australian restrictions and South African embargo are examples. Non proliferation concerns provide other restrictions due to perceived problems. Most of these problems are due to incorrect perceptions and attitudes.

10. Personnel

It is becoming increasing apparent that we do not have sufficient professionals or professionally competent managers experienced in uranium exploration and mining for the tasks required to increase production as dramatically as the doubling of production in the next 15 years which is probably required. We do not have the experienced personnel to supervise and manage the projects which must be placed into production now to fill the gap. However, retraining personnel from other industries and educating and training can be achieved in a reasonable time by professional managed organizations and professional training programs. Many educational institutions, especially the commercial institutions with experience in specialized short course training programs, more than the universities, can help fill this gap. In other industries, that are more healthy and less limited than uranium mining, we have worked with local educational institutions to train personnel.

However; in fact, I started up the first In Situ Uranium mine with almost completely untrained personnel and provided on the job training, while developing the technology; so it is not so difficult for experienced supervisors and managers. At this time, I had extensive training and experience developed for working for years for major oil companies that take the time to train and educate their managers. Also, I had very good financial support. However, we lack these kinds of people, but it is a management skill; not a technical skill to manage this. Certain key functions are generally available anyway. Particularly, training drilling personnel may be a limitation. We notice that there are serious training efforts underway in Kazakstan to fill the need for geologists and drilling personnel. This is an indication of the good planning by KazAtomProm and their partners. Perhaps a more interesting limitation is the lack of interest in this profession as it offers too limited an opportunity to attract high quality candidates. Especially this is true of more specialized production techniques such as In Situ Leach, which requires a depth of experience in the management for the projects to succeed. The former Soviet Union Republics contain a wealth of experienced and well qualified personnel in all these areas and should be better utilized by all the industry.

11. Equipment and supplies

The shortages in this area are primarily infrastructure, chemicals, drill rigs, technical equipment, sulfuric acid, etc. However, there are other larger more mature industries that use this equipment and

materials which can be adapted to uranium mining and exploration activity. Infrastructure must be developed for each project. Since the largest portion of the increase in production from known resources will most likely be Central Asian in situ uranium, the greatest shortage will be drill rigs. Many of the manufacturers of drill rigs have gone out of business. In Kazakstan, the lack of competition from government licensed drilling companies (only two are licensed) has limited the development of competitively effective drilling equipment and methods. It takes 120 hours and twice the personnel to complete a 500 foot deep production well there, compared to 20 hours with methods and equipment which I use. This seriously changes the nature of the problem. However, since the contractors in Kazakstan are using 1 600 Russian drill rigs, it is a serious time and financial constraint to improve on this situation.

12. Financing

Since the limitations on developing new sources can be cured by good management and money over time, the most serious limitation is probably financing, provided the price is sufficient to incentivize the organizations and there are not any serious public attitude or government regulations problems. The limitations on financing are severe. While the Canadian equity market is quite excited about the uranium price, they have yet failed to raise serious money for developing uranium mines or exploration programs and sustain the efforts. Also, the number of companies that are generating funds internally are severely limited. There is perhaps one strictly uranium mining company and subsidiaries of other companies or byproduct producers or government companies.

In the past most uranium exploration and development was subsidized by Governments, either directly or indirectly or subsidized by financing from larger companies in related industries, such as oil or mining. Government subsidies applies to all countries at one time or another, but in some countries it still applies. However, with the recent privatization of state owned enterprises and the stopping of subsidies, it will be very difficult to make the large investment needed to get the industry to a healthy and competitive situation. The large mining and oil companies are not interested in this difficult industry as even the large projects do not provide sufficient cash flow to interest them and effect their bottom line. Especially, considering the many nuisance type problems with this industry.

Increasing, financing must be provided by Nuclear Utilities if the supplies are to be available. Some production prepayment financing was done in the past and some is being done now, but the scale is not sufficient to make much a dent in the problem. Financing of Exploration and Production facilities is the biggest challenge to the industry’s performance in my opinion.

Closing the cycle: life-cycle impact assessment of materials used in nuclear energy systems

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Abstract. Life-cycle management (LCM) and life-cycle impact assessment (LCIA) are responses to a change in paradigms whereby (environmental) problems are being anticipated and avoided, rather than treated after they have occurred. Optimal use of (natural) resources, minimization of overall contaminant production and waste generation are essential environmental-related goals to enhance sustainability of nuclear energy systems including the mining and processing of uranium. Demonstrating an optimal use of resources with minimal environmental impact will help to increase the public acceptability nuclear energy systems.

Understanding and quantification of material flows, including those from the mining and processing of fuel-cycle related materials, is an essential tool for assessing and comparing options of nuclear energy systems in terms of their use of resources. Consequently, all relevant materials flows in the system should be accounted for.

The IAEA has inititated a new co-ordianted research project aiming at mapping out the various material streams, including those from the fuel cycle.

1. Introduction

In recent years a slow change in paradigms occurs: a move away from treating environmental problems after they have occurred - without positive feedback into the activities that have caused the problem - towards a more integrated management of human activities. This life-cycle management (LCM) approach aims to treat each stage in the life of a process or facility not as an isolated event, but as but one phase in its overall life (see Fig. 1). Thus, the planning does not just cover each individual stage, but is a continuing activity, taking into account actual and projected developments and feedback mechanisms between different stages in the life-cycle. In particular, the environmental impact of all components and all stages of a system is being assessed, i.e. a so-called life-cycle impact assessment (LCIA) is undertaken. This approach is of particular relevance to mining and milling projects, where long-term liabilities may arise from the near-surface disposal of residues.

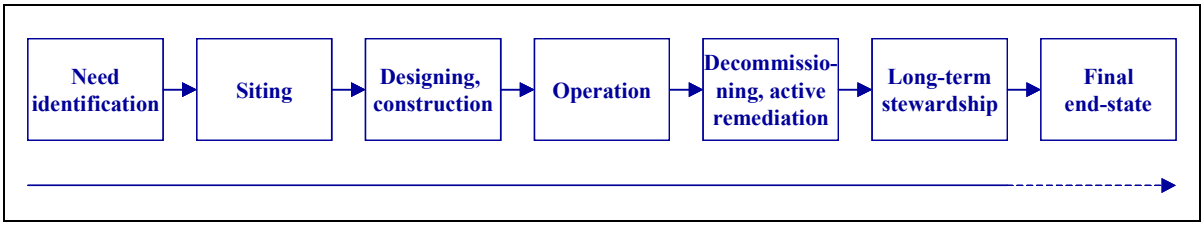

FIG.1. Life-cycle management.

Because of these residues, uranium mining and milling sites often cannot be remediated to residual levels of contamination that are below concern and cannot be released for unrestricted use. They have to remain under some form of institutional control. Residual contamination, mill tailings or low-grade ore, and other hazards may remain on or near the surface for several reasons after clean-up is complete: technical limitations, economic feasibility, worker health and safety issues, or prevention of collateral environmental impacts. An optimisation between social and economic cost on one side and

level of protection on the other side has to be found. With long-lived radionuclides present, maintenance of institutional control is likely to be required for nearly unlimited periods of time.

Careful management of all materials involved is an essential element of the life-cycle management in the mining and milling of uranium. And: minimization and optimization of the use of raw materials and energy is a fundamental strategy on the way to achieve sustainability. It is built on the basic hypothesis that the minimization of the use of materials and energy will reduce the associated environmental impacts. Another basic hypothesis is that the optimization of their use will reduce the associated environmental impacts. Not only the target materials of the nuclear fuel cycle, namely uranium and thorium, are of relevance, but other raw materials, such as gravel as aggregate, or water for cooling purposes. There may be competing interests in their uses, e.g. the use of gravel aquifers for drinking water production.

2. The context

2.1. Environmetal impact assessment

Nuclear energy systems can and do have effects (thermal, radiation, chemical and physical) on the environment. The main impacts have arisen in the past at the front end of the fuel cycle, namely uranium or thorium mining and milling and at the back end from poorly managed radioactive waste. Severe accidents and their impacts remain a public concern. In choosing energy options, perceived environmental and health impact, and hence the lack of acceptance, has been recognised as one of the critical issues for the development of nuclear energy systems. This is in contrast to the actual environmnetal and health impact arising from e.g. fossil fuel-based energy systems. If it can be demonstrated that environmental and health impacts can be kept within acceptable limits, together with other critical factors (such as cost, safety including waste safety, resources availability and supply security, proliferation risks) the nuclear energy option has a potential to be further deployed and accepted by society and industry.

Hence, an essential element of the strategy to achieve sustainability (in an environmental sense) is the minimisation of use of non-renewable resources. Conceptualising and quantification of material flows in turn is a prerequisite for minimising the use of resources.

All human activities result in flows of material and energy, which in turn bring about a change in the respective environment. It is obvious that reducing such flows or eliminating particular flows will reduce the related environmental impact. Alternatively, for flows of a certain material that cause a significant impact, there may be an option to replace it with another material or another flowpath that causes less impact or impact to another environmental compartment, where the impact is of less concern. Given the complexity of the economic activities of even less developed societies, the environmental impacts caused by certain activities are not obvious or are not easily traced to their root cause. Following the respective material streams can help make this more transparent and facilitate in a quantitative way the selection of more benign options.

2.2. Supply security and optimisation of resources use

Various scenarios for global energy use project that demand will at least double over the next 50 years[1]. Electricity demand is projected to grow even faster. These scenarios suggest that the use of all available generating options, including nuclear energy, will inevitably be required to meet those demands. However, the location and availability of technology for the utilisation of those resources pose political, economic and environmental challenges, the impacts of which vary between different regions of the world. The long-term outlook for nuclear energy needs to be considered in the broader perspective of resources availability, supply security, and environmental impacts.

A variety of raw materials may become scarce and are in the danger of exhaustion. Analysing their flows in society or in a given industrial process will show where in the life-cycle and for what purpose they are actually being used and where ‘losses’, e.g. to waste, may occur. Identifying such losses to the

environment will help to better utilise resources and at the same time help to reduce impacts from their use. Material flow accounting (MFA) will also indicate critical pathways and uses for which no alternatives exist. Widening the scope to the sources of materials will also indicate competing users for the same resource. It needs to be remembered, however, that sources and users and, hence, pathways may change over time. Flowpath can be very complex: for instance, a country may critically depend on the primary flow of a particular raw material from the outside, or export a material for processing to later import the product. Predicting flows for nuclear energy systems may require a demand and supply forecast for a range of other industries or countries in order to evaluate competitions.

The optimisation of resources use is likely to have both, econcomical and environmental benefits. (Re-) cycling of materials improvement the overall cycle efficiency and is a possible strategy to minimise resources use. However, minimisation alone is not sufficient, but the type and nature of resource used and of waste streams generated may be significant with respect to environmental impacts arising or avoided. This again would be supported by MFA.

3. An essential tool: Materials flow accounting

The assessment of the material flows involved in an industrial activity, such as mining and processing of fuel-cycle related materials, can be carried out from two perspectives:

- centred on a particular material, chemical element, product, commodity, etc.; this is followed through its 'life', which is called 'life cycle analysis' (LCA);
- centred on a domain of interested, e.g. a plant, a country, or the whole earth, the input and output of a material, chemical element, commodity etc. is balanced for various sub-domains, which is called 'material flow accounting'.

Materials flow accounting was developed as a tool from the 1970s onward, stimulated by the fear of essential resources becoming depleted on a country or even global scale. The tool later has been used to identify dispersive losses of harmful chemical substances, e.g. heavy metals, to the environment and to reduce or phase out their use [2].

It consists of assessing, where a substance enters or leaves an environmental compartment, an (industrial) process, and where it appears in products, intermediates, residues and wastes. MFA can be undertaken at various scales, ranging from single plants or mines to whole countries (see Fig. 2 for an example). As a matter of fact, many industrial operations routinely apply MFA techniques to manage and control their materials requirements during the production process and to identify the potential for reducing wastes and emissions.

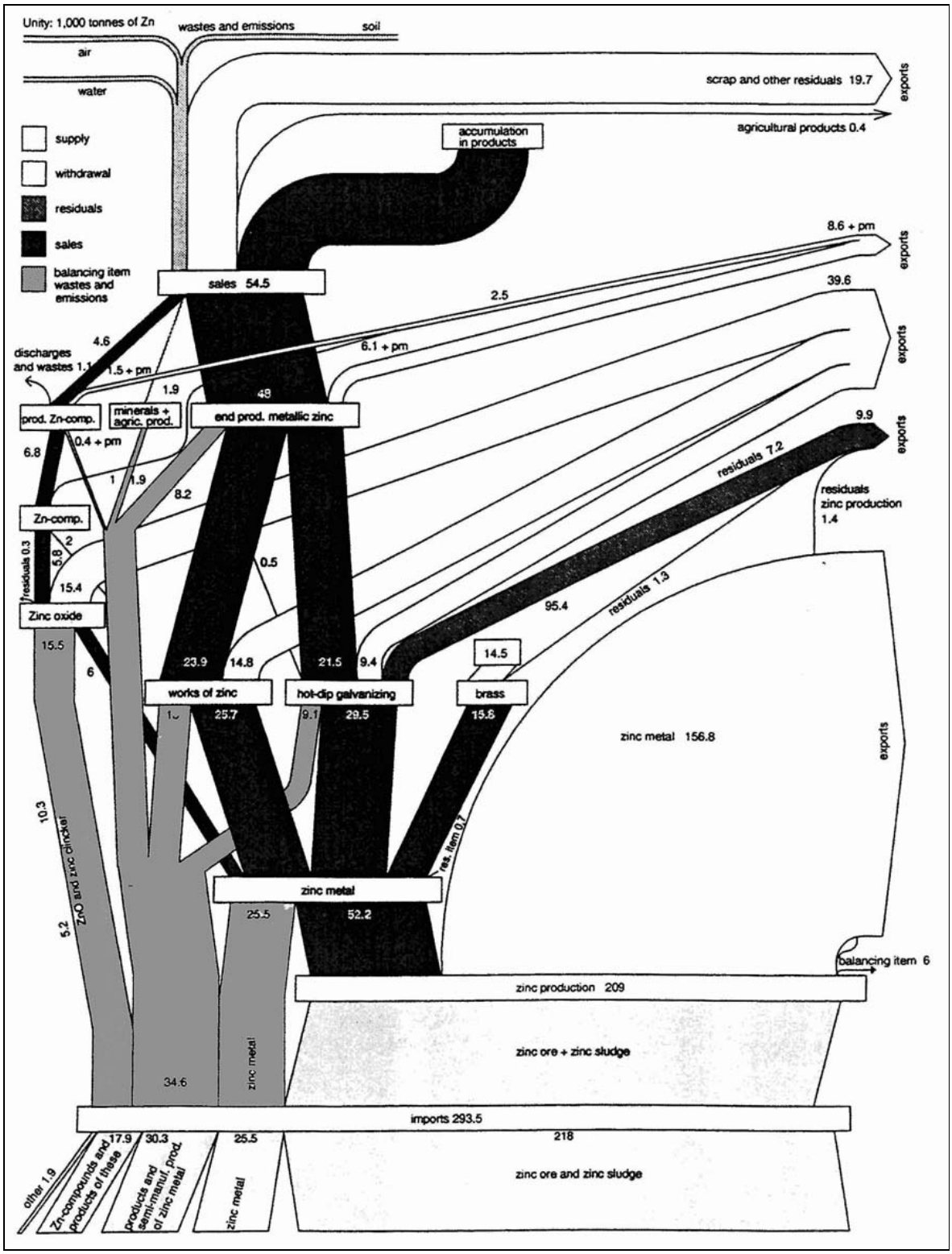

FIG.2. Example for material flow accounting: flowchart of zinc in the Netherlands in 1990 [3]. Note: no example for such MFA in the fuel cycle, except for minor actinides [4], is known.

4. Life-cycle impact assessment

4.1. The concept

While MFA is substance oriented, life-cycle impact assessment focuses on a product, e.g. a fuel element or a service, and is a method for evaluating the impacts this product or service has or might

have on the environment and natural resources. LCIA is a concept that combines environmental impact assessment (EIA) with materials flow accounting. While EIAs are a standard requirement in any licensing procedure for fuel cycle and other nuclear facilities, the assessment of the associated material and energy flows is rarely carried out in any detail. However, today this is a standard procedure, for instance, in the context of the manufacturing industry. This evaluation method takes into account the impacts that arise from the extraction of natural resources to waste disposal, including the end of life of a product ('cradle to grave'). LCIA is a decision-making tool that is promoted inter alia by the International Organization for Standardization (ISO 14000 series) [5]. LCIA was developed in response to enterprises for which environmental protection was a prime concern in the production, improvement and development of their products or their processes. Environmental certification according to the ISO14000 series is seen by many companies as a means to exhibit an 'environmentally friendly' image and thus increase their competitiveness. Typically a LCIA consists of four elements:

(1) Goal definition (ISO 14040) – the basis and scope of the evaluation;
(2) Inventory analysis (ISO 14041) – process trees and material balances;
(3) Impact assessment (ISO 14042) – resources use and emmission are related into impacts;
(4) Improvement Assessment/Interpretation (ISO 14043) – corrective actions are identified.

4.2. Life-cycle costing

Traditional costing approaches normally take into consideration the so-called 'conventional costs', i.e. direct and indirect costing items that cannot be avoided by undertaking a certain project: capital costs, equipment, energy, utilities, supplies, etc.

Life-cycle management requires the adoption of broader costing concepts in which all costs involved in the implementation of the project, from the initial planning phase to the decommissioning and stewardship phases have to be taken into account (Fig. 3) [6]. This life-cycle costing concept is a key issue when developing financial instruments to cover long-term liabilities.

A nuclear installation installation will only produce revenues for a certain period of time, while the costs involved in the management of environmental and societal issues may extend far beyond the operational period of the installation. As a consequence, a concept similar to an 'pension plan' will need to be developed. The concept is similar to a personal 'pension fund' in the way that provisions are made during the period in which it is generating revenue to cover the final period of its life.

It is generally accepted that new installations need to be planned from the very early phases to meet this concept, thus providing adequate financial coverage to meet future predictable liabilities and to promote the identification of the actual environmental costs of goods, inducing a greater efficiency in the use of resources.

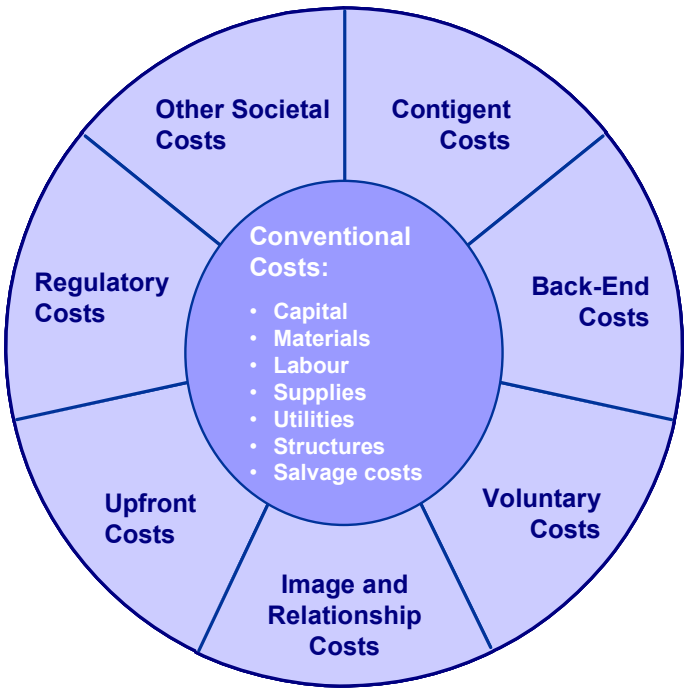

FIG.3. Life-cycle cost elements.

Installations already in the operational phase need to also be encouraged to perform life-cycle cost planning, not only because it induces the accomplishment of a thorough environmental audit and risk assessment of the installation, but also because it allows for planning the financial and technical requirements to meet all future liabilities, including those previously unrecognized.

4.3. Life-cycle impact management for nuclear energy systems

Surprisingly the concept of MFA and LCIA has not found appreciable and explicit use in the nuclear industry as a whole, with the exception of a few specific areas, such as in the chemical engineering of reprocessing and related areas [4] and maybe the generating plants themselves. Probably for the first time the concept of a holistic life-cycle impact management, comprising mining and milling, construction of nuclear facilities, their operation and decommissioning, and associated waste disposal operations, was promoted as one of the strategies of the INPRO project[1].

The scope and the options for applying LCIA as a tool to ensure and demonstrate the (environmental) sustainability of nuclear energy systems needs to be further explored. There is particular scope for it in the mining and milling of uranium ore, where in the past considerable impacts have occurred [7][8], resulting in resentment to new developments from a wide variety of stakholders.

5. Supporting research initiatives

5.1. Overall objectives

While the basic concept of material flow accounting is readily understood, many IAEA Member States do not have the skills, methodology and instruments to carry out comprehensive analyses. Based on the reasoning outlined above, the IAEA has initiated a new Co-ordinated Research Project (CRP). The objectives of this new area of work are to

— investigate and compare current MFA methods used in IAEA Member States and applicable to (innovative) nuclear energy systems with a view to make this method more widely usable;

— develop methods for assessing reactor and fuel cycle related material flows that can be used in the Member States. The materials to to be investigated include in addition to fissile and fertile materials, materials of critical importance due to their scarcity or competing users.

5.2. Holistic assessment

It is envisaged to develop a system of material flow accounting methods pertaining to nuclear energy systems in a holistic sense as detailed in the following.

MFA can be extended to the whole range of materials required to construct, operate and decommission installations from of nuclear energy systems. Such MFA is likely to be very complex, given the high interconnectivity between various combinations of nuclear plants and fuel cycles. On the other hand, it can be restricted to a specific fuel-cycle, for instance, or certain components (e.g. zirconium for fuel cladding, lead or sodium as coolant). Mapping of the materials flows will help to better understand them. In the following, specific groups of materials are outlined, but the same material may well fall into more than one group, that is they could be, for instance, both scarce and having a significant environmental impact.

5.3. Mapping of material flows

5.3.1. Nuclear fuel cycle materials

Certain material flows are (almost) unique to nuclear power generation, in particular that of uranium. Other (secondary) material flows are associated with the processing of materials specific to the nuclear power generation, for instance calcine.

The unique material flows will be illustrated and ways to their control and hence impact minimisation will be pointed out.

5.3.2. Material flows with a significant environmental impact

Not all materials or their uses have the same type and level of impact. The potential impact tends to be related to the volume of raw material used and to the level of hazardousness associated with the constituents of the raw materials as well as the processes used in their abstraction and processing. A preliminary ranking of material flows with respect to their potential impact will be developed in order to focus further work on those of particular relevance and thus to make the task more tractable. Previous experience with MFA in other sectors will be helpful in selecting the relevant materials.

5.3.3. Critical materials and materials for which competition with other users exists

Certain materials may be critical to nuclear reactor and fuel cycle systems and only available, processed or produced in a few countries or facilities. A nuclear energy programme will thus depend on a sure of supply of the materials needed.

Examples include copper, where reserves are limited, zircon with various industries competing, (cooling) water, or aggregate for concrete, where drinking water aquifers and gravel pits compete for the same locations.

6. Conclusions

Life-cycle impact assessment will help to demonstrate the sustainability or otherwise of a nuclear energy system or parts thereoff, including the mining and milling of uranium or thorium. It will also help to identify areas and operational aspects where there is scope for improvement. Such improvements can include the preventing of losses of materials to e.g. waste, identify the potential for recycling or re-use, reduce environmental impact by reduced use of materials or direct their flows into

areas where they may have less impact. Understanding where and in what form materials are being used over the life-cycle will also aid the decommissioning and decontamination process. Potential problems can be understood before they are actually arising, thus reducing the life-time impact of nuclear engergy systems.

The analsysis and the mapping out of material flows in nuclear energy systems are basic tools to assess and manage the life-cycle of such systems in a holistic and integrated way.

A structured life-cycle assessment and management based upon it will be of benefit to a wide variety of stakeholders, including planners, operators, licensing authorities and not the least the concerned public.

This paper outlines a new IAEA co-ordinated research project in this area. The result of this project will be a set of methods that can be applied specifically in the assessment for sustainability and resource of nuclear energy system, viz. innovative nuclear fuel cycle and reactor systems.

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Risk, legitimacy and governance
CSR, stakeholder dialogue and indicator systems through the life cycle of uranium

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Abstract. This paper outlines the methodological framework for a top-down/bottom-up approach for project evaluation, stakeholder dialogue and CSR reporting, with particular reference to radioactivity considerations. The tool-development phase is based partly on comparative analysis of international initiatives for sustainability indicators in the mining sector. Analyses at selected African mining projects will permit the adequacy of the methods to be tested in challenging conditions quite different from those addressed by licensing, safety and environmental regulations in the North. The goal is to achieve integration of stakeholders' preoccupations with experts' considerations to produce a set of indicators that can be understood and accepted as legitimate by a wide spectrum of stakeholders as an evaluation and monitoring framework across the full life cycle of a mine.

1. Introduction

The decade of the 1990s has been marked by a new societal demand for measuring the performance of the business sector relative to sustainable development goals. This emerging profile of Corporate Social Responsibility (CSR) places distinct requirements on company management, notably the Triple Bottom Line of economic, social and environmental performance. There is also an emphasis on social dialogue as a contribution to company reporting, strategy definition and decision making.

Nevertheless, designing indicator systems that respond to all stakeholders' claims and needs is a time-consuming and complex exercise, with certain questions still unsolved: How can the different life-cycle phases be taken into account? At what scales (local, national, global) can the indicators be applied? Is a utilisation of the same indicator at different scales possible? Is it pertinent to create a common framework for the whole mining industry for comparative purposes, considering the marked differences between sites (political, social and economic aspects, ore type, exploitation method, etc.)? Can the same system be used for uranium as for other raw materials (such as aluminium)? Can a single system be used for all phases of the uranium life cycle (extraction, electricity, reprocessing, site rehabilitation, waste management)?

This paper outlines methods of an ongoing project being carried out in partnership between BRGM's Mineral Resources Division and the C3ED* of the Université de Versailles St-Quentin en Yvelines (France). A top-down/bottom-up design for project evaluation, stakeholder dialogue and CSR reporting is proposed, based partly on participatory governance considerations, partly on comparative analysis of international initiatives for sustainability indicators in the mining sector and partly on empirical analyses at selected African mining projects. The adequacy of methods will thus be tested in challenging conditions quite different from licensing, safety and environmental regulations in the

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North. The goal is to achieve integration of stakeholders' preoccupations with experts' considerations to produce a set of indicators that can be understood and accepted as legitimate by a wide spectrum of stakeholders, across the life cycle of a mine.

Economy :

- ✓ Share in the country GDP
- ✓ Available resources
- ✓ Companies tax paid
- ✓ Payments to local suppliers

Social :

- ✓ Number of personal annual radiation exposure above 20mSv (employees and local community)
- ✓ Jobs (n/kWh)
- ✓ Number of loss time injuries (n/year)

Environment :

- ✓ Energy consumption
- ✓ Fresh water consumption/tonne of ore processed
- ✓ Energy use/tonne of ore processed (Mj/t)
- ✓ CO_2 emissions (kg/t)
- ✓ Waste management (radioactive and non-radioactive)

Institutional :

- ✓ Compliance with the local social and environmental regulations
- ✓ Provision made for post-mining management

2. CSR and advances in methods

CSR evaluation and reporting must consider not just individual industrial sites, but also the transferability, or not, of indicators suggested at one site, to other sites having comparable characteristics. Methods must be developed with a view to appraising the usefulness (and limits) of indicators at different organisational scales, notably in moving from a site management and communication context to higher-order coordination perspectives. Within political, economic and territorial coordination perspectives, there are good reasons for seeking indicators of a 'generic' character. But, for effectiveness of communications at all levels, there are also good reasons for being attentive to specific features of an industrial site, or sector, or country. The challenge is to bring these two concerns together. Work since 2000 by the C3ED has led to the development of a scientifically based "bottom-up/top-down" process for developing CSR indicators that takes into account the differences between plants, activities, countries and relevant stakeholder groups and bridges the gaps between site-level and higher levels of performance reporting. The framework that is proposed for a robust CSR reporting procedure is built up with the following six main steps.

2.1.1. STEP ONE: Identification of CSR performance &communication goals

One component in successful stakeholder dialogue and CSR communication is the use of a standard set of CSR performance issues to structure information management and communications [1]. The literature refers widely to four dimensions of sustainability (financial/economic, social, environmental and political/institutional). Stakeholders often convey, of sustainable development as built on four pillars: economic opportunity, social development, environmental safeguards and effective transparent management systems. We suggest therefore that selection and deployment of indicators should be made with reference to a standardised list of CSR Performance Issues, this classification being with reference to the "4 dimensions of sustainability". For example, a recent study carried out by the C3ED developed a consensus on the following set of CSR categories (Table I).

- STEP ONE — Identification of CSR performance and communication goals: Define the full spectrum of sustainability concerns and also the full spectrum of relevant stakeholder dialogue contexts;

- STEP TWO — Create or mobilise a relevant "data bank" of candidate indicators;

- STEP THREE — Exploit a selection of these indicators in a site-level CSR reporting process engaging stakeholder dialogue with target groups;

- STEP FOUR — Harmonise the site-level CSR evaluation and reporting process so that it responds also to higher-level coordination requirements;

- STEP FIVE — Assess satisfaction of the target groups with the results of the CSR reporting process.

- STEP SIX — Establish procedures for regular cycles of CSR evaluation and reporting.

Table I. CSR standard indicator categories [1]

Economic	Social	Environmental	Institutional
Competitiveness	Working Conditions / Health and Safety	Resource Use (National/European)	Environmental Management system
Pay & Benefits	Employee Opportunities and Relations	Resource Use – Global (International exchange)	Company CSR Strategy/Policy
Revenues and Payments	Internal Communications	Emissions and Impacts	Supply Chain Relationships
Production (physical)	Community Relationships	Product Use (Life Cycle)	

In a full life cycle appraisal attention must evidently be given to all phases: planning, operation and closure/post-mining; we return to this point later on.

2.1.2. STEP TWO: A catalogue of candidate indicators

Work in the field on CSR indicators demonstrates the importance of many different sources of information and expertise for obtaining "candidate indicators" which can be considered for deployment in a CSR monitoring and reporting process. These sources include:

- Identification directly through a stakeholder consultation process;
- Appraisal of indicator concepts provided by sector associations, international agencies, etc.;
- Looking at information sets the company uses for purposes other than CSR reporting;
- Assessment of the indicator concepts identified or deployed at other sites.

This is one example of the ways that appraisal of and communication about CSR performance must engage stakeholders across all relevant scales. The question of "generic" versus "site specific" character of indicators has to be resolved with reference to the several different purposes of evaluation, their distinctive communication contexts and their respective organisational scales. In this regard, an integrated framework for CSR reporting needs to be based on three main principles:

- **Recognition of Site Specificities:** What are the social, geographical & technological factors that have a bearing on the range of sites at which a CSR indicator can meaningfully be applied?

- **Stakeholder Diversity:** CSR reporting must include procedures for stakeholder dialogues that build up a shared understanding of the different stakeholders' concerns, permitting an appropriate balance of site-specific as well as generic indicators.

- **Full Spectrum of CSR Performance Issues**: A common ground for stakeholder dialogues and for CSR reporting at site and industry levels can be assured through use of a standardised set of CSR indicator categories based on sustainability considerations.

The associated knowledge management challenges can be resolved by using standardised indicator database (or meta-information system), here referred to as an INDICATOR DIALOGUE BOX, which provides for all users a common framework for the characterisation of CSR "candidate indicators". This creates, among other things, a space for a dialogue between producers and users of information. For each information category (viz. a potential indicator), it provides a descriptive profile relating to the several contexts of possible deployment of an indicator, viz., **Pertinence at what Scales of Description?; Pertinence Where? Pertinence for What? Pertinence for Whom?**

2.1.2.1. STEP THREE: Constructing a CSR evaluation matrix

CSR performance can and evidently will be considered from a variety of different points of view. This leads to the concept of a "CSR Evaluation Matrix". In a multi-criteria, multi-stakeholder perspective, an evaluation of CSR performance for a selected site results in an array of judgements, where each cell within the array corresponds to a judgement to be made by a specific category of stakeholder for each category of performance issue. In the selection of indicators for a site-level evaluation, we must be attentive to: (1) Which category of stakeholder is suggesting the indicator for application? (2) With reference to which CSR Performance Issues is the indicator being suggested or applied? A stakeholder dialogue process for making a site-level CSR assessment can have, for its goal, to select indicators allowing the target stakeholders to arrive at a judgement for each cell of the CSR Evaluation Matrix. We refer to this as "filling in the cells of the CSR Evaluation Matrix".

2.1.2.2. STEP FOUR: Multi-stakeholder multi-scale interface

A stakeholder dialogue process for making a site-level CSR assessment can have, for its goal, to select indicators allowing the target stakeholders to arrive at a judgement for each cell of the CSR Evaluation Matrix. We refer to this as "filling in the cells of the CSR Evaluation Matrix". For example, representatives from each category of stakeholder may work together to select, with reference to each CSR Performance Issue, a "basket" of indicators from amongst the available "candidate indicators". If participants feel that the list of candidate indicators is insufficient to cover their specific concerns, new indicator suggestions will emerge which can be used to complement the existing list in an iterative process. Based on the resulting selection of indicators, an overall judgement is to be put forward, by each category of stakeholders, for each of the performance issues being considered.

For the specification of the stakeholder categories, we follow the reasoning and experience of recent studies [2] which distinguishes three main categories of stakeholders. To illustrate, the Table II below shows, on the left the C3ED's three categories; in the centre column a "generic" typology of mining site stakeholders and, on the right the situation of the SOMAÏR company in Niger [3].

We propose that the indicator mix for any site-level or sector-level CSR reporting process should respect a principle of "representative diversity". We use this term in an intuitive way, to mean that no important consideration should be omitted. For example, it is essential to maintain the "Representative Diversity" of indicators that signal the "specificities" of individual stakeholder groups and the full spectrum of performance issues. We can also express this as a principle of equitable stakeholder visibility. This is not a purely quantitative equity. As in other forms of industrial bargaining or multi-stakeholder negotiations, compromises can be made if honour is preserved. Just as important as the retention of an individually "preferred" indicator, is the visible trace of the deliberation process and of the meaningful participation of the cross-section of stakeholders [4].

Table II. Monitoring the uranium production and use cycle

C3ED stakeholders categories	**Mining site stakeholders**	**Arlit mining site stakeholders** **[Source:** Capus G., Bourrelier P., Souley M. (2004)**]**
The internal stakeholders of activities at site	Mining Company	Somaïr
	Employees	565 employees in 2003
	Labour unions	One main labour: Syntramin
The "external" stakeholders as traditionally identified business partners	Suppliers	Many different suppliers: international, national or local companies, depending on the type of product
	Customers	Mainly AREVA
	Shareholders	AREVA-France & affiliates (63.4%), ONAREM-Niger (State of Niger, 33.6%)
	Banks and insurance	-
The broader external "community" stakeholders	NGOs	Local and international NGOs
	Local population	The city of Arlit was created when the extraction began. There are now 70 000 inhabitants, all directly or indirectly dependent on the activity.
	Artisanal or small-scale miners	No artisanal or small scale mining activity in the site

CSR reporting is not an end in itself; it is an input to wider stakeholder dialogue and governance, and it is a reference point for forward planning, investment and other strategic decisions for the plant management, companies and industrial sectors concerned. In project planning contexts, there is generally a need to identify, appraise and choose amongst the various different options or courses of action that present themselves. The different protagonists concerned will have divergent views about what is their interest, their right or their due; and they may also propose quite different principles for deciding what to do or what "should" be done. There are various degrees of uncertainty due partly to technological and natural system complexity and partly to 'social' indeterminacies. In this context of "complexity", a pragmatic and robust evaluation approach is to frame the problem of 'social choice' as a multi-stakeholder deliberation about the merits and demerits of policy alternatives that present themselves to the society. A comparison of project or regulatory policy options (e.g., mine site development, or post-mine site management regimes, etc.) can be developed in terms of:

1. ***The exploration of options: Minerals exploitation strategies, site rehabilitation, radioactive waste policy or other strategic perspectives are explored in terms of a small number of scenarios each of which expresses distinct technological, economic and governance features.***

2. ***The diversity of stakeholders: The scenarios of distinct possible futures are to be evaluated explicitly from as many distinct stakeholder perspectives as seem germane to the task.***

3. ***Multiple evaluation criteria: The stakeholders will make evaluations of each scenario in terms of a range of key performance issues, using a variety of different criteria reflecting the spread of societal concerns.***

This leads to a three-dimensional **Deliberation Matrix** (Fig. 1) as an intuitive framework for organising the judgements offered by each category of stakeholders, for each of a variety of scenarios, across a spectrum of governance or performance issues. The hypothesis is that, as the multiple perspectives are brought to bear on a common ground (viz., the scenario set) then the tensions, conflicts of interests, uncertainties and dissent (amongst scientists as well as decision makers, administrators and stakeholders from different walks of commercial activity and civil society) can be articulated and explored in a structured way. The participatory 'evaluation' activity proceeds through the step-by-step phase, which can be undertaken on an individual or a collective basis within the group, of the filling out of cells of the Deliberation Matrix. Individual reflection and/or exchanges of views between protagonists in a deliberation/negotiation process may lead to modifications at any or all or the steps of the choices and judgements.

For applications to the uranium life cycle, attention should be given to the specificities of the main life phases: planning, operation and closure/post mining and to the specificities of uranium itself. For methodological purposes we focus on the 'closure/post-mining' phase and to focus on the features for which uranium is singled out — namely the long time-scale aspects of managing health and environmental risks associated with mineral extraction and transportation and post-mining site rehabilitation — situations which present some similarities with nuclear power plant decommissioning and long-term radioactive wastes management. The generic challenge here is the *governance* of situations of risks associated with long life radioactive by-products and wastes, which may be *in situ* (e.g., around a mining activity) or in transport, or delocalised to temporary or permanent storage facilities. At the end of this discussion, we return to the integrated view of planning, operational and post-mining phases.

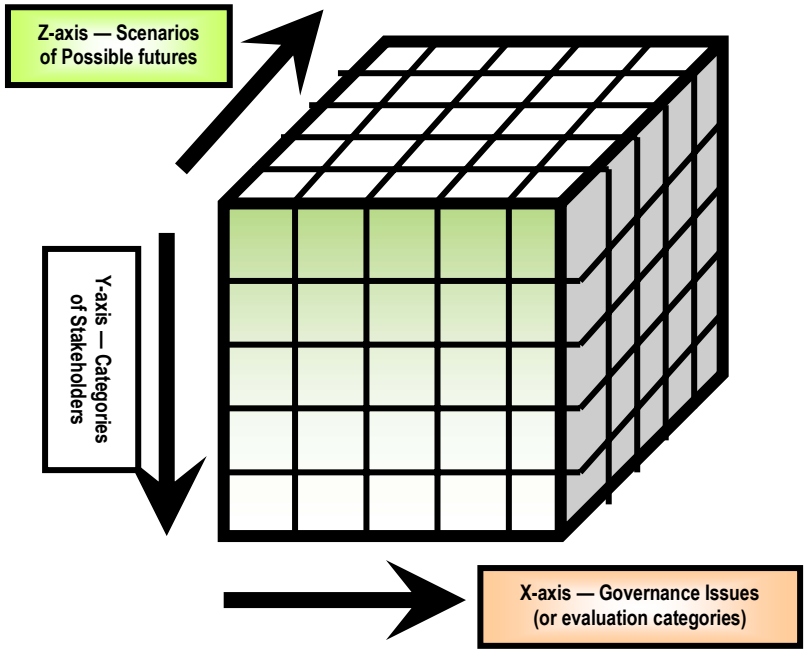

FIG. 1. 3-dimensional deliberation matrix.

Science and technical expertise address (among other things) *ways and means* of controlling the exposure of present and future generations to radiation, relative to what is considered safe or otherwise satisfactory. Can we deduce from experts' statistics and scenario speculations about the present and possible future levels of exposure, what 'should' be done? The short answer is, no. The radioactivity risks, by-products and wastes in question, constitute socially constructed risk situations. The significance – and hence the acceptability or not – to an individual, to members of a community, to a society of exposure (or a danger of exposure) to a dose may depends partly on how, by whom and why the dose (or potential dose) has been produced. In order to assess to what extent or on what basis the members of a society will judge acceptable (or not) a given strategy for development or site management, decision makers will have to consider the distinctive meanings and *relationships* that the alternative strategies might establish between the people – individuals, classes, neighbouring villages, economic interest groups, succeeding generations, whole nations – implicated in the situations of mineral production, transport and storage, site management, and the monitoring of wastes [5].

To highlight this *social dimension* of project appraisal and design, we draw on an instructive example from the OECD Nuclear Energy Agency's 'Forum on Stakeholder Confidence' Workshop held in

Ottawa, Canada, in October 2002 [6].[1] This is the experience of the communities of Port Hope, on the shores of Lake Ontario, whose townships have been contaminated with (mostly low level) long lived radioactive wastes due to past factory activities of radium and uranium refining. A striking feature of this 'case study', is that the Port Hope (and neighbouring) communities have consciously set about to *build a social – and societal – relationship with the wastes*. Emerging from more than 20 years of inconclusive discussions, suggestions and deliberations is a clear affirmation by the Port Hope community that it accepts 'ownership' of the contamination problem. It is a *historical liability* that the community *affirms as a part of its identity*. The community has actually refused certain proposed solutions for long-term waste management that depend on expertise and knowledge that they feel is not sufficiently accessible to them – that is, that would place the problem 'out of their hands'. They prefer a *solution that they can see and understand*. Their favoured solution concept is to accommodate the radioactive wastes as modern-day burial mounds. The radioactive wastes, piled together and suitably 'capped', will become landscape features integrated into the everyday life of the community. The managed wastes thus become features in a kind of theme park, this becomes (it is hoped) a tourist draw card rather than a reason to shy away.

The message we may take from this example is that the 'appropriation' of a site rehabilitation or waste/contamination problem by 'local' stakeholders and their identification of a solution concept *that they can live with* are probably essential ingredients for "durability" of a project and for the long-term viability of any site rehabilitation or waste management solution. There are thus three key components for successful piloting of projects at any phae of the uranium extraction and use cycle:

- Scientific knowledge and Technical competency about risks: e.g., to measure and to control the present and eventual exposure of living beings to radioactivity;

- The Social Dimension – Building Social/Societal Relationships with the Wastes: the envisaging and invention, in social and symbolic terms, of how the relevant communities will relate to and interact with the site (before, during and after industrial activity) and/or the off-site wastes;

- Political/Economic Partnerships: permitting to mobilise the relevant knowledge and resources for the implementation of an agreed societal solution to the disposal and watching over of the wastes.

Consider, within this framework, the problem of developing CSR (quality assurance, sustainability) indicators for the long-term post-mining phase, e.g., site rehabilitation and/or stewardship programmes (analogous, in many respects, to long-run radioactive waste management programmes). The obvious question arises of *the nature of the relationships* that will be established and maintained by different components of the affected societies society with the sites and with, in their various forms, the radioactive materials. Generalising from the Post Hope (Canada) example and others, we propose a checklist thats permit waste/site management solutions to be classed within a typology of stewardship paradigms. This typology thus provides a framework for assessing, with reference to broad societal considerations as well as technical considerations, the likely acceptability — or not — of stewardship strategies proposed for a given site.

In the presentation below (inset box), the questions are first formulated in descriptive language (viz., specifying features of the actual or proposed solution). Then, as a function of circumstance and of stakeholder points of view, the questions can each be modified with normative or prescriptive language, showing how they can function as criteria of acceptability. Examples of this normative reformulation are suggested in italics.

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[1] The argument that follows is adapted from parts of O'Connor (2003). For further details of the NEA's Forum on Stakeholder Confidence and their programme of workshops since 2000, see the website http://www.nea.fr/html/civil/welcome.html.

- **Q.1. Is there official recognition of a waste, residual risk or contamination problem at the site?** *(Should there be official recognition of a waste, residual risk or contamination problem?)*
- **Q.2. If yes, is there, or is there planned to be, active stewardship of the site?** *(Should there be active stewardship of the site?)*
- **Q.3. Is there, or is there planned to be, an ongoing public interaction with the site as a dimension of the stewardship process?** *(Should there be an ongoing public interaction with the site?)*
- **Q.4. If yes, is the "historical liability" made a feature of the site's new public identity or use?** *(Should the historical liability be made into a feature of the site's new identity and use?)*
- **Q.5. If yes, what sorts of activity are mainly associated with the contamination or waste features, e.g., public good activities such as education, training and research; or private benefit activities such as recreation, tourism?** *(What sorts of activities should be associated with the contamination or waste features?)*
- **Q.6. What sort of socio-economic status and prestige is accorded to the stewardship process?** *(What socio-economic profile, prestige or importance should be associated with the stewardship process?)*

These questions are ordered in such a way that, by specifying responses yes/no sequentially for Q.1 to Q4, one obtains four fundamentally distinct classes of stewardship solution. We designate these: **No problem; Orphan site; Segregation; Social reintegration**. The responses to questions Q.5 and Q.6, which are more of a qualitative character, permit to develop a typology of solutions on the basis of further socio-economic considerations, within each of the four fundamental classes of solution (see examples of stewardship concepts/metaphors in the inset box, below).

This typology process helps to highlight the qualitative range of different models that can be (and have been) envisaged for stewardship of toxic waste or contaminated sites. As highlighted by the range of examples proposed in the schema, each category of stewardship solution has its appropriate analogies and metaphors, and thus privileges different aspects of social life, different types of prestige & status, different communities, different relationships and so on. A wide spectrum of technical, engineering, financial, management, record-keeping, monitoring and communication procedures must all be framed — tacitly or explicitly — with recognition of these qualitative societal and institutional choices.

Framing the technical and operational considerations explicitly with reference to societal considerations can probably enhance the prospects of reaching agreement about appropriate and satisfactory stewardship solutions.[2]

These examples give the backdrop for returning to the main theme of our paper, which is the identification of performance indicators for mining and site rehabilitation projects and the prospect of carrying out a multi-stakeholder multi-criteria appraisal of past, present and future developments. The three axes of the CSR **Deliberation Matrix** (as outlined above) can be used to frame an evaluation process, within which individual indicators find their place. The general idea is that a number of options, here described as 'scenarios', might be identified and assessed in a comparative way by people bringing a variety of preoccupations, expertises and points of view.

We focus on qualitatively different social models, e.g., for watching over the site (as in the inset box, above) or, in the case of a mining development, different models of the relationships (economic, employment, money flows, communication, etc.) with local communities. Then, we consider each of

[2] Take the example of the jobs attached to the long-term site stewardship activity, meaning salaries to be paid, residences to be occupied, and so on. In what terms will the jobs of site warden be advertised? Who will be recruited (job opportunities for the locals?)? What will be the sorts of skills required? What skin colour? What salary scale? What will be the relation of the site wardens to others in the local community (if there is a local community), and the perception of their role by the rest of the society?

these solution concepts as proposals of ethically principled action. The 'ethical' dimension of management consists, in fact, of the articulation of the different principles that may underlie operational criteria. When we consider the spectrum of stewardship strategies as being ethically principled actions, we seek to identify the ways in which, as individual and collective actions, they satisfy or respond to particular criteria of good or sound practice that are suggested by members of the community. The following list gives principles of quality, performance and responsibility that have been advanced in relation to contaminated site stewardship.

Site stewardship concepts: some examples

- If the response to **Q.1** is **"No"**, there may nonetheless be ongoing controversy about whether or not there is danger associated with a site.

- The sequence **Q.1 "Yes", Q.2 "No"** would imply identification of an 'orphan' site, and therefore to the question of the acceptability of this orphan status.

- The sequence **Q.1 "Yes" Q.2 "Yes" Q.3 "No"** would lead to concepts of a segregated or isolated site, with restricted access. Appropriate analogies might be a dangerous natural site, a rubbish dump, a warehouse for storing dangerous goods, a mausoleum, or a nursing home. Answers to Q.6 would permit a characterization of the socio-economic status of the stewardship activity for the site.

- The sequence **Q.1 "Yes" Q.2 "Yes" Q.3 "Yes" Q.4 "No"** leads to suggestions for "ordinary" uses of the site, e.g., industrial or forestry production, or recreational activities (such as a golf course) that do not in any way rely on (or 'exploit' the stewardship status of the site). These activities will, however, be under a regulatory shadow, and answers to Q.5 and Q.6 would highlight whether or not a negative stigma is associated with the site.

- The sequence Q**.1 "Yes" Q.2 "Yes" Q.3 "Yes" Q.4 "Yes"** leads, by contrast, to suggestions for uses of the site that specifically rely on or 'exploit' the historical liability as a distinctive feature of the site. This could include "ordinary" commercial uses of the site such as tourist and recreational activities, but that specifically play on the identity of the site (e.g., an advertising gimmick of a golf course with grass that glows in the dark), or installations such as a shrine or temple, museums and educational facilities that draw substantively on the heritage of the site.

The general idea of a multi-stakeholder deliberation process is that a *comparative evaluation* of the stewardship scenarios should take place from a variety of *different points of view* corresponding to distinct preoccupations. Each distinct stakeholder group will bring a different balance of preoccupations to the evaluation process. Each stakeholder group may express different criteria of adequacy or quality in relation to each of the 'governance issues'. The objective should be that, where tensions, conflicts of interests, uncertainties and dissent emerge (e.g., amongst scientists as well as decision makers, administrators and stakeholders from different walks of commercial activity and civil society), these differences and the underlying reasons should be documented. The reasons for dissent can then be discussed in a transparent way, which sometimes opens up prospects for novel strategies.

A set of 'Ethical bottom Lines' (principles of responsibility) for the radioactivity stewardship domain is as follows.

PR.1 Have the responsibilities of existing parties been appropriately assigned? For example

- Application of a principle of national autonomy/responsibility ('take care of your own wastes' at national scale)
- Application of the principle that 'the polluter pays'
- Clear expression of, and respect for, local, national and international regulatory conditions

PR.2 Have responsibilities 'towards other parties' in the short term been adequately addressed? For example:

- Health security to workers and the public on or close to the site
- Security against attack in the face of external or internal sources of aggression

PR.3 Have responsibilities 'towards other parties' in the longer term been adequately addressed? For example

- A 'sustainability' principle of inter-generational responsibility (don't pass on problems to others that you cannot cope with yourself)
- A thorough characterisation of risks/uncertainties/future contingencies (with reference to: the dangerous substances, the engineering works, the living environment, and future societal evolutions)
- An application of some version of the principle of precaution
- Is there likely long term stability of the necessary knowledge base (e.g., transmission of records, specialised know-how, local knowledge) for competent stewardship?

PR.4 Has available technical knowhow and systems science been mobilised? For example

- Rigorous profiling (in technical, medical and sociological terms) of the exposure risks
- Standards of best practice (technical reliability, simplicity)
- Monitoring procedures attentive to the full spectrum of identified risks/uncertainties/future contingencies

PR.5 Is the solution economically viable? For example

- Are the immediate costs of stewardship affordable with the available resources?
- Clear picture of the trade-offs and relationship between clean-up and stewardship
- Are the solutions cost-effective for the identified risk reduction results?
- Are there major financial costs shifted into the future?
- Reasonable prospects of mobilising resources for the forecast stewardship costs in the longer term?

PR.6 Does the solution enhance the prestige of the host communities and other stakeholder groups closely associated with the residual/waste site?

- Viable partnership between local and national stakeholders (e.g., agreed distribution of responsibilities; legal mandate for stewardship activity; agreement on bases for financing of different cost components, etc.)
- Site specificities clearly in evidence?
- Local competencies clearly in evidence?
- Well defined framework for ongoing involvement of stakeholders in stewardship oversight and review
- Links to educational and training activities at local and wider scales.

3. Summing Up

The multi-stakeholder dialogue should be considered at the outset of any mining activity, in the project conception, approval and planning phase. The considerations of performance, quality assurance and responsibility to be addressed *ex ante*, ought to mirror the considerations that would be addressed *ex post* in the operational and closure phases. With this in mind, to close our presentation we suggest in a schematic way (via the Table III) an integrative framework for addressing performance and responsibility across the life cycle of a mining activity.

Table III. Integrative framework – performance and responsibility

Planning : 7Qs	**Operation : Aluminium**	**POST-MINING : « ETHICAL BOTTOM LINES » FOR THE RADIOACTIVITY STEWARDSHIP DOMAIN**
Q1 : Engagement : Are engagement processes in place and working effectively ?	• Company CSR strategy	PR1 : Have the responsibilities of existing parties been appropriately assigned ? PR2 : Have responsibilities « towards other parties » in the short term been adequately addressed ? PR3 : Have responsibilities « towards other parties » in the long term been adequately addressed ?
Q2 : People : Will people's well-being be maintained or improved ?	• Community relationship • Working conditions / Health and safety • Employee opportunities and relations	PR6 : Does the solution enhance the prestige of the host communities and other stakeholder groups closely associated with the residual/waste site ?
Q3: Environment: Is the integrity of the environment assured over the long term?	• Resource Use (National / European) • Resource use – Global (International exchange) • Emissions and impacts • Product use (life cycle) • Environmental management system	PR1: Have the responsibilities of existing parties been appropriately assigned? PR2: Have responsibilities "towards other parties" in the short term been adequately addressed? PR3: Have responsibilities "towards other parties" in the long term been adequately addressed?
?	?	PR4 : Have available technical know-how and system science been mobilised ?
Q4 : Economy : Is the economic viability of the project or operation assured, and will the economy of the community and beyond be better off as a result ?	• Competitiveness • Pay & benefits • Revenues & payments • Production	PR5 : Is the solution economically viable ?
Q5 : Traditional and non-market activities : Are traditional and non-market activities in the community and surrounding area accounted for in a way that is acceptable to the local people ?	?	PR6 : Does the solution enhance the prestige of the host communities and other stakeholder groups closely associated with the residual/waste site ?
Q6 : Institutional arrangements and governance : Are rules, incentives, programs and capacities in place to address project or operational consequences ?	Company CSR strategy/policy	PR1 : Have the responsibilities of existing parties been appropriately assigned ? PR2 : Have responsibilities « towards other parties » in the short term been adequately addressed ? PR3 : Have responsibilities « towards other parties » in the long term been adequately addressed ?
Q7 : Synthesis and continuous learning : does a full synthesis show that the net result will be positive or negative in the long term, and will there be periodic reassessment ?	?	PR1 : Have the responsibilities of existing parties been appropriately assigned ? PR2 : Have responsibilities « towards other parties » in the short term been adequately addressed ? PR3 : Have responsibilities « towards other parties » in the long term been adequately addressed ?
?	Internal communication	?
?	Supply chain relationships	?

Key : For the planning phase categories, we show the checklist developed by the North America MMSD working group called *7 Questions for Sustainability* (left hand column). For the 'operation' or production phase categories, we show the C3ED's aluminium industry CSR categories (from O'Connor et al., 2004; middle column). For the post-mining phase, we show the "Ethical bottom lines" for the radioactivity stewardship domain as outlined above (right hand column).

This comparison process — which obviously can be deepened — demonstrates the relative similarities and specificities of the three phases in the mining life cycle. Three major categories are clearly transposable: the « responsibility » aspects and the focus on economic and social impacts (which show up variously as concerns for community impacts or for working conditions, wages, etc.). The environment dimension is given very specific treatments in the planning and operational phase checklist, but has a more implicit and transversal presence in the list of responsibilities for post-closure stewardship. The longer term aspects are, not surprisingly, in clear evidence in the planning and the post-mining models, but less explicitly developed in the operational CSR framework. Finally, the issue of good use of technical know-how and systems science is explicitly mentioned in the post-mining checklist, but does not appear in the planning and operational phases. This is an example of implicit principles: it would be quite astonishing if technical performance and good use of knowledge were not inherent in quality assurance for planning and operational phases! So, without developing further the process of reconciliation across phases, we leave question marks in the table to signal the interrogation: does the absence of a criterion in this cell mean that the issue is not pertinent in this phase or that it comes up under a different heading, or that it is implicit but not identified per se in the checklists employed for the compilation of the table?

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Uranium mine project licensing
Cameco's current experience

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Abstract. Environmental assessment and licensing requirements for new uranium projects have become more complex, and can have a substantial influence on the timelines needed to bring new production on-line. This increased complexity is taking place in an era that is witnessing a resurging interest in uranium exploration. The assessment and licensing process has evolved to include more sophisticated ecological risk assessment, more detailed waste rock and tailings management plans and comprehensive socio-economic impact assessments. While such assessments are fully compatible with sustainable development objectives, they do take time. The current challenges, as encountered by Cameco in its most recent work, are associated with timelines, predictability and effectiveness. All are needed in the process if market demands are to be met efficiently. The good news remains that the assessment process, while frustrating at times in its duration, strongly supports our main collective environmental goal, which is to solidly support the clean environment aspects of nuclear power at our end of the nuclear fuel chain.

1. Introduction

There are many challenges to be addressed in developing projects to maintain an adequate global supply of uranium, needed to fuel one of the world's cleanest energy sources - nuclear power. While the challenges in finding new, economically viable ore deposits are daunting, so too can be the environmental licensing requirements for these new developments. The uranium world is much changed from its inception, not only in terms of the exploration technology, the exploration targets and the mining methods, but also in the Environmental Assessment (EA) and licensing processes needed to bring these new discoveries to fruition.

Not only has it become more complex to find economic ore deposits, it is also more complex to get them licensed for development The licensing process has become more time-consuming and costly as it has evolved. Given the current outlook for the uranium market, with the ever-present gap between primary uranium production and consumption rates, it is very important that the EA process be carried out as expeditiously as possible. While closer environmental examination offers the potential to generate more problem-free developments in the long run, the EA process itself can be an important factor in deciding which uranium deposits get developed and which do not, as well as the timing of the development.

Following a brief review of the evolution of EA as experienced by Cameco Corporation and its predecessors, generic requirements associated with the current EA process for uranium projects are reviewed. This is followed by a discussion of the specific EA requirements for new, greenfield developments as well as for new project developments on existing properties, commonly called brownfield developments.

Cameco has had much experience over the past decade in tackling these issues both in Canada and elsewhere. This paper offers Cameco's current perspective on the modern licensing or permitting process. The intent is to outline the dominant environmental licensing issues, what we felt works well

in the process and areas where we think improvements could be made. The basis of this paper are the licensing processes to commence operations at the McArthur River and Cigar Lake uranium mine projects in northern Saskatchewan, Canada. Also considered are related efforts to permit the use of the Key Lake mill facilities to process McArthur River ore, efforts to expand production capabilities at McArthur River/Key Lake, and recent efforts to licence the processing of Cigar Lake ore solution at the Rabbit Lake mill facility.

2. Historical context

During the nuclear power era, there have been three generations of uranium mines developed in Canada. The first generation of mines produced ore in the 1950's - 1960's, from small, low-grade deposits in the Uranium City area of northern Saskatchewan and from the much larger low-grade deposits in the Elliot Lake area of northern Ontario. At that time, and common to all mining sectors, little thought was given to formal environmental assessment during initial project development. This era was hallmarked, in the Uranium City area, by: small operators, short mine lives, and abandoned mines and mills. The licensing process of the day reflected this type of development.

Mines of the second generation were brought into production in the 1970's and 1980's. At ore grades in the 2-4% U_3O_8 range, these mines, including Rabbit Lake, Cluff Lake and Key Lake, were high-grade mines relative to the world norm at that time. Although the environmental assessment science was not as well developed relative to today's standards,, these projects were subject to substantial assessments. These assessments focused on the collection of baseline data. Primary emphasis was placed on tailings management and mine/mill effluent quality. The assessment of secondary metal content of the ore, such as arsenic and nickel, were part of the EA scope. These assessments were also the first attempts to address larger socio-economic issues associated with the projects.

Mines of the third, or current, generation were discovered in the 1980's and assessed in the 1990's. These mines, including the McArthur River and Cigar Lake mines in northern Saskatchewan, are even higher-grade deposits, with average grades of 15-20% U_3O_8. The mill at the Cogema McClean Lake operation, commissioned in 1999, is the first mill expressly designed to allow the direct treatment of these higher-grade ores. The environmental assessment process has evolved to include ecological risk assessments (including long-term contaminant transport pathways modeling,), hydrogeological modeling, sophisticated radiological assessments, detailed waste rock management planning, and comprehensive socio-economic impact assessments.

3. Current environmental assessment requirements

3.1. Regulatory context

As practiced in many countries, in Canada there are extensive regulatory oversight mechanisms for new uranium developments. While this regulatory process has limited impact on the initial exploration stage, it has a major influence on the delineation of the discovery, and its development, operation and decommissioning.

There are two main phases to the Canadian regulatory approval process. First is general government environmental assessment approval to proceed with the project once it has been discovered, followed by the licensing or permitting phase. It currently takes up to one decade to obtain these approvals for a major new front-end nuclear fuel chain operation, and develop it, starting from initial discovery. However, with more and more experience brought on by the resurgence of interest in uranium exploration, we fully expect to see timeline reductions as good development prospects are discovered. Environmental issues are of particular priority at the front end of the nuclear fuel chain. Suffice it to say that there are more potential environmental effects associated with ore extraction and concentration than from the utilization of the finished uranium product. This additional emphasis on environmental impact assessment at the front end of the fuel chain is offset by the inherently reduced radiological and nuclear safety accident risk relative to the power generation end of the chain.

Early on in a project's life, there is fairly wide-ranging assessment of the more generic, or "big picture" issues. A modern uranium project must convincingly demonstrate how it will not generate significant environmental impact either during operation or upon completion. If subject to a full scale EA, the project must also demonstrate social and economic benefit to local communities. In northern Saskatchewan, these social objectives are codified in the initial government approval process, through a surface lease arrangement, since government owns the land in question.

The second regulatory approval phase is the actual licensing process. This involves approvals by government-created regulatory agencies. In Canada, the primary nuclear regulator is the Canadian Nuclear Safety Commission. Permits are required to construct, operate, modify and decommission a particular facility or part of a facility.

3.2. Generic requirements

Over the past decade, the environmental assessment requirements for uranium mining projects have gone through major changes. Modern environmental assessments can serve both as an early-phase project planning tool and as a way of defining the predicted, and subsequently approved, envelope of environmental impact associated with the project. There is the inherent tension between using EA as an early phase planning and as a mechanism to provide detailed impact prediction once the design has advanced to the point that reasonably accurate predictions can be made. The EA must articulate credible waste rock and tailings management plans and must include a solid conceptual site reclamation and decommissioning plan for post-operational recovery of the site. Being definitive on such matters at the early stages of a project is challenging.

The EA influences subsequent detailed design, both positively and negatively. On the positive side is the establishment of clear environmental and safety design objectives. On the negative side is a potential damper on creative, alternative ways to meet these objectives. The EA needs to predict impacts from mining methods that are often innovative, given some of the geological challenges associated with modern ore bodies. Air and effluent emission impacts must be predicted, and not just to end-of-pipe concentrations and loadings. In other words, environmental modeling must extend to estimate impact on near-field aquatic and terrestrial life, and also include all major chemicals, not just radionuclides. Predicting the impact on aquatic sediment has also become increasingly important.

The shift away from sole reliance on effluent chemical quality prediction to the more effects-based considerations such as build up of contaminants in near-field aquatic sediment, and its impact on the plants and animals which interact with the sediment and water quality has been one of the major new challenges in EA work. With this more sophisticated analysis come new questions such as how far afield should impacts be allowed to accumulate, or put another way, what should be the downstream control point. Some ecological compartments are primarily affected by the concentration of a contaminant, and others by overall accumulated contaminant load over the lifespan of the facility. It is difficult enough to predict effluent concentrations and loadings. Subsequent predictions of their effect are even more complex. With added complexity comes higher risk of ending up with less-than-accurate predictions. One adds conservatism to the predictions to compensate for this increased uncertainty, but at the risk of over-designing the necessary mitigation measures to deal with these predictions. On the other hand, conservative estimates are desirable, given the regulatory difficulties associated with operating with either higher loadings or higher concentrations than originally forecast in the EA.

One of the other priority aspects in current EA work not found in earlier EA's is the concept of groundwater control points and performance standards. While this is the main event in EA work for in-situ leach (ISL) mining opportunities, it also has application in conventional uranium mining as well, particularly where one is modeling the long-term performance of tailings and waste rock. In Canada, the focus has traditionally been on surface water rather than groundwater impact prediction.

The EA must describe environmental protection alternatives and contingencies, with the need to articulate follow-up environmental monitoring requirements. Post EA monitoring is not just for

compliance verification. It must also serve as an early warning for unanticipated effects, and also be of sufficient scope to judge the accuracy of any pre-operational EA predictions. Mining developments, more so than man-made constructs, must cope with the vagaries of nature. The inherent unknowns associated with mining bring additional complexity to the EA process. On the one hand, flexibility is needed given these uncertainties in mine development, yet as much precision and certainty as possible is called for in environmental assessment to accurately predict potential effects and reduce the need for ongoing re-assessment.

Socioeconomic considerations must be articulated in a sustainable development context and generally speaking, much more extensive public consultation efforts are now required. We seek social licence, not just regulatory licence. All this more complex EA process is not, of course, unique to the uranium industry, and while laudable, takes time. As the requirements expand, so too must the level of effort. A level playing field must be maintained with peer mining and energy industries if we are to attract the investment needed for new uranium development and compete with other energy alternatives.

3.3. Greenfield developments

There are some EA challenges that are particular to new developments, commonly called greenfield sites. These are most often associated with new exploration activity. It is fundamentally important to get the site environmental baseline articulated as well as possible, particularly the hydrogeological and biological setting for the development. All too often, environmental comparison work is statistically limited by the scope of the original baseline data, when evaluating current conditions against pre-development conditions. There are often good synergies between baseline exploration data collection and baseline environmental assessment work. For instance, the exploration drill results for the Key Lake ore deposits proved to be one of the major data sources for subsequent waste rock characterization studies. To reduce the time needed for an EA, baseline environmental data is quite often being collected at the same time as advanced exploration work is underway. To fast-track a project, one must often decide to proceed with environmental baseline work before project feasibility is assured, particularly in places like northern Saskatchewan where environmental conditions must be characterized for four very distinctive seasons.

Since reclamation criteria are often benchmarked against pre-development conditions, it is important to define them as thoroughly as possible, particularly when these benchmarks are biological as opposed to chemical. Basic definitions must be established on what constitutes an acceptable level of impact and where it will be measured. Conceptually, the goalposts, which will be used as benchmarks going forward, must be clearly spelled out from the onset. Failure to do so increases the risk of re-doing the EA when project changes crop up, as they inevitably do during the life of the mine.

For complex new developments, there are often requirements to do two EA's, one for the test mine necessary to prove out the mining method and to calculate project economics leading to the decision (often multi-party) to proceed, and the second EA for full-scale development of the resource. There are difficulties in proposing adaptive management (wait and see) strategies in a regulatory system that must come up with definitive decisions, not tentative or conditional decisions. There are challenges introduced by the interpretation of the precautionary principle. New developments, being more theoretical than existing developments, are much easier to challenge on precautionary grounds. There is a natural inclination to try to solve all problems at the front end of the project, particularly when it has not yet been approved for development. Excess conservatism can significantly increase project costs. These are some of the special challenges most strongly associated with getting approvals for a clean-slate project.

3.4. Brownfield developments

As in the case of greenfield site development, there are some EA challenges particular to development modifications on existing sites. These are often called brownfield site developments, however, one would be hard-pressed to say that modern uranium mine developments generate the types of environmental impacts most often associated with the word "brownfield". Environmental assessments

done on existing facilities are both helped and hindered by the presence of real data. One is faced with the messiness or statistical uncertainties of real data, and must explain how the real data fits into unambiguous environmental transport and impact assessment models.

With existing sites come existing issues. The scope of the EA for a new proposed development on a brownfield site must be carefully defined. For instance, is the assessment to be based on existing absolute levels of impact or project-specific incremental impact? To what extent should potential future developments be considered at an ever-evolving, dynamic site? Should the basis of assessment be geologic reserves or resources? There is the problem of mixing the old with the new in an EA. For example, assessing the impact of blending existing waste rock with EA-scoped new tailings. There are the problems associated with the fact that goalposts defined by the original EA may have been changed by new science or changing societal expectations, and there may be entirely new goalposts as well relative to the site's original EA. Generally speaking, it has been our experience that compared to a greenfield development, there is a higher level of regulatory and public acceptance for the concept of adaptive environmental management if a facility is already in existence.

4. Current EA process challenges

While there is a litany of issues associated with a modern uranium environmental assessment, the issues are far from insurmountable. The problem is more with the time needed to address these challenges more so than the content of the regulatory negotiations. A balance is needed, with EA effort commensurate with environmental risk. The EA must add value and not just end up reiterating existing knowledge. Given all of the topics that could be covered in an EA and the scope of work that could be carried out to address these issues, it is very important to reach agreement on the scope of the EA to a fairly detailed level early in the project. As previously noted, there is a strong temptation to try and address all issues as thoroughly as possible at the front end of a project, at the EA end of what will be a long regulatory journey over the life of a project. At this EA front end, there is not as much data as might otherwise be available were the issue to be addressed in the subsequent licensing phase, either once the detailed design of a project has been completed or once some initial operating data is available.

A balance of effort must be achieved in environmental management, between measures to control operational-phase routine releases, operational-phase major environmental accident prevention, and long-term post operational liability management. All three aspects present predictive challenges, especially for new projects, where lack of real data prevents verification using the observational method, resorting solely on model-related predictions. In the case of operational-phase releases, biological endpoints need to be well defined – such as protection to the cellular, individual organism, or population level. In the case of accident prevention, evaluation methods and design objectives must be clearly defined – such as probabilistic analysis and acceptance criteria vs. a more deterministic approach. In the case of liability management, the end-state decommissioning objectives need to be determined – such as long-term passive control vs. active institutional control, leachate control objectives, and in-situ treatment options vs. relocation options.

As an EA is developed, one is invariably faced with data gaps in the ability to estimate environmental effects. Lack of site-specific data, and such things as chemical speciation effects, or the interaction between various chemical species in the effluent to mediate their potential toxicity are compounding factors. Regulatory response to such uncertainties is to apply conservatism or the precautionary principle. This can be overused. Within reasonable bounds, uncertainty should not be used as a justification to stop or delay worthy projects. Environmental research opportunities often arise from these uncertainties, and are a useful addition to the overall environmental management program. However, one cannot wait for basic research before an EA is completed, since research is most often a journey, not an endpoint.

A balance must be maintained between management of the environmental aspects of radionuclides and management of other metal constituents of the ore. Naturally, we are expected to demonstrate good control of radionuclides, and there are few allied industry practices upon which we can benchmark our

performance. This is not the case in the management of non-nuclear substances in the ore. In northern Saskatchewan, the issues revolve around nickel, arsenic, molybdenum and selenium. There are allied industry benchmarks, but the regulatory framework, with nuclear-specialized regulation, often restricts the extent to which these external benchmarks can be applied.

5. Future opportunities

To effectively address the needs of the uranium market, it is important that the environmental assessment process be both timely and flexible. Current EA's are unquestionably more extensive than those done in the past, but with more complexity comes the need to be more effective and more efficient. Defining the scope of both the project and the scope of the assessment is critical to improve timeliness. In detailed examination of issues, particularly existing issues, there often can be a difference between project scope and EA scope. The EA process timeline suffers greatly under repeated Q&A processes to sort this all out.

We believe that the public consultation requirements of the EA process could be further improved. Concepts such as environmental workshops and annual community consultation updates are being tried to better inform the public. Environmental indemnification agreements, above and beyond regulatory controls, can alleviate public concern. Ongoing work to maintain regulatory-approved, up-to-date assessments of known EA issues has proven useful, reducing the need to undertake such studies in the formal EA process. A current trend is the generation of evergreen supporting documents for the EA and licensing process. For instance, pre-approved environmental models, up-to-date contaminant inventories and current environmental risk assessments can be produced. These building blocks, if accepted prior to the formal EA/licensing application, can greatly facilitate the process.

We also believe there is a need to do a better job in distinguishing the EA requirements for a new greenfield facility from the EA requirements for continued, but modified, operation at an existing facility.

Looking down the road, we see the need to put more priority on generating well-written, plain-language, short EA's, with a higher focus on quality over quantity. All too often, we generate documents that are not reader-friendly. This typically is a result of time pressures, given the axiom that a complex technical document must first be cumbersome before it can effectively been distilled down to its essence. Reader burden, and hence the speed of reader response, be it public or regulatory, can be facilitated by brevity.

There are undoubtedly many ways the exploration work can assist the EA process. As noted earlier, mineral deposit delineation also serves to better define the characteristics of waste rock, particularly in cases where it hosts secondary contaminants. Geochemical analysis provides insight into long-term behavior, whether it is being done in exploration to better understand a particular deposit's potential, or in EA to better predict how its halo mineralization will behave in the long term. Exploration tools such as lake sediment analysis give insight into how various ore constituents will be sequestered in biologically active zones over the long term.

6. Conclusions

The environmental assessment and licensing process is an integral part of the overall sustainable development attribute expected in a modern uranium development project. Although the term 'sustainable development' is commonly used today, there is no one commonly accepted definition as it applies to the uranium production business. It could be argued that the term is simply a modern name for the long-standing practice of diligent, responsible management. Most definitions of sustainable development encompass what has become known as the triple bottom line of economic growth, environmental protection, and social progress. The EA and licensing process is an important tool in meeting sustainable development environmental goals.

Risk reduction initiatives have become commonplace, in part prompted by the EA and licensing process. For instance, major strides have been made in waste minimization and recycle, reduced water usage, tailings' physical and chemical optimization, effluent treatment, emergency response measures, and such concepts as secondary containment around key pipelines and processing facilities.

There have been major increases in both the time required to carry out environmental assessment and the necessary scope of such assessments over the last two decades. While, as an industry, we may have concerns regarding the amount of time necessary to develop a new project, there is no doubt that the process of thorough, independent analysis prior to design, construction, and operation of a new facility is fully compatible with sustainable development, particularly in the area of post-closure analysis.

Stringent assessment and licensing processes are now part of the entrance requirement to get into the uranium business. They influence how that business will be structured, for instance, in determining the extent to which there will be a series of satellite mines and regional mills, as opposed to a series of integrated facilities. Another example would be the extent to which innovative mining techniques are developed to reduce the environmental footprint of a facility, and in minimizing dewatering requirements and waste rock generation. The use of ISL technology is a good example of the synergy between the geology of lower grade uranium deposits, mine development technology, and modern environmental management requirements.

What will be essential in the coming renaissance of uranium development will be the need to have assessment and licensing processes that can keep pace with the world's need for uranium fuel. The industry will require timeliness, predictability, and effectiveness in the EA and licensing processes if it is to meet market demands efficiently. The good news remains that the assessment process, while frustrating at times in its duration, strongly supports our main collective environmental goal, which is to solidly support the clean environment aspects of nuclear power at our end of the nuclear fuel chain.

Analysis of uranium world resources and ways of their extension

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Abstract. Demand of world nuclear capacity for the first half of the 21st century is estimated for three growth cases, Low, Middle and High. The known conventional uranium world resources will last for the Low and Middle cases. At the High demand case it will be necessary to process all uranium stocks and resources. It can be achieved by improvement of each stage of uranium production cycle from exploration to a final product. The complex of new effective mining and milling technologies including ***in-situ*** leaching, several combinations of radiometric ore sorting with heap and stope/block leaching of uranium are considered in the paper.

1. Introduction

One of the basic problems of development of world nuclear electricity generating capacity in 21st century is the natural uranium production. Projections of nuclear capacity and reactor-related uranium requirements are executed by the IAEA under condition of use thermal reactors in nearest 50 years without the account of fast breeder reactors, which will play an essential role only in second half of the century.

2. Uranium resources and ways of its extension

There are various methods of forecasting the nuclear generating capacity growth. As usual, calculations are carried out for three cases of growth, as a low, middle and high. Prior to 2020 these forecasts are reliable enough, because they are based on requirements of operating, constructing or projected reactors. For the period from 2020 till 2050 these figures of the prospective annual consumption of natural uranium can essentially differ by different estimations. For example, for 2050 the lower limit is 50 thousand tonnes of uranium, and upper limit is 270 thousand tonnes. The real limits of general requirements in uranium are shown in Table I [1].

Table I. Reactor related uranium requirements to 2050

The case requirements	Uranium (1 000 tU)
Low	3 100 – 3 300
Middle	4 200 – 5 000
High	6 500 – 7 500

Whether the resources of known uranium deposits available for today are sufficient for the uranium requirements? (Table II and III).

Table II. Resources of uranium (1 000 t), as of 01.01.2003 [1]

Cost categories (US $/kg U)	RAR	EAR-I	EAR-II	Total
< 40	1 730	793		2 523
40 – 80	575	275		850
< 80	2 458	1 079	1 475	5 012
80 – 130	662	321		1 832
< 130	3 169	1 420	2 255	6 844

As seen from the Tables II and III, the known conventional uranium world resources (RAR and EAR-I) will last for the low and middle demand cases only. At the high demand case it will be necessary to process all uranium stocks and undiscovered conventional resources (EAR-II).

As of 1-st January 2003, prognosticated and speculative uranium resources are estimated at about 7.539 million t U.

Table III. Percentage provision of reactor requirement with uranium resources to 2050, %

Categories of resources	The case requirement		
	Low	Middle	High
RAR	96 – 102	63 – 75	42 – 49
EAR-I	43 – 46	28 – 34	19 – 22
RAR + EAR-II	139 – 148	92 – 109	61 – 71
EAR-II	68 – 73	45 – 54	30 – 35
Total	207 - 221	137 – 163	91 – 105

Thus, all existing uranium resources will quite suffice up to middle of the century even at the high demand case, and up to the end of century at low and middle cases with condition of use even half of prognosticated resources.

However, the most part of the uranium resources is unprofitable under existing uranium prices, Table IV.

Table IV. Percentage provision of reactor requirement with different cost categories of uranium resources to 2050, %

Cost categories (US$/kg U)	The case requirement		
	Low	Middle	High
< 40	75 – 80	50 – 60	35 – 40
40 – 80	75 – 80	50 – 60	35 – 40
< 80	150 – 160	100 – 120	70 – 80
80 – 130	55 - 60	35 – 45	25 – 30
Total	210 - 220	140 - 160	90 – 110

The resources of the < US $40/kg U cost category will not suffice up to 2050 even at a low demand case. At the time, mainly resources of the < US $40/kg U and only part of resources of the US $40-80/kg U are involved into production. At a high demand case it is necessary to use up to 30% of resources of the < US $80-130/kg U cost category.

In the future, more expensive resources will be committed into production under International Atomic Energy Agency estimation on the basis of International Institute for Applied Systems Analysis and World Energy Council data [2] (Table V).

Table V. Percentage distribution of uranium production by time

Cost categories (US $/kg U)	2005 - 2010	2011 - 2020	2021 - 2030	2031 - 2040	2041 – 2050
< 40	52	43	20	18	24
40 – 80	48	57	60	49	46
80 - 130			20	33	30

From the above-mentioned analysis of requirement and demand ratio of various cost categories it is clear that the major problem of raw uranium sources for nuclear power engineering is necessity to reduce production cost of uranium owing to improvement of each stage of uranium production from deposits prospecting to final product obtaining. All volume of each reliability categories and cost resources are to be involved into uranium production in the case. Simultaneously, expansion of uranium production will be promoted by the tendency of uranium cost rise caused by rapid exhaustion of nuclear fuel secondary reserves.

The possibilities of improvement of natural uranium production can be considered only in conformity with concrete industrial types of deposits. The distribution of uranium resources and uranium production by type of deposits according to IAEA classification is presented in Tables VI and VII.

It is necessary to note that information about resources and uranium production by type deposits is not officially included into the IAEA questionnaire, therefore the figures of the Tables VI and VII are the author's and can contain some possible discrepancies. Especially it concerns the last column of the Table VI, where the total resources of category EAR-II specified in the Red Book - 2003 are given [1] together with reserve deposits resources which are not taken into account by the IAEA for the some reasons. For example, these reserve deposits include the known metasomatite deposits of Russia, Ukraine and Canada, intrusive (pegmatite) deposits of Canada, Ukraine, Australia, etc., vein deposits of Russia, Canada and USA, quartz-pebble conglomerates of Canada.

Table VI. Distribution of uranium resources by type of deposits (1 000 t U)

	Type of deposit	RAR + EAR-I <80US $/kg U	EAR-II + reserve deposits	Total
1.	Sandstone	990	1 300	2 290
2.	Unconformity-related	720	50	770
3.	Breccia complex	680	-	680
4.	Vein	500	520	1 020
5.	Quartz-Pebble conglonerate	220	200	420
6.	Metasomatic	220	850	1 070
7.	Intrusive	210	160	370
8.	Other types	-	-	720
	Total	3 540	3 080	7 340

The most striking example of commitment into profitable operation owing to improvement of various stages of uranium production is processing of low grade ores of sandstone, metasomatite and vein type of deposits. Many new mining and milling technologies were applied by the Soviet specialists in the former USSR and countries of Eastern Europe for the first time.

Table VII. Distribution of world uranium production by type deposits

	Type of deposit	Pre - 1989		2002	
		(1 000 t U)	%	(1 000 t U)	%
1.	Sandstone	450	27.1	9.8	27.2
2.	Unconformity-related	85	5.1	15.4	42.7
3.	Breccia complex	2	0.1	2.4	6.7
4.	Vein	630	37.9	3.8	10.6
5.	Quartz-Pebble conglonerate	270	16.2	0.8	2.2
6.	Metasomatic	50	3.0	1.3	3.6
7.	Intrusive	47	2.8	2.0	5.6
8.	Other types	30	1.8	0.0	0.0
	Total	100	6.0	0.5	1.4

Percentage distribution of world uranium production by processing methods is in the Table VIII. [1]. 6 600 tonnes of uranium were recovered from sandstone type deposits in 2002, and 7 300 tonnes in 2003. Profitable uranium resources equal about 700 thousand tonnes of six countries including Kazakhstan, Uzbekistan, USA, Australia, China and Russian Federation which produce uranium by *in situ* leaching technology. The uranium *in situ* resources by can be increased up to more than 2 million tonnes as a result of the method modernization, namely, choice of more effective oxidizers and solvents, optimization of leaching regime, development of uranium extraction ways from low-permeable rocks, etc. For example, in the United States where ores of uranium grade more than 0.1 % are processed at the present time, *in situ* resources are estimated above 102 thousand tonnes, whereas the total resources of all known deposits of this type exceed 1.5 million tonnes in the country.

Table VIII. Percentage distribution of world uranium production by processing methods, %

Processing method	1998	1999	2000	2001	2002	2003
Open-pit	39	35	28	26.1	26.8	27.9
Underground	40	36	43	44.2	43.1	39.5
In situ leaching	13	17	15	15.5	18.3	20.7
Heap leaching	a*	a	a	1.2	1.7	1.9
Block leaching	a	a	a	0.1	0.1	0.2
Co-/by-product	a	a	a	12.4	9.1	9.4
Other methods	8	12	14	0.5	0.8	0.5

*) included into other types

Heap leaching and block leaching technologies are favorable for low-grade vein, metasomatite and intrusive type deposits in accordance with the result of the latest researches in the Russian Federation, Ukraine, Kazakhstan, Brazil and China. The especially promising data are received in the Russian Federation and Ukraine because of combination these methods with radiometric feed ore sorting.

At the time radiometric sorting of uranium ores is applied at Rossing mine in Namibia. The ore mined from the open-pit of three sizes +160 - 300 mm, +80 -160 mm and -80 mm feed to radiometric ore sorting plant. Yield of the sorting able size ore is 45 % from the feed ore. Uranium grade is 0.035 % in the feed ore, 0.038 % in non-sorting size, 0.06 % in concentrate, 0.005% in sorting tailings. Yield of the tailings equals 23.4 %. Sorting ore product including concentrate and non-sorting ore size of uranium grade 0.043 % feed to the processing plant. Concentration coefficient is 1.2 only, and profitability is ensured practically because of reduction by a quarter of total feed ore processed at the milling plant.

Modern radiometric sorting separators used in the Russian Federation and Ukraine allow to sort uranium ores more effectively, first, owing to reduction of ore sorting able size till -25 mm and even -15 mm. The yield of non-sorting ore size decreases to 20-30%. Secondly, the separators permit to obtain a rich concentrate and middle product, simultaneously.

For example, the ore of uranium grade 0.1 % feed to the radiometric sorting plant at one of Ukrainian mine of metasomatite type deposit. The yields of sorting products are distributed in equal shares, roughly by 30%. Uranium grade is 0.02% in tailings, 0.1% in non-sorting ore size, 0.18% in concentrate. Uranium grade decreases to 0.14 %, i.e. to 25 % due to dilution by non-sorting ore size in the blended product. Profitability is ensured owing to separate processing of non-sorting ore size by heap leaching technology and by sorting concentrate common leaching at the local milling plant.

It is possible to use multistage radiometric sorting of uranium ores with obtaining low-grade middle product and high-grade concentrate at a one deposit of Aldan shield (Yakutia). Uranium grade is 0.16% in the feed ore, yield of non-sorting ore size – 25 mm is 33% of uranium grade 0.19 %, yield of sorting tailings of uranium grade 0.02 % is 35 %. Yield of sorting concentrate of uranium grade from 0.7 to 1.0% equals 10%; yield of middle product of uranium grade 0.12% is 17%. Non-sorting ore size and middle product blend into single product of uranium grade 0.17% which is to be treated by heap leaching. The high-grade sorting concentrate is to be transported to milling plant. Applications of such solution allow reducing considerably the cost of uranium production and involving into operation rather significant resources of low-grade uranium ores.

Combination of heap leaching and block leaching technologies can be promising for uranium ore processing of vein, metasomatite and intrusive type deposits which are unprofitable for common processing methods. Such combination method was used for finishing mining of veinlet-stockwork uranium deposits Beshtau and Byk at Caucasian Mineral Waters region for the first time. Quantity of uranium was produced more than estimated by prospecting data. At the time it is intend to use the method at a new undeveloped before uranium vein and metasomatite type deposits of Ukraine and the Russian Federation. Principle of the operation is separate parts of ore bodies mining in order to create compensating space. The mined ore feed to heap leaching or to milling plant. Drilling and blasting works are carried out at the rest of the ore bodies. Uranium is to be extracted from the crushed ores at the depleted blocks by means of sulphuric acid or sodium carbonate leaching.

As a result of the wide implementation of the above mentioned technologies the natural uranium profitable resources can be considerably extended, including for sandstone deposits up to 3 million tonnes, for vein and metasomatite type deposits up to 1 million tonnes each, for intrusive type deposits up to 370 thousand tonnes, and for other type deposits up to 700 thousand tonnes, see Table VI. Uranium resources can be committed more than 7 million tonnes which will be sufficient for the first half of the century.

It is necessary to pay a particular attention to prospecting "Breccia complex" type deposits which are currently presented by single U-Au-Ag-Cu complex deposit Olympic Dam, Australia. Purposive searches of such type deposits in other countries almost were not made. Perspective areas for searches of such deposits are ancient platforms borderland of all continents in view of the Australian geologists experience especially on use whole complex of geophysical methods.

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TOPIC 2 - URANIUM GEOLOGY AND DEPOSITS

Millennium deposit – basement-hosted derivative of the unconformity uranium model

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Abstract. The Millennium uranium deposit, discovered in 2000, and situated 35 kilometres north of the Key Lake mine in the prolific Athabasca Basin of northern Saskatchewan Canada represents an under explored derivative of the unconformity model. This deposit is arguably the most significant basement-hosted discovery in the basin in more than 30 years. The deposit is hosted almost entirely within Paleoproterozoic metasedimentary rocks at vertical depths ranging from 600 to more than 750 metres from surface. Although uranium mineralization is found in a variety of rock types the deposit is essentially stratabound and situated in the hanging wall to a major reverse fault. The ore mineralogy consists dominantly of pitchblende with lesser amounts of coffinite and uraninite. The mineralization is essentially monominerallic although Pb and V contents generally increase with uranium enrichment. The most striking macroscopic feature of the Millennium deposit is the extensive hydrothermal overprint of the basement lithologies, with illite and chlorite as the dominant clay species. The Main Zone mineralization, which is centered 100 metres below the sub-Athabasca Group unconformity, has been defined for approximately 70 metres down dip and along strike for a minimum of 230 metres. True width and grade of the zone are variable with grades ranging between 1 and 4% U over widths of 20 to 30 metres. Although an alteration envelope surrounds the deposit, the mineralization itself is hosted by competent lithologies and the use of conventional mining techniques are envisaged should sufficient resources be defined. The Millennium discovery has directed exploration methodology within the basin toward the search for additional basement-hosted uranium deposits.

1. Introduction

The Athabasca Basin of northern Saskatchewan Canada is host to the world's largest and highest-grade uranium deposits including McArthur River and Cigar Lake. The Athabasca deposits are classified as unconformity-type deposits since uranium deposition is spatially related to the sub-Athabasca Group unconformity. Within the unconformity model the highest-grade ore usually straddles the unconformity, although economic mineralization can extend several hundred metres below this boundary.

The Rabbit Lake deposit discovered in 1968 was the first deposit within the Athabasca Basin to be put into production. Although considered to be an unconformity-type deposit, mineralization in the Rabbit Lake deposit was hosted entirely within the underlying Paleoproterozoic metamorphic rocks of the sub-Athabasca basement. Other significant basement-hosted deposits include Eagle Point, Sue C, and Dominique Peter. Although basement-hosted, the McArthur River Zone 2 deposit is excluded as the mineralization here is clearly connected to the unconformity.

The Millennium discovery made by Cameco Exploration in 2000 represents the latest significant basement-hosted deposit to be found in the Athabasca Basin. This paper reviews the exploration history, the geological setting, structure, alteration and mineralization characteristics, and resource estimation for what is arguably the most significant basement-hosted discovery in more than 30 years.

It should be noted that comments and conclusions made in this paper are largely empirical and based on macroscopic observations from drill core, supported by geochemistry and limited petrology. The next phase of understanding the Millennium deposit will be to incorporate scientific research including the age dating of mineralization along with mineral paragenesis.

2. Project location and historical exploration

The Millennium deposit, which occurs within the Cree Extension project, is located in the eastern Athabasca Basin 35 kilometres north of the former Key Lake mine (Fig. 1). This area of the basin is considered a mature exploration region as activity as been ongoing since 1978. The Cree Extension project is a uranium exploration joint venture among Cameco Corporation - operator (30.17%), JCU (Canada) Exploration Company Ltd. (30.10%), UEM Inc.[1] (23.59%) and AREVA (16.14%).

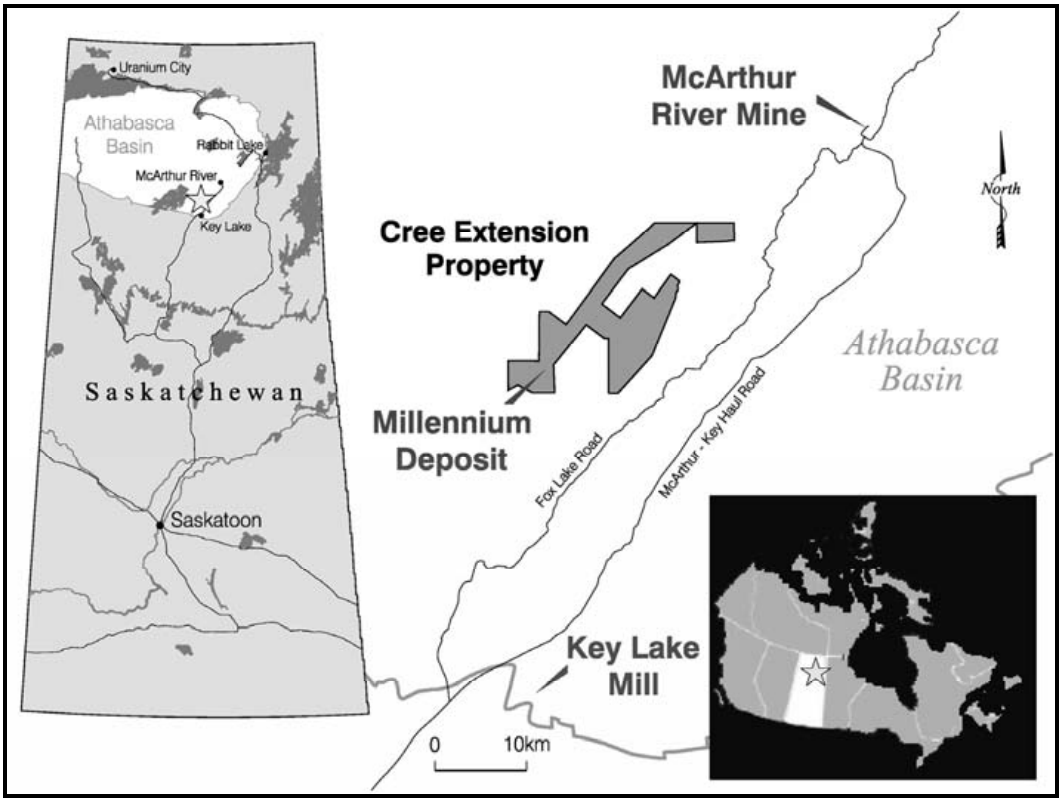

FIG. 1. Location map Millennium deposit, Athabasca Basin, Saskatchewan Canada.

Project lands comprise 12 777 hectares and represent the core of a much larger project that originally totaled nearly 200 000 hectares. Historic exploration on the Cree Extension project comprised a series of airborne and ground geophysical electromagnetic surveys supplemented by ground geochemical surveys and radiometric prospecting. By the mid 1980's four distinct north-northeast trending conductive packages totaling 70 km in length were identified. These conductors identified as A_1, A_2, B_1, and C_1 were due to graphitic metasedimentary rocks in the basement. Initial reconnaissance drill programs identified weak unconformity-hosted uranium mineralization along the A_1 and B_1 conductors. Exploration focus was increasingly directed towards the B_1 corridor where positive indications of post-Athabasca faulting, and anomalous sandstone lithogeochemistry were coincident with the southern portion of the conductive trend.

In 1998, Cameco became project operator. Although no exploration was undertaken in 1999 data compilation and drill core review reinforced the potential and prospectivity of the southern portion of the B_1 trend, in particular near DDH CX-38, which was one of the final holes completed by the previous operator Uranerz Exploration and Mining. Specifically the lower 200 metres of variably altered sandstone intersected by DDH CX-38 averaged 0.9 ppm U and basement lithologies displayed a strong hydrothermal overprint in excess of 80 metres below the unconformity. Anomalous Pb and B values were also present in both the sandstone and basement. Re-examination of DDH CX-38

[1] UEM Inc. is owned 50% by Cameco and 50% by AREVA-Cogema Resources Inc.

identified a strong foliation control to alteration in the basement rocks. Projecting this altered basement stratigraphy along with the graphitic conductor up dip to the unconformity presented a priority drill target.

The Millennium discovery hole CX-40, drilled in March 2000, was a vertical hole collared 40 m west of DDH CX-38 (Fig. 2). The hole intersected weak to moderate grade uranium mineralization 40 metres below the sub-Athabasca unconformity and persisting over a core length of 153 metres (608 to 761 metres). The best section of continuous mineralization was 29 metres averaging nearly 1% U.

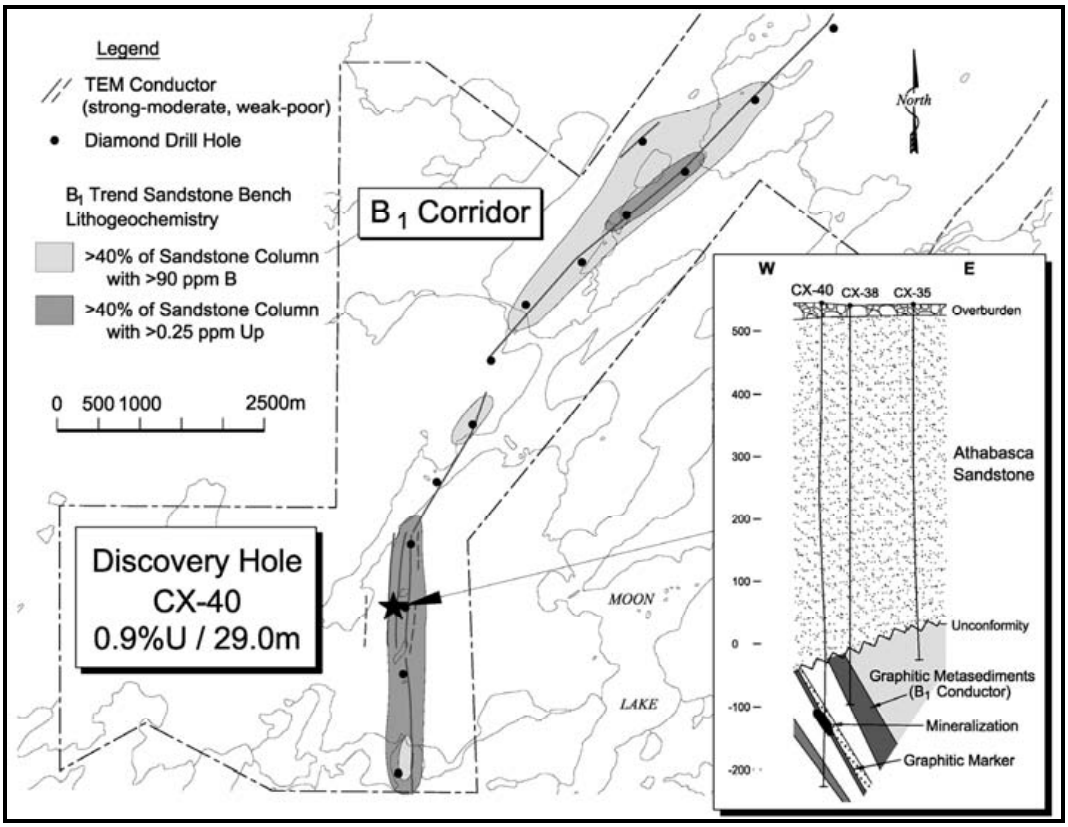

FIG. 2. B1 corridor showing past diamond drilling and location of discovery DDH CX-40.

3. Geological setting

3.1. Regional geology

The Athabasca Basin of northern Saskatchewan lies almost exclusively on the Archean and Paleoproterozoic Rae and Hearne provinces of the Precambrian Shield. The crystalline basement rocks underlying the eastern portion of the Athabasca Basin comprise a polydeformed and metamorphosed basement complex consisting of Archean granitoid gneisses and Paleoproterozoic metasedimentary rocks.

The crystalline basement rocks within the eastern Athabasca Basin are in the Hearne province, which was previously referred to as the Cree Lake Zone (CLZ) by Lewry and Sibbald (I). The Hearne province can be subdivided into several lithotectonic domains based on variations in structural styles (Fig. 3). These include a central zone, termed the Mudjatik Domain, which is characterized by an arcuate magnetic map pattern resulting from regional basin and dome fold interference. The Mudjatik Domain consists mainly of granitoid gneisses containing discontinuous arcuate zones of Archean and Paleoproterozoic supracrustal rocks. To the west of the Mudjatik Domain is the Virgin River Domain, a northeast-trending zone of mylonitic gneisses, which forms the boundary between the Hearne and Rae provinces. To the east of the Mudjatik Domain lies the Wollaston Domain, which is characterized

by a northeast trending, more elongated, dome and basin pattern comprising Archean granitoids and Paleoproterozoic metasedimentary rocks. The metasedimentary rocks referred to as the Wollaston Group comprise a dominantly pelitic to semipelitic assemblage with lesser calc-silicates, amphibolites and arkoses. Widespread anatexis of the supracrustal sequences has generated abundant pegmatites and granitoid rocks throughout the lower Wollaston Group. This structural grain was inherited from deformation and metamorphism during the 1800-1820 Ma Trans-Hudson orogeny.

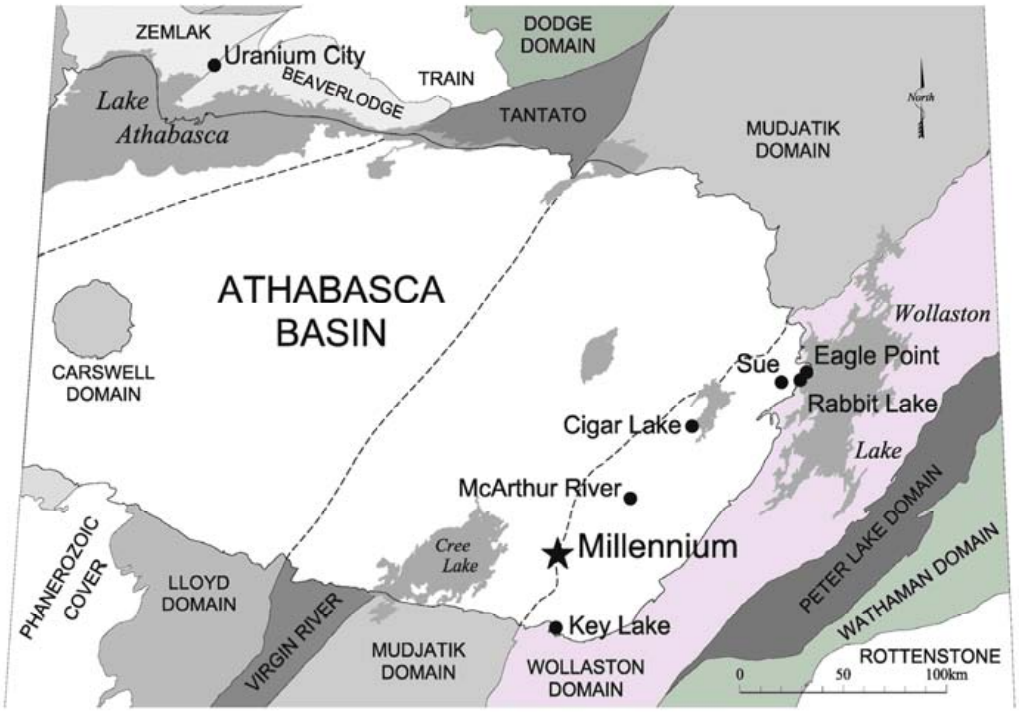

FIG. 3. Lithotectonic domains of the Athabasca Basin and location of major deposits.

Subsequent uplift and post-Trans Hudson peneplanation of the Archean and Paleoproterozoic basement complex was followed by deposition of late Paleoproterozoic quartz-rich sandstones of the Athabasca Group. Deposition via broad fluvatile systems into the Athabasca Basin appears to have been largely from a hinterland situated to the northeast, east and southeast. The Athabasca Basin was intruded by diabase dykes associated with the Mackenzie Igneous Event ca. 1267 Ma ± 2 Ma [2].

The Millennium discovery appears to be situated on or close to the boundary between the Wollaston and Mudjatik Domains.

3.2. Millennium geology

3.2.1. Athabasca group stratigraphy

The project area is underlain by diagenetically altered sandstones and conglomerates of the Manitou Falls Formation, (MF) a to d members as defined by Ramaekers [3] (Fig. 4). Cumulative thickness of this sequence ranges from 500-750 metres, increasing in thickness towards the north and northwest.

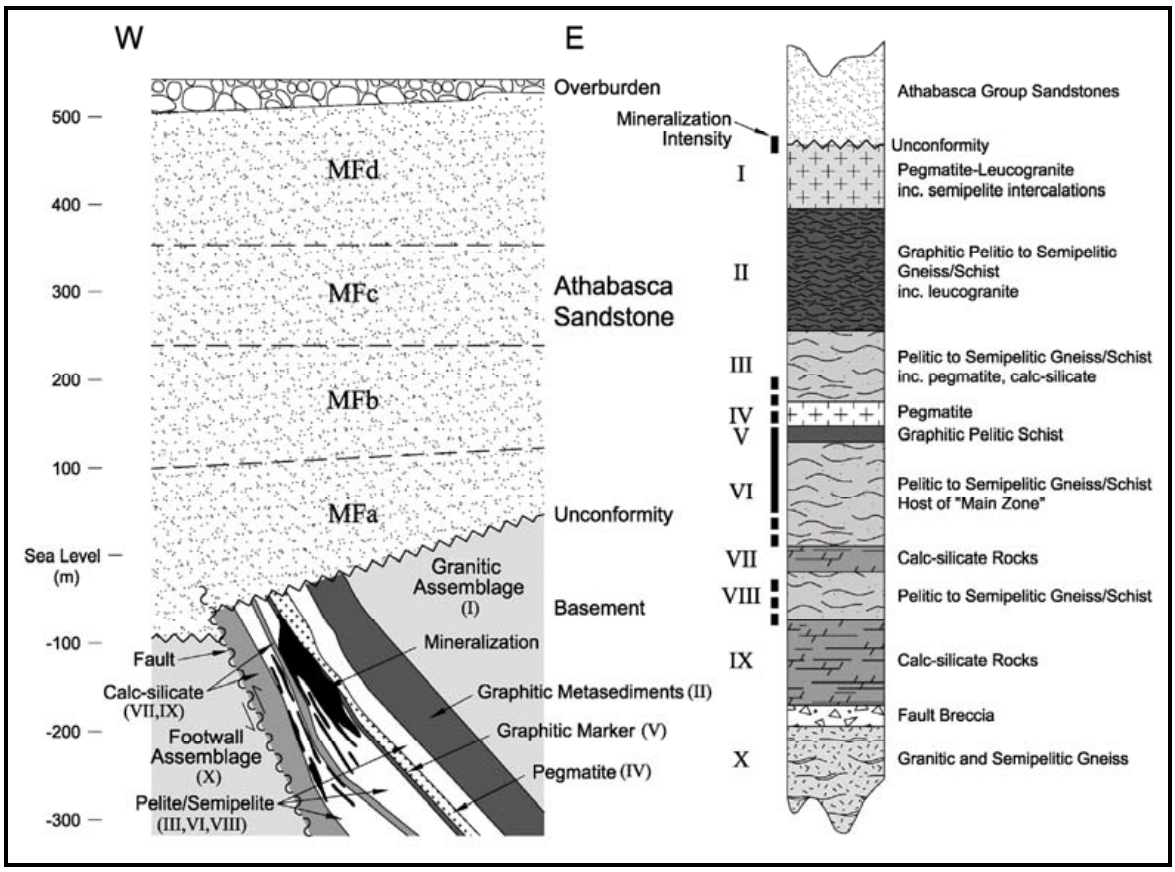

FIG. 4. Schematic geological cross-section of the Millennium deposit and stratigraphic column.

Immediately overlying the unconformity, the MFa member, consists of a sequence of fluvial sandstones, pebbly sandstones and minor conglomerates. This unit attains a maximum thickness of 100 metres and immediately underlies the main fluvial wedge of the MFb to MFd members.

The MFb member consists of interbedded sandstones and clast-supported conglomerates. This unit typically contains purple specular hematite and blackish heavy mineral bands with various degrees of superimposed pink to red hematization. Heavy mineral bands are usually thorium enriched resulting in higher background radioactivity, compared to the overlying MFc member. The thickness of this member averages 150 metres.

Sandy braided stream deposits exhibiting abundant planar and trough cross bedding, and cross and horizontal lamination, typify the MFc member. Although some clay intraclasts are locally present, they are not abundant. This unit is typically less than 100 metres thick.

The uppermost member of the Athabasca Group is the MFd member, which consists of generally uniform sandstones with abundant clay intraclasts and local thin lenses of bedded siltstone and mudstone. This unit is generally up to 200 metres thick.

The bedrock is overlain by extensive unconsolidated Quaternary glacial and periglacial deposits consisting of ground moraine, esker, outwash, aeolian, and lacustrine deposits, which effectively mask much of the bedrock in the area.

3.2.2. Basement geology

The basement stratigraphy in the Millennium area can be divided into ten generally correlative assemblages and units as depicted in Fig. 4.

Granitic Assemblage (I) - A pegmatite-leucogranite dominated assemblage with minor semipelitic intercalations typically underlies the unconformity east of the deposit. Thickness of this unit is unknown.

Graphitic Metasediments (II) - Underlying the granitic assemblage are variably graphitic pelitic to semipelitic gneisses and schists, commonly intermixed with leucogranite. Graphite, up to several percent, is disseminated throughout this upper unit (B1 conductor). The apparent thickness of this graphitic package varies from 40 to 55 metres.

Heterogeneous Metasediments (III) - A heterogeneous metasedimentary assemblage underlies the graphitic metasediments. Texturally and compositionally varied, non-graphitic pelitic to semipelitic gneiss/schist with minor calc-silicates predominate over this interval. Intercalated anatectic pegmatites sheets, between a few centimeters to several metres thick, are present throughout this assemblage. The contacts of these pegmatites are locally the sites of weak uranium accumulations within this stratigraphic assemblage. The apparent thickness of this unit varies from 20 to 40 metres.

Hanging Wall Pegmatite (IV) - A pegmatite body herein referred to as the 'hanging wall pegmatite' unit. The pegmatite unit, varying between 3 and 20 metres thick, generally overlies the main uranium mineralization in the Millennium area.

Graphitic Marker Unit (V) - A distinctive, moderately to strongly graphitic, cordierite porphyroblastic pelitic schist underlies the pegmatite. This marker unit, varying between 0.5 and 4.5 metres in thickness, is spatially coincident with the first ore-grade uranium mineralization. This unit commonly exhibits multiple graphitic slip planes and locally semi-brittle shear fabrics.

Host Assemblage (VI) - This assemblage consists of a series of non-graphitic pelitic to semipelitic gneisses / schists, that host the Main Zone Millennium mineralization. The apparent thickness of this assemblage varies from 25 to 55 metres. The lower limit of this assemblage is less well defined due to intense hydrothermal overprinting.

Upper Calc-Silicate Assemblage (VII) - The unit is dominated by calc-semipelitic gneiss/schist. This interval ranges from 9 to 15 metres thick and exhibits extensive intercalation between calc-semipelitic and semipelitic schists. Local occurrences of weak uranium mineralization are preferentially distributed within the latter lithologic component.

Bracketed Assemblage (VIII) - An interval of pelitic to semipelitic schists underlies the calc-silicates and in turn is underlain by a second calc-silicate assemblage. The pelitic/semipelitic assemblage ranges in apparent thickness from 15 to 25 metres. The unit commonly exhibits erratic, weakly disseminated uranium mineralization and/or elevated background radioactivity over its entire thickness.

Lower Calc-Silicate Assemblage (IX) - This interval is predominately comprised of interbedded calc-semipelitic and calc-pelitic schist/gneiss with lesser amphibolitic gneiss. The assemblage generally displays intense argillic alteration, common dravite ±quartz-healed hydraulic brecciation and for the most part is not mineralized. This assemblage ranges in thickness from 25 to 40 metres and represents the immediate hanging wall margin of a major fault breccia within the Millennium area.

Footwall Assemblage (X) - This assemblage consists of a series of non-graphitic semipelitic gneiss intercalated with massive to well foliated granite gneiss. Predominance of the latter component and disappearance of the former is evident with increasing depth and separation from the overlying fault breccia. The thickness of this unit is unknown.

3.2.3. Structure

The Millennium deposit is situated within a regional north-northeast trending structural corridor as defined by airborne and ground geophysics and diamond drilling. Interpretation of airborne magnetic

data suggests that the basement rocks have been deformed into a complex fold interference pattern. Two principle axial surface traces (D_1 and D_2) are interpreted. The earliest D_1 folds are inferred to be relatively shallow dipping recumbent structures that may verge to the northwest. The early structures are subsequently refolded into more upright northeast trending folds that are inclined to the northwest. The Millennium Zone is interpreted to lie within a north-trending D_2 synform.

A pronounced rotation of the Athabasca Group stratigraphy within the Millennium area is observed. Oriented drill core measurements of sandstone bedding surfaces indicate a consistent westerly dip to the sandstone bedding, which becomes evident at approximately 300 metres vertical depth and increases in severity towards the unconformity. This bedding rotation is interpreted to reflect structural drag of the hanging wall stratigraphy proximal to reverse faulting.

Within the deposit area the most significant structural feature is the presence of a major fault zone located at the base of the Lower Calc-Silicate Assemblage. The fault zone is characterized by angular wall rock clasts set in a clay/dravite matrix. This fault is approximately 10 metres thick, strikes northerly and has a moderate easterly dip. This structure is interpreted to represent the main hydrothermal conduit along which oxygenated, uranium bearing fluids infiltrated deep into the basement. The mineralized fluids then moved along fracture and foliation planes with mineralization being precipitated and deposited within structural and chemical traps.

At the southern end of the deposit a steeply dipping east-striking fault with reverse and sinistral oblique slip movement displaces the Main Zone mineralization and stratigraphy by 30- 40 metres. The presence of significant uranium mineralization well above the graphitic marker horizon within this portion of the deposit may reflect the migration of mineralizing fluids along this cross-cutting structure.

3.2.4. Alteration and geochemistry

Clay species distributions within the Athabasca Group as derived from reflectance spectroscopy exhibit polyphase hydrothermal clay assemblages (illite, ± chlorite, ± kaolinite, ± dravite) within the upper and lower sandstones bracketing a dickite-dominated middle sandstone. Mixtures of illite and chlorite are the predominant basement clays associated with the Main Zone mineralization. Strong illitization is synonymous with increased argillization.

Geochemical data indicates the mineralization is essentially monominerallic as Ni, As, Cu and Co contents typically display low to background distributions (generally less than 200 ppm). Pb and V enrichment are directly associated with and generally proportional to coincident uranium enrichment (Fig. 5). In addition to these established pathfinder elements, LREE and HREE elements along with Bi, Li, Mo, W and Y display elevated concentrations coincident with uranium mineralization.

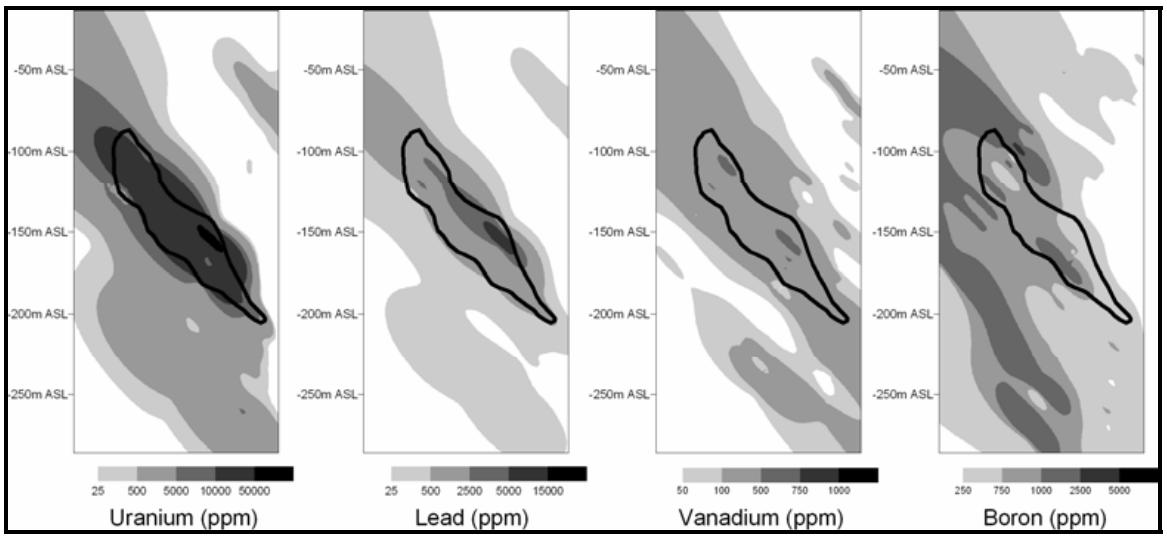

FIG. 5. Schematic cross-section showing trace metal association of the Millennium deposit.

The most striking feature of the Millennium deposit is the extensive hydrothermal alteration overprinting both the Athabasca Group and basement lithologies. Alteration in the Athabasca Group is characterized by a pervasive bleaching and increased clay content of the lower sandstone. The alteration of the basement lithologies is more intense and includes: i) a distal halo of saussuritization and sericitization, ii) through a more proximal zone of chloritization into iii) a central zone of increasing argillic alteration and dravitization. The main area of uranium mineralization is coincident with the proximal alteration assemblage and commonly associated with the dark chlorite. An asymmetric distribution to the hydrothermal overprint is apparent relative to the speculative hydrothermal conduit. Notably, pervasive hydrothermal alteration is preferrentially developed within the hanging wall block and poorly developed to absent within the basement rocks footwall to the reverse fault (Fig. 6). Geochemically the alteration is characterized by B enrichment and Na_2O and Zn depletion.

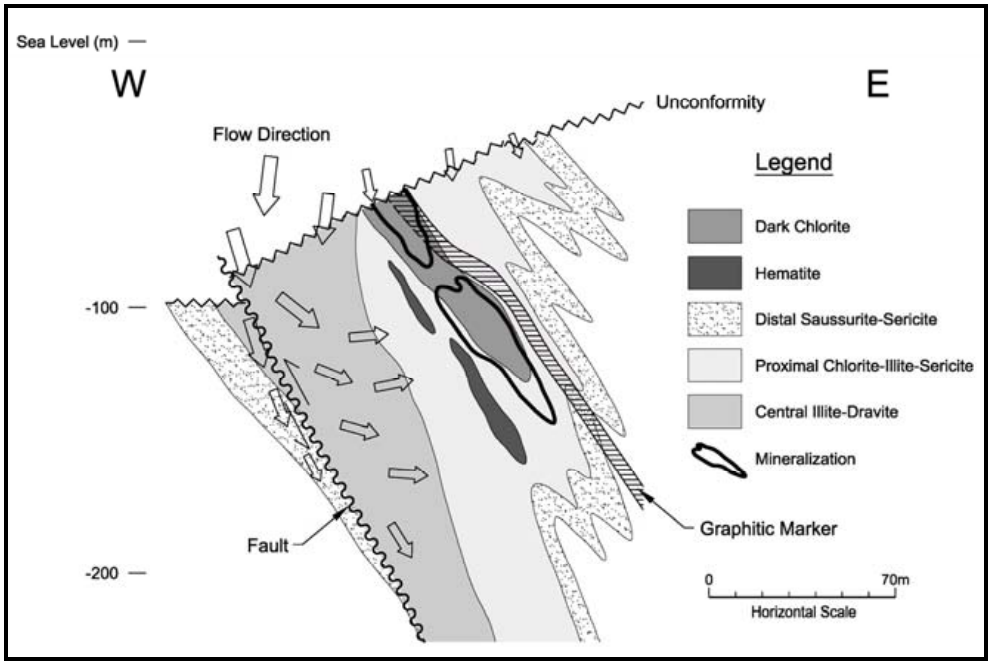

FIG. 6. Schematic cross-section showing distribution of hydrothermal alteration.

3.2.5. Mineralization

The Main Zone mineralization is characterized by alternating higher and lower grade intervals that can be traced from section to section along strike. Although the majority of the Millennium mineralization is basement-hosted, two holes have encountered unconformity mineralization leading to speculation that potential also exists for classic unconformity-hosted uranium accumulations.

The basement-hosted Main Zone mineralization occurs in a variety of styles including; massive foliation-controlled replacement, pitchblende matrix in breccias, irregular fracture-controlled fillings and thin vein-type pitchblende, bleb-like aggregates and thin discordant pitchblende veinlets and rims around fragments of quartz veins. Massive replacement type mineralization is the dominant style while fracture filling and vein-type is less developed. The dominant replacement style in the absence of strong fracturing, suggests the mineralizing fluids infiltrated the rocks on a very fine to microscopic scale. It is proposed that the main permeability-controlling feature is the penetrative S_1/S_2 foliation as well as lithologic contacts and discordant features such as pre-existing quartz veins (Fig. 7).

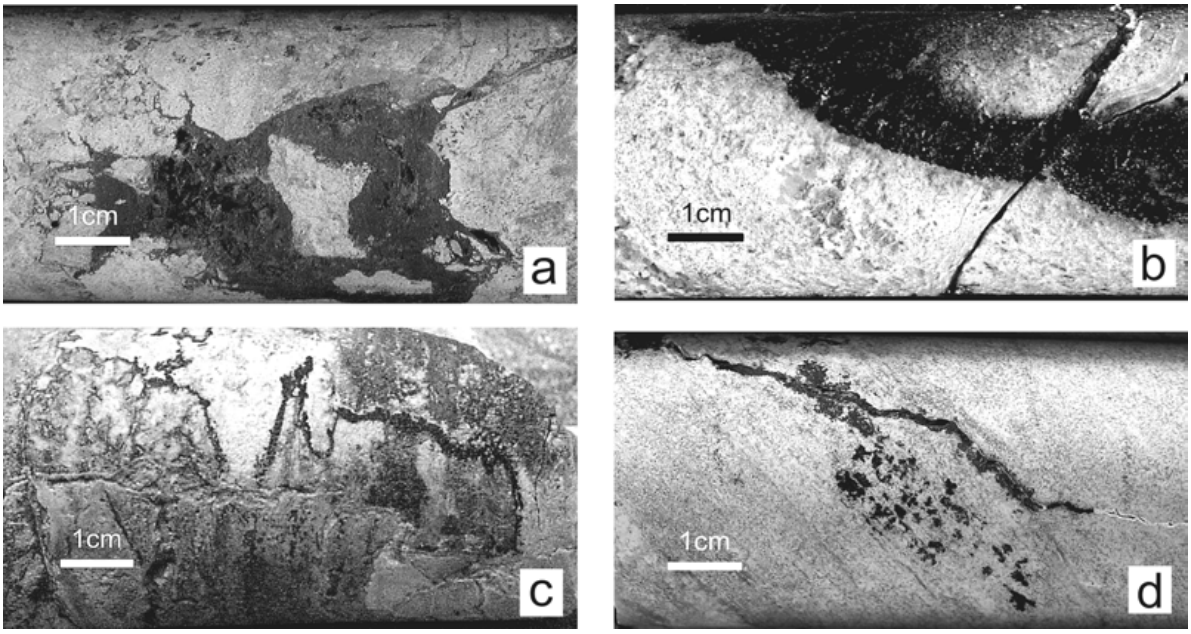

FIG. 7. Mineralization styles; a) breccia fill, b) foliation controlled, c) redox style and d) fracture fill and blebs along foliation planes.

The ore mineralogy within the Main Zone consists largely of pitchblende as the primary uranium mineral and lesser amounts of coffinite and uraninite. The deposit is considered to be of the simple mineralogy type as is typical of other basement-hosted deposits in the basin (e.g. Eagle Point and Sue C). Cu, Co, Mo, Ni and As are present but in low concentrations. In comparison, the unconformity-hosted uranium occurrences of the Millennium area contain higher concentrations of associated metals.

A second stratigraphic assemblage (Bracketed Assemblage – VIII) lower in the sequence carries persistent, albeit weakly disseminated uranium mineralization over its entire thickness.

4. Resources

Since the discovery in late March 2000 thirty-six diamond drill holes totaling 16 845 metres have been drilled in the Millennium deposit area on nominal 50 metre sections. Directional drilling using oriented cuts from pilot holes has been successfully employed. This technique while being more cost effective, also serves to better and more accurately define the deposit geometry. A significant uranium resource has been defined within the Main Zone mineralization (Fig. 8). The Main Zone

mineralization, which is centered approximately 100 metres below the Athabasca Group unconformity, has been drill defined to approximately 70 metres down dip and along strike for a minimum of 230 metres. True width and grade of the drill-defined intercepts are variable with grades ranging between 1 and 4% U over widths of between 20-30 metres. The best individual uranium intercept within the Main Zone is 4.8% U over 33 metres. For purposes of resource estimation the Main Zone mineralization has been subdivided into several subparallel lenses that are continuous and traceable from section to section.

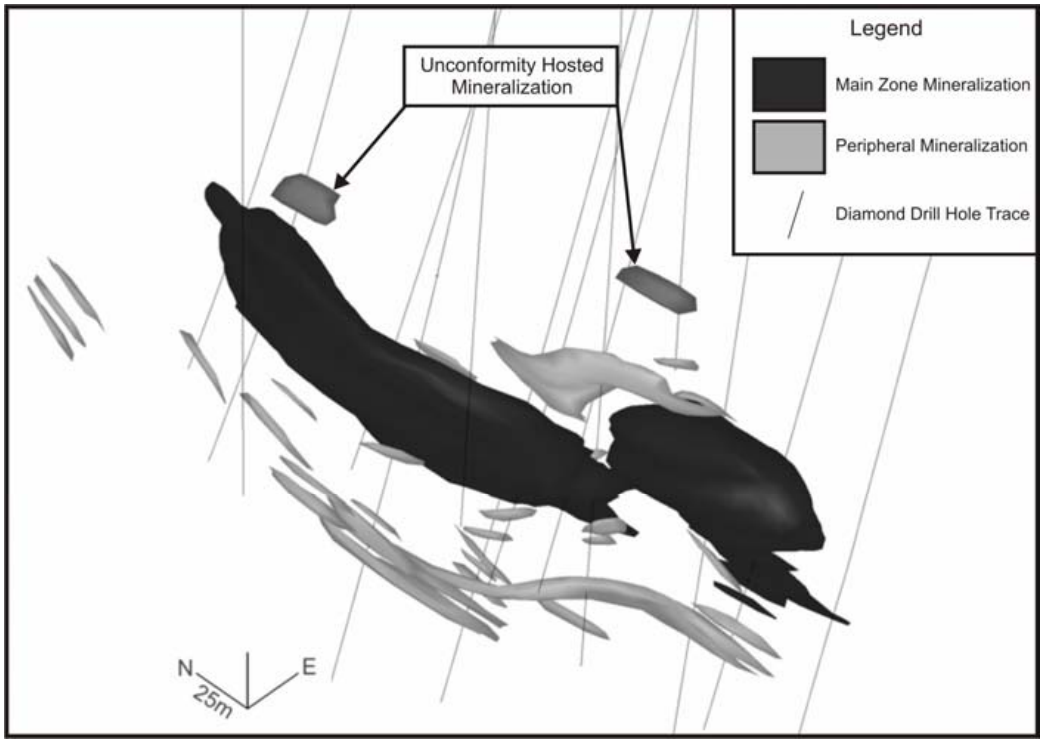

FIG. 8. 3D visualization of the Millennium deposit looking northeast. Only pilot diamond drill hole traces shown.

Drill indicated resources are 547 000 tonnes at 2.43% U while an additional 293 000 tonnes at 2.07% U are classified as inferred. At the end of 2004 the Millennium deposit was estimated to contain a total of 19 370 tonnes U, thereby ranking it second in size to Cameco's Eagle Point mine for known basement- hosted deposits within the Athabasca Basin. If conventional unconformity-type deposits are considered (including McArthur River and Cigar Lake) Millennium would rank sixth in size.

5. Discussion and conclusions

The first significant uranium discovery in the Athabasca Basin was the Rabbit Lake basement-hosted deposit in 1968. This deposit had no apparent physical or genetic link with the Athabasca unconformity. It was not until the discovery of the Deilmann and Gaertner deposits at Key Lake in 1975-1976 that the unconformity-type uranium deposit model was first formulated. The resulting metallogenetic model comprised diagenetic-hydrothermal systems involving sandstone-basement interaction [4]. Over the last 25 years subsequent discoveries of both basement-hosted and unconformity related deposits have supported the concept that these deposits are genetically linked and that basement-hosted deposits are a derivative of the unconformity model. Basement-hosted deposits comprise a single sandstone sourced mineralizing fluid resulting in deposits of simple mineralogy [5].

From an exploration perspective the recognition of the extent of the sandstone and basement alteration combined with anomalous uranium and boron chemistry was key in prioritizing the southern portion of the B_1 trend, which ultimately led to this discovery.

The Millennium model is relatively simple. Uranium bearing oxidized fluids, sourced within the sandstone, travel along the unconformity and down a major reverse fault and are dispersed latterly along foliation, fractures and any permeable passage way. This hanging wall block has been structurally prepared preferential to the footwall lithologies. Uranium mineralization was precipitated where Eh and pH conditions were optimal.

Although a distinctive alteration envelope surrounds the deposit, the mineralization itself is hosted by altered yet competent lithologies. Therefore, should sufficient resources be identified to allow the deposit to be put into production the need for expensive ground stabilization by freezing is not considered necessary. In addition, the ore grades are amenable to conventional mining and handling methods.

Exploration activities have been on going in the Athabasca Basin for nearly 40 years. However, much of this exploration has been at depths of less than 500 metres and until a few years ago most drill holes stopped less than 50 metres into basement. The discovery of the Millennium deposit has reinforced the continued prospectivity of the Athabasca Basin but more importantly it has increased the significance for the potential of basement-hosted deposits and the significance of the associated macroscopic argillic alteration as an exploration guide.

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Ion microphrobe CAMECA IMS-3fREE and isotopic U-Pb analyses of uranium oxide

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Abstract. REE analyses were performed by ion microprobe on uranium oxides from: (i) two unconformity-type deposits from Athabasca Basin (Saskatchewan, Canada): the Shea Creek and the McArthur deposits, (ii) a vein-type deposit: the perigranitic Pen Ar Ran deposit (Vendée, France), (iii) a volcanic caldera related deposit: Streltsovka, (Tranbaikalia, Russia). These analyses were conducted to try to characterize each type of deposit from their REE signatures, and to test whether different generations of uranium oxides in the same deposit may be distinguished with respect to their REE composition. In situ analyses of the uranium oxides were performed by Secondary Ion Mass Spectrometry (SIMS) on a CAMECA IMS-3f ion microprobe. The Rare Earth Elements are particularly interesting in the case of the uranium oxides because U^{4+} in eight-fold coordination has a ionic radius close to that of the intermediate REE and thus should be much less mobile than lead, which has a much larger radius, to characterize different uranium oxide generations.

All REE patterns from the Shea Creek and the McArthur deposits are characterised by bell-shaped patterns centred on Tb or Dy and similar to REE patterns available on uranium oxides from unconformity related deposits of the East Alligator River Uranium Field. Bell-shaped REE patterns may therefore be considered as a typical signature of uranium oxides from Mesoproterozoic unconformity related deposits. The REE patterns from Pen Ar Ran deposit show a fractionation from LREE to HREE with anomalous abundances of Sm, Eu and Gd with respect to the REE, similar to the pitchblende pattern volcanic related deposit of Streltsovka.

1. Introduction

Natural uranium oxides incorporate during their crystallization variable quantities of elements, according to their ionic radius, to the physical-chemical conditions existing in the environment (temperature, nature of ligands in the mineralizing fluids), the composition of the rocks with which the mineralizing fluid has been equilibrated and to post-depositional reequilibration in relation with later fluid circulations. REE represent a particularly interesting set of elements, because their ionic radii are close to that of U^{4+} in eight-fold coordination and most of them are not sensitive to changes of redox conditions. Hence, they are much less mobile than radiogenic Pb which has a much larger ionic radius than U^{4+} and thus may better preserve their primary distribution within uranium oxides. A literature survey of available data about REE distribution in uranium oxides shows that each type of uranium deposit seems to be characterized by a specific signature [1][2][3][4], although strong variations seem to occur within a specific type of uranium deposits [5].

The purpose of this study was first to set up the methodology for in situ analysis of the Rare Earth Elements in uranium oxides on micro-domains and second to establish the REE signatures of uranium oxides from various deposits in the world and from different uranium oxide generations within a single deposit, on carefully dated samples, by in situ isotopic U-Pb determinations, both type of analyses being performed by Secondary Ion Mass Spectrometry (SIMS) on a CAMECA IMS-3f ion microprobe.

2. REE analyses methodology

Most uranium ore bearing samples are generally highly heterogeneous as a result of post-depositional alteration and frequently present several generations of uranium oxides which can be mixed at an inframillimeter scale, as shown by scanning electron microscopy images in Back Scattered Electron Mode (BSEM) and electron microprobe analyses. Therefore, the selection of homogeneous areas for isotopic or trace element analyses cannot be generally achieved using classical Thermal Ionization Mass Spectrometry (TIMS). REE being present in most occurrences in trace amounts ($<10^4$ ppm), in situ analyses by ion microprobe (SIMS) represents one of the most appropriate techniques for the determination of trace element contents together with the isotopic compositions of uranium oxides with a space resolution of about 20-40 μm.

2.1. BSEM methodology

BSEM images adjusted to get the highest contrast of grey have been used to detect the slightest variations of average atomic number in the uranium oxides, for revealing their internal structure. The revealed structure reflects either primary growth features such as zoning of the mineral during its deposition, or more or less complex alteration features produced by post-depositional fluid circulations with generally introduce elements with lower ionic radii and atomic weight than U or Pb such as Si, Ca, Fe. Consequently, such substitutions confer to the altered zones a lower average atomic number (LAZ), which appear as darker grey domains in the BSEM images compared to the non or less altered zones which present the highest uranium and lead contents and thus the highest average atomic number (HAZ), and thus which will appear brighter in the BSEM images.

2.2. SIMS methodology

The determination of REE abundance in natural uranium oxides by SIMS has been only recently performed for the first time in Japan using a SHRIMP (Sensitive High-Resolution Ion Microprobe) [6][7]. New calculation procedures and an appropriate standard sample have been developed for the deconvolution of the raw signals and to quantify the element concentration in ppm for the present work.

The instrumental conditions used for REE analyses in uranium oxides with the CAMECA IMS 3f ion microprobe are similar to those described in [8][9]. The samples of uranium oxides analysed were prepared as gold coated thin section or section of some millimeters in thickness. A 10 kV O^- primary beam of 10 nA intensity was focussed to a spot of 30 μm in diameter. The secondary ions emitted (Ca^+, Pb^+, U^+, UO^+, UO_2^+ mainly) were accelerated at 4 500 eV. The intensity of these REE isotopes were analysed at the lowest possible mass resolution under conditions of energy filtering at 80 eV to reduce the contribution of LREE oxide isobaric interferences at the HREE masses [8]. The low energy filtering avoids high counting rates when there are interferences due to complex molecules formation. The magnet was cyclically peak-stepped on 31 masses between mass 89 ($^{89}Y^+$) and mass 251 ($^{235}UO^+$), including the background, mass 235 ($^{235}U^+$) and masses of all significant REE isotopes (Table I). The counting time was of 5 s on each peak of the masses 89 235 and 251, and it was of 10 s on each peak of the others masses. 16 successive measurement cycles were cumulated for about two hours on each sample position, producing accounting statistic precision of less than 10% on most of the peaks. Interferences which stayed between light REE oxides and heavy REE were eliminated by a deconvolution technique [8].

Table I. Natural abundance of isotopes of elements and element oxides corresponding to the masses that were measured by SIMS [10]

	Y	La	Ce	Pr	Nd	Sm	Eu	LaO	CeO	PrO	Gd	Tb	NdO	Dy	Ho	SmO	Er	EuO	Tm	Yb	GdO	TbO	Lu	DyO	^{235}U	^{235}UO
89	1,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
139	0,0000	1,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
140	0,0000	0,0000	0,8850	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
141	0,0000	0,0000	0,0000	1,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
142	0,0000	0,0000	0,1110	0,0000	0,2710	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
143	0,0000	0,0000	0,0000	0,0000	0,1220	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
146	0,0000	0,0000	0,0000	0,0000	0,1720	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
147	0,0000	0,0000	0,0000	0,0000	0,0000	0,1500	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
149	0,0000	0,0000	0,0000	0,0000	0,0000	0,1380	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
151	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,4780	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
153	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,5220	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
154	0,0000	0,0000	0,0000	0,0000	0,0000	0,2271	0,0000	0,0009	0,0026	0,0000	0,0215	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
155	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,9967	0,0000	0,0000	0,1473	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
156	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,8850	0,0000	0,2047	0,0000	0,0000	0,0006	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
157	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,1570	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
159	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,1214	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
161	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0830	0,1890	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
162	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,1720	0,2550	0,0000	0,0000	0,0014	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
163	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,2490	0,0000	0,1500	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
165	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,1380	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
166	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0560	0,0000	0,0000	0,0740	0,3340	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
167	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,2290	0,4780	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
168	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,2670	0,2710	0,0000	0,0000	0,0014	0,0020	0,0000	0,0000	0,0000	0,0000	0,0000
169	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,5205	1,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000
171	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,1430	0,1469	0,0000	0,0000	0,0000	0,0000	0,0000
172	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,2190	0,2042	0,0000	0,0000	0,0005	0,0000	0,0000
173	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,1610	0,1564	0,0000	0,0000	0,0000	0,0000	0,0000
174	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,3180	0,2481	0,0000	0,0000	0,0009	0,0000	0,0000
175	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,9976	0,9740	0,0000	0,0000	0,0000
235	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000	0,0000
251	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	0,0000	1,0000

The real Y and REE concentrations were then determined following a two-step procedure:

(1) **deconvolution** of the energy filtered signals from masses 139 to 251 into M^+ and MO^+ contribution, to determined the REE intensities. There are 14 monoatomic species involved (Y, La to Lu, and U), and 9 oxide species (LaO to DyO), for 28 masses. The intensities were obtained after three iterations, realized using Excel software and the Fahey equations (1988): (1) « absREEdeconvolution.xls » to calculate absolute REE intensities and (2) « errREEdeconvolution .xls » to calculate REE intensities errors. This technique used the Guthrie and Heath natural isotopic abundances datas [10]: for example the masse 151 Eu represents 47.8% of total Eu, and the 153 Eu represents 52.2%. MO^+/M ratios are variable for uranium oxides, thus they are systematically determined for every analysis by using the tool "solver" of Excel, what gives rough values of MO^+/M (calculated HREE abundances remain rather reliable because the filtered energy reduces considerably the influence of the molecular ions to the atomic anions masses) [8]. However we note Gd as exception, because its mass interferes with those of three LREE oxides (LaO, CeO and PrO), which gives intensities with more than 100% of error: thus the results were not taken into account. Also, the masses corresponding to Yb interfere with those of GdO, the results of calculated intensities of this REE thus, cannot be taken into account either. A least square fit was done to determine the elemental intensities, using the equations of Fahey (1988).

(2) **conversion** of element count rate, obtained previously by deconvolution, to ppm by comparing the REE^+/U^+ ratios in the sample with the ratio measured in a standard sample. The drift of REE^+/U^+ ratio with respect to UO^+/U^+ during the analytical sessions was modelled by a least square regression line. The standard sample was an uraninite from Mistamisk [11], the REE composition of which was determined independently by ICP-MS (Table II) [7]. Conversion was calculated according to the formula (1):

$$REE/^{235}U_{sample} = \frac{(REE^+/^{235}U^+)_{sample}}{A.(^{235}UO^+/^{235}U^+)_{sample} + B}.(REE/^{235}U)_{s\,\tan\,dard}\,, \qquad (1)$$

A and B are the coefficients of the least squares regression line used to model the evolution of the REE^+/U^+ ratio with respect to UO^+/U^+ during the analytical sessions.

Table II. REE composition (ppm) in uraninite from Mistamisk determined by ICP-MS

Analysis n°	Y	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
1	17955,6	1121,0	4695,0	1146,4	5488,5	1631,9	717,3	1328,7	355,6	2796,1	495,5	1229,6	146,4	720,1	65,9
2	16887,0	1065,8	3223,2	1142,1	4629,9	1434,7	691,8	1209,8	331,9	2629,7	464,9	1162,2	137,0	683,4	65,1
3	18812,0	1156,1	2480,9	1077,2	4557,9	1526,3	772,4	1371,8	386,3	3014,1	517,8	1301,0	155,5	785,1	69,8
4	20325,2	1193,4	3696,8	1375,9	5524,3	1746,2	832,2	1456,7	410,0	3184,5	561,7	1369,8	162,3	830,7	72,9
5	19645,1	1152,2	2789,7	1113,1	4977,3	1608,2	805,7	1391,4	399,8	3133,3	541,1	1343,0	161,2	823,7	74,1
6	17921,3	1044,6	2957,0	1077,0	4825,3	1519,5	744,9	1307,4	370,8	2877,0	491,0	1230,9	144,0	741,1	66,1
7	20205,1	1230,6	4890,1	1341,3	6354,0	1871,4	823,7	1459,5	408,6	3239,1	574,0	1413,4	170,1	849,9	76,7

The peak of ^{235}U was employed to control U concentration, because its intensity was large enough to be counted during the same scan as the REE^+ ions. $(REE/U)_{standard}$ refers to the known composition of the Mistamisk standard sample.

Uranium concentration at the spot for SIMS analysis, which was needed to obtain absolute REE concentrations, was determined by electron microprobe in the same conditions as those described in [12].

However, this technique presents instrumental limitations:

1. the stability of the SIMS signal remains lower than with TIMS,

2. complex matrix effects of the concomitant element, spectroscopic interference of HREE from oxides of LREE and instrumental fractionation occur with SIMS. A specific calibration has to

be done for each type of matrix using a standard with a composition as close as possible to that of the analysed sample.

3. REE signatures of uranium oxides from the Shea Creek and McArthur deposits (Canada)

Geological setting

The McArthur River and the Shea Creek uranium deposits are located in eastern and western part of the Athabasca Basin (Saskatchewan, Canada) respectively. They both belong to unconformity-related uranium deposits [12]. The McArthur River deposit is the world largest high grade uranium deposit and is poor in associated arsenides-sulfides (monometallic). It is nearly entirely hosted by the Wollaston belt graphitic schist, metamorphosed during the Transhudson orogeny (1850-1750 Ma) but also extend in part in the overlying Manitou Falls sandstone Formation. The Shea Creek deposit has a lower U grade and tonnage and it is associated with a complex Cu-Ni-Co arsenides-sulfides paragenesis (polymetallic). It is mainly enclosed in the Manitou Falls Formation sandstone at the unconformity but the deposits also straddle into a graphitic metasedimentary slab comprised between two acidic granitic gneisses blocks. Metamorphism of the sediments and granitic emplacement and deformation are coeval and have occurred during the Talston orogeny (2000-1900 Ma, [13]). The location of the deposit in both occurrences is controlled by reverse faults rooted into graphitic structures in the basement. The cumulated amplitude of the displacement along the reverse faults reaches 80m for the McArthur River deposit but only 25m for the Shea Creek deposit.

3.1. U-Pb isotopic ages

In the Athabasca Basin, previous U-Pb dating of uranium oxides revealed a great variety of ages:

1. the most common U-Pb ages plot within a time interval of 1330 to 1380 Ma [14][15];

2. the most recent in situ analyses of the McArthur River deposit revealed ages from 1460 to 1540 Ma [16][17], over 100 Ma older than the most common ages;

3. numerous younger ages inferred from upper Concordia intercepts are scattered between 800 and 1300 Ma, and generally attributed to remobilization events ;

4. rare pitchblende analyses have been dated between 200 and 570 Ma from upper intercepts.

Most these ages were inferred from highly discordant data, displaying non-zero lower intercepts scattered between 200 and 700 Ma, without systematic link with the geological context. These data show that Athabasca Basin uranium oxides have a complex history, marked by several stages of deposition and remobilization of U and/or Pb. However, they do not indicate if there were one or several uranium deposition stages. Data indicated that the two uranium deposits did not recorded the same events. Using in situ U-Pb analysis by CAMECA IMS3f ion microprobe, Kister [12] has evidenced three stages for the McArthur River deposit, ca. 1460 Ma, 1335 Ma and 1275 Ma, while only one old event was recorded in the Shea Creek deposit, around 1275 Ma. Conversely, in the Shea Creek deposit at least three remobilisations events have been evidenced (ca. 400 Ma, 130 Ma and 60 Ma), while only one young event has been recorded in the McArthur River deposit (800 Ma).

3.2. REE analytical results

REE patterns from the Shea Creek (Fig.1, Table III) and McArthur River (Fig.1, Table IV) deposits have been determined for the different generations of uranium oxides and different states of hydrothermal alteration of the minerals. In both deposits REE patterns are featured by bell-shaped curves centred on Tb or Dy, in accordance with available REE data published on other unconformity-type deposits, such as Nabarlek, Australia [18], Collins Bay, Canada [1], Cluff D, Canada [4], and McArthur River [5].

Table III. REE abundances in uraninite (ppm). Shea Creek samples

sample		location	Y	La	Ce	Pr	Nd	Sm	Eu	Tb	Dy	Ho	Er	Tm	Yb	Lu	REE	LREE	HREE
She 100-1, 759.2																			
1	(b)		7795,4 ± 1300,1	40,7 ± 8,5	321,7 ± 95,4	204,9 ± 44,3	1307,0 ± 296,3	694,2 ± 175,8	230,8 ± 61,1	230,7 ± 60,9	1269,4 ± 317,1	225,5 ± 57,0	393,0 ± 106,2	59,8 ± 18,1	252,0 ± 107,1	16,3 ± 5,7	6290,7	2799,3	1914,4
2	(b)		7646,2 ± 1440,0	22,4 ± 5,0	165,8 ± 51,5	113,6 ± 27,4	815,8 ± 201,5	545,4 ± 146,7	206,9 ± 58,6	242,1 ± 70,2	1304,7 ± 350,8	240,4 ± 65,5	471,1 ± 137,8	70,7 ± 23,6	226,9 ± 107,9	17,0 ± 6,6	5543,5	1870,0	2002,7
3	(b)		6836,3 ± 697,0	27,2 ± 4,3	205,5 ± 55,6	142,0 ± 26,2	1002,0 ± 179,2	585,9 ± 91,7	194,5 ± 27,1	183,6 ± 25,8	1196,4 ± 162,5	221,4 ± 30,7	439,6 ± 62,4	54,7 ± 7,2	155,5 ± 29,3	9,2 ± 1,4	4630,5	2157,1	1791,5
4	(b)		6527,2 ± 565,9	27,7 ± 3,2	220,9 ± 54,0	137,9 ± 17,6	887,6 ± 120,8	558,6 ± 73,3	199,9 ± 25,5	177,6 ± 18,6	1184,1 ± 141,7	220,3 ± 24,9	434,2 ± 50,7	54,6 ± 6,2	178,4 ± 26,7	8,5 ± 1,1	4472,2	2032,6	1796,7
She 94-1, 742.4																			
1	(a)	HAZ	3857,1 ± 283,2	17,5 ± 1,5	110,0 ± 25,3	54,9 ± 5,0	295,6 ± 29,5	181,2 ± 14,2	85,3 ± 6,4	n.d. ± n.d.	846,3 ± 66,7	n.d. ± n.d.	272,8 ± 18,4	n.d. ± n.d.	175,2 ± 13,0	9,0 ± 0,6	3895,8	744,5	1294,4
2	(a)	HAZ	4171,3 ± 291,2	16,5 ± 1,3	112,4 ± 25,8	56,3 ± 5,1	310,2 ± 30,8	214,2 ± 16,5	86,1 ± 6,8	n.d. ± n.d.	976,5 ± 75,7	n.d. ± n.d.	326,8 ± 21,6	n.d. ± n.d.	209,0 ± 15,3	11,1 ± 0,7	4268,1	795,7	1512,3
3	(a)	HAZ	3867,5 ± 287,6	22,0 ± 1,9	124,1 ± 28,6	59,7 ± 5,6	325,6 ± 32,8	207,5 ± 16,4	89,3 ± 6,8	n.d. ± n.d.	833,5 ± 67,0	n.d. ± n.d.	280,5 ± 22,8	n.d. ± n.d.	184,6 ± 13,9	8,8 ± 0,6	4395,5	828,2	1298,6
4	(a)	HAZ	3492,7 ± 245,7	19,1 ± 1,6	118,7 ± 27,3	55,7 ± 5,0	291,2 ± 29,0	167,3 ± 12,9	87,3 ± 6,4	n.d. ± n.d.	762,5 ± 59,5	n.d. ± n.d.	244,1 ± 16,3	n.d. ± n.d.	159,1 ± 11,7	8,2 ± 0,5	3429,6	739,2	1165,6
5	(a)	HAZ	3952,5 ± 272,8	15,0 ± 1,2	92,8 ± 21,2	50,9 ± 4,6	300,4 ± 29,6	209,3 ± 16,0	94,1 ± 6,8	n.d. ± n.d.	896,5 ± 69,3	n.d. ± n.d.	285,7 ± 18,8	n.d. ± n.d.	190,5 ± 13,8	10,2 ± 0,7	3955,9	762,6	1372,7
6	(a)	LAZ	3785,5 ± 284,0	44,5 ± 3,6	272,3 ± 62,8	114,3 ± 10,5	554,7 ± 56,0	225,4 ± 18,0	100,1 ± 7,7	n.d. ± n.d.	704,4 ± 57,0	n.d. ± n.d.	234,4 ± 16,4	n.d. ± n.d.	160,2 ± 12,2	7,3 ± 0,5	4354,8	1311,3	1099,0
7	(a)	LAZ	4179,7 ± 299,6	25,9 ± 2,0	199,1 ± 45,8	103,9 ± 9,4	596,9 ± 59,8	303,1 ± 23,7	139,5 ± 10,4	n.d. ± n.d.	752,0 ± 59,4	n.d. ± n.d.	245,0 ± 16,7	n.d. ± n.d.	182,3 ± 13,5	8,7 ± 0,6	4900,0	1368,5	1179,4
8	(a)	LAZ	3773,5 ± 279,2	39,5 ± 3,3	212,9 ± 49,1	94,7 ± 8,8	498,2 ± 50,3	226,5 ± 18,1	101,7 ± 7,8	n.d. ± n.d.	718,4 ± 57,6	n.d. ± n.d.	237,5 ± 16,4	n.d. ± n.d.	159,5 ± 12,1	7,5 ± 0,5	4109,5	1173,6	1115,4
9	(a)	LAZ	5769,2 ± 379,3	29,8 ± 2,5	237,5 ± 54,1	112,9 ± 9,8	598,9 ± 58,9	292,7 ± 22,2	139,6 ± 10,3	n.d. ± n.d.	1059,5 ± 80,0	n.d. ± n.d.	371,1 ± 23,8	n.d. ± n.d.	270,2 ± 19,4	20,0 ± 1,4	4623,1	1411,4	1700,8
10	(a)	LAZ	3977,0 ± 296,3	38,9 ± 3,2	226,0 ± 52,2	101,7 ± 9,3	512,1 ± 51,6	216,1 ± 17,1	101,3 ± 7,8	n.d. ± n.d.	716,4 ± 57,4	n.d. ± n.d.	238,6 ± 16,5	n.d. ± n.d.	163,6 ± 12,3	7,5 ± 0,5	4131,6	1196,2	1118,6
11	(a)	LAZ	4303,5 ± 323,0	23,8 ± 2,1	173,3 ± 40,0	85,9 ± 7,9	472,3 ± 47,9	220,9 ± 17,6	107,5 ± 8,3	n.d. ± n.d.	753,8 ± 60,8	n.d. ± n.d.	253,8 ± 17,8	n.d. ± n.d.	171,0 ± 13,0	7,6 ± 0,5	4420,4	1083,6	1178,6
She 99-2, 704.7																			
1	(a)	LAZ	8941,2 ± 596,5	3017,3 ± 181,2	2880,4 ± 655,9	594,3 ± 51,2	1888,4 ± 184,9	572,4 ± 43,2	535,6 ± 37,7	n.d. ± n.d.	1480,0 ± 122,2	n.d. ± n.d.	391,5 ± 25,3	n.d. ± n.d.	377,0 ± 26,7	23,7 ± 1,5	16322,5	9488,5	2248,5
2	(a)	LAZ	9106,5 ± 624,9	3002,6 ± 180,9	2957,7 ± 674,3	608,1 ± 52,7	1930,8 ± 190,5	587,4 ± 44,4	551,8 ± 39,0	n.d. ± n.d.	1587,7 ± 121,0	n.d. ± n.d.	452,3 ± 29,7	n.d. ± n.d.	389,6 ± 28,0	23,8 ± 1,6	17018,0	9638,4	2429,6
3	(a)	LAZ	9405,4 ± 617,3	2867,1 ± 173,7	2931,3 ± 667,7	605,9 ± 52,4	1953,5 ± 191,4	602,0 ± 45,1	564,9 ± 39,8	n.d. ± n.d.	1626,6 ± 122,7	n.d. ± n.d.	446,1 ± 28,2	n.d. ± n.d.	406,1 ± 28,7	24,3 ± 1,5	16856,5	9524,7	2478,8
4	(a)	LAZ	8585,0 ± 586,2	2938,6 ± 181,9	2804,3 ± 639,1	572,0 ± 49,3	1820,0 ± 178,3	550,2 ± 41,6	513,1 ± 36,4	n.d. ± n.d.	1459,3 ± 111,0	n.d. ± n.d.	399,8 ± 26,0	n.d. ± n.d.	368,1 ± 26,3	21,2 ± 1,4	16510,4	9198,2	2227,2
5	(a)	HAZ	4692,2 ± 316,3	7,5 ± 0,6	40,9 ± 9,5	19,0 ± 1,7	120,0 ± 12,1	208,7 ± 16,0	178,8 ± 13,0	n.d. ± n.d.	1317,2 ± 99,4	n.d. ± n.d.	376,8 ± 23,9	n.d. ± n.d.	213,6 ± 15,2	14,1 ± 0,9	5122,0	574,8	1907,5
6	(a)	HAZ	4551,6 ± 690,6	9,7 ± 1,5	52,6 ± 12,4	21,9 ± 2,7	134,0 ± 15,8	245,5 ± 22,8	195,3 ± 15,5	n.d. ± n.d.	1378,0 ± 108,5	n.d. ± n.d.	397,4 ± 28,2	n.d. ± n.d.	234,5 ± 21,1	13,6 ± 1,4	6202,8	659,0	2009,9
7	(a)	HAZ	5359,8 ± 371,5	9,7 ± 1,2	52,4 ± 12,3	20,2 ± 2,0	122,2 ± 12,4	229,6 ± 17,9	188,6 ± 13,8	n.d. ± n.d.	1377,2 ± 106,4	n.d. ± n.d.	385,0 ± 25,1	n.d. ± n.d.	215,5 ± 15,7	12,2 ± 0,8	5851,0	622,7	1977,7
8	(a)	HAZ	4876,2 ± 335,9	3,5 ± 0,5	32,6 ± 7,5	14,7 ± 1,3	91,4 ± 9,1	164,5 ± 12,7	144,5 ± 10,5	n.d. ± n.d.	1054,1 ± 81,7	n.d. ± n.d.	296,5 ± 19,4	n.d. ± n.d.	156,6 ± 11,4	9,0 ± 0,6	4316,3	451,2	1507,2
She 100-1, 717.8																			
1	(a)	pitchblende	2179,4 ± 355,0	232,0 ± 61,9	124,1 ± 29,6	26,4 ± 3,9	129,8 ± 19,4	115,1 ± 17,7	47,7 ± 5,4	n.d. ± n.d.	244,5 ± 24,2	n.d. ± n.d.	85,9 ± 8,9	n.d. ± n.d.	58,1 ± 6,6	2,6 ± 0,4	2756,4	675,0	388,6
2	(a)	pitchblende	936,0 ± 74,6	108,9 ± 10,7	76,4 ± 18,1	13,7 ± 1,6	56,7 ± 6,5	65,5 ± 6,5	24,2 ± 2,2	n.d. ± n.d.	73,5 ± 6,7	n.d. ± n.d.	26,8 ± 2,2	n.d. ± n.d.	14,8 ± 1,4	0,6 ± 0,1	1302,3	345,4	115,2
3	(a)	pitchblende	978,4 ± 78,4	322,1 ± 25,4	98,2 ± 23,2	23,5 ± 2,4	103,8 ± 11,2	122,2 ± 10,5	41,1 ± 3,4	n.d. ± n.d.	99,7 ± 8,4	n.d. ± n.d.	31,6 ± 2,5	n.d. ± n.d.	29,3 ± 2,4	1,2 ± 0,1	2124,1	711,0	160,5
4	(a)	pitchblende	546,6 ± 43,2	170,2 ± 13,9	28,5 ± 6,7	5,6 ± 0,7	29,1 ± 3,7	56,2 ± 7,3	17,9 ± 1,7	n.d. ± n.d.	37,4 ± 3,5	n.d. ± n.d.	13,8 ± 1,3	n.d. ± n.d.	11,2 ± 1,1	0,4 ± 0,1	924,9	307,6	62,5
5	(a)	HAZ	6025,7 ± 478,9	76,9 ± 6,4	578,7 ± 134,1	135,8 ± 12,8	596,7 ± 61,3	428,9 ± 34,3	460,4 ± 35,5	n.d. ± n.d.	1318,4 ± 108,3	n.d. ± n.d.	414,2 ± 29,5	n.d. ± n.d.	280,9 ± 21,7	11,8 ± 0,8	10952,2	2277,4	2013,4
6	(a)	HAZ	5880,2 ± 457,4	84,8 ± 6,7	542,1 ± 125,5	115,3 ± 10,7	533,9 ± 54,7	413,9 ± 33,1	434,5 ± 33,4	n.d. ± n.d.	1294,7 ± 105,9	n.d. ± n.d.	398,8 ± 28,2	n.d. ± n.d.	276,5 ± 21,3	11,8 ± 0,8	10384,9	2124,5	1970,1
7	(a)	HAZ	6165,8 ± 484,0	84,4 ± 7,1	525,0 ± 121,9	106,1 ± 10,4	499,1 ± 52,8	407,8 ± 33,0	403,3 ± 31,5	n.d. ± n.d.	1291,3 ± 107,0	n.d. ± n.d.	406,8 ± 29,4	n.d. ± n.d.	260,1 ± 20,2	10,7 ± 0,7	11039,0	2025,6	1958,1
8	(a)	HAZ	6401,1 ± 511,8	90,8 ± 7,6	541,5 ± 125,8	160,8 ± 15,3	711,4 ± 73,5	485,1 ± 39,3	375,7 ± 29,5	n.d. ± n.d.	1508,8 ± 125,8	n.d. ± n.d.	493,0 ± 35,9	n.d. ± n.d.	305,3 ± 24,0	12,2 ± 0,8	11778,9	2365,5	2307,1
9	(a)	LAZ	3747,6 ± 312,4	252,1 ± 24,0	448,0 ± 105,9	189,4 ± 18,7	779,3 ± 82,5	513,0 ± 43,2	214,7 ± 17,5	n.d. ± n.d.	1332,6 ± 114,9	n.d. ± n.d.	343,2 ± 26,4	n.d. ± n.d.	304,9 ± 24,8	13,3 ± 0,9	13274,7	2396,5	1980,6
10	(a)	LAZ	3737,2 ± 312,5	244,9 ± 21,7	477,0 ± 112,6	197,4 ± 20,2	807,6 ± 86,7	533,0 ± 45,9	217,3 ± 18,3	n.d. ± n.d.	1345,9 ± 117,7	n.d. ± n.d.	355,6 ± 28,4	n.d. ± n.d.	306,5 ± 25,5	13,3 ± 1,0	13957,7	2477,2	2008,0
11	(a)	LAZ	3615,9 ± 322,0	242,0 ± 23,2	456,7 ± 107,5	190,9 ± 19,1	781,9 ± 83,5	524,4 ± 44,6	212,5 ± 17,7	n.d. ± n.d.	1316,7 ± 115,1	n.d. ± n.d.	350,2 ± 27,6	n.d. ± n.d.	298,0 ± 24,7	12,7 ± 0,9	14465,2	2408,4	1964,9
12	(a)	LAZ	2918,1 ± 245,6	191,9 ± 24,1	350,0 ± 82,2	132,7 ± 13,4	528,6 ± 57,1	366,7 ± 31,7	153,3 ± 12,7	n.d. ± n.d.	980,0 ± 85,4	n.d. ± n.d.	289,7 ± 23,2	n.d. ± n.d.	206,2 ± 17,8	8,5 ± 0,7	9993,9	1723,2	1475,8
13	(a)	LAZ	3745,1 ± 325,0	248,1 ± 22,9	449,2 ± 106,2	185,2 ± 18,6	759,9 ± 81,4	516,3 ± 44,3	209,7 ± 17,6	n.d. ± n.d.	1286,0 ± 113,7	n.d. ± n.d.	336,9 ± 26,9	n.d. ± n.d.	301,0 ± 25,1	12,3 ± 0,9	15508,8	2368,3	1923,9
14	(a)	LAZ	3276,4 ± 278,7	271,8 ± 25,8	476,6 ± 113,2	189,2 ± 19,6	753,5 ± 81,8	525,6 ± 45,9	210,5 ± 17,6	n.d. ± n.d.	1176,8 ± 105,3	n.d. ± n.d.	308,2 ± 24,7	n.d. ± n.d.	267,2 ± 22,1	11,1 ± 0,8	14876,0	2427,1	1752,2

Table IV. REE abundances in uraninite (ppm). McArthur River samples

sample		location	Y	La	Ce	Pr	Nd	Sm	Eu	Tb	Dy	Ho	Er	Tm	Yb	Lu	REE	LREE	HREE
H293-98.3																			
1	(a)	core	1837,3 ± 174,0	2,1 ± 0,3	5,7 ± 1,3	2,4 ± 0,3	12,9 ± 1,5	21,5 ± 2,3	27,9 ± 2,4	n.d. ± n.d.	416,0 ± 36,5	n.d. ± n.d.	125,8 ± 9,7	n.d. ± n.d.	78,1 ± 6,5	3,6 ± 0,3	1590,4	72,5	619,8
2	(a)	core	2010,8 ± 159,3	2,2 ± 0,2	7,6 ± 1,8	3,0 ± 0,4	15,1 ± 1,7	22,0 ± 2,0	29,6 ± 2,5	n.d. ± n.d.	427,8 ± 35,8	n.d. ± n.d.	124,7 ± 9,1	n.d. ± n.d.	77,7 ± 6,1	3,6 ± 0,3	1503,2	79,5	630,3
3	(a)	core	1874,5 ± 161,8	1,1 ± 0,1	3,9 ± 0,9	1,7 ± 0,2	10,3 ± 1,1	23,1 ± 2,0	29,9 ± 2,4	n.d. ± n.d.	467,7 ± 39,4	n.d. ± n.d.	136,5 ± 10,1	n.d. ± n.d.	87,4 ± 7,0	4,1 ± 0,3	1663,5	70,0	691,6
4	(a)	core	1813,4 ± 144,6	1,2 ± 0,2	3,5 ± 0,8	1,5 ± 0,2	8,9 ± 1,0	20,8 ± 1,9	25,7 ± 2,1	n.d. ± n.d.	444,6 ± 37,0	n.d. ± n.d.	128,7 ± 9,4	n.d. ± n.d.	78,4 ± 6,3	3,7 ± 0,3	1475,0	61,6	651,7
5	(a)	core	1820,7 ± 170,5	1,5 ± 0,2	3,6 ± 0,9	1,8 ± 0,2	11,0 ± 1,3	23,4 ± 2,1	29,1 ± 2,5	n.d. ± n.d.	465,0 ± 40,3	n.d. ± n.d.	135,3 ± 11,0	n.d. ± n.d.	90,2 ± 7,4	3,8 ± 0,3	1715,2	70,4	690,4
1'	(b)	core	1796,8 ± 182,0	1,2 ± 0,2	2,6 ± 0,7	1,6 ± 0,2	9,3 ± 1,4	22,8 ± 3,5	25,6 ± 3,9	47,3 ± 6,0	345,7 ± 48,8	54,5 ± 7,5	89,3 ± 12,7	12,7 ± 1,8	65,5 ± 12,2	2,8 ± 0,4	672,2	63,0	500,5
6	(a)	border	5207,3 ± 436,6	7,8 ± 1,1	42,9 ± 10,1	22,9 ± 2,5	130,8 ± 14,5	118,4 ± 10,8	113,3 ± 9,4	n.d. ± n.d.	1156,6 ± 96,6	n.d. ± n.d.	335,1 ± 24,6	n.d. ± n.d.	188,9 ± 15,0	8,9 ± 0,7	5299,8	436,1	1680,6
7	(a)	border	5059,5 ± 401,6	8,4 ± 0,8	49,8 ± 11,6	27,3 ± 2,6	148,0 ± 15,2	121,7 ± 9,9	120,1 ± 9,3	n.d. ± n.d.	1052,7 ± 86,3	n.d. ± n.d.	313,3 ± 22,4	n.d. ± n.d.	169,3 ± 13,1	8,2 ± 0,6	4823,0	475,3	1535,3
8	(a)	border	5322,8 ± 431,3	6,3 ± 0,6	48,6 ± 11,3	27,8 ± 2,7	154,0 ± 15,9	140,0 ± 11,5	131,9 ± 10,4	n.d. ± n.d.	1163,0 ± 95,9	n.d. ± n.d.	352,5 ± 25,3	n.d. ± n.d.	227,4 ± 17,6	11,0 ± 0,8	5590,9	508,7	1742,9
9	(a)	border	5179,8 ± 360,3	8,7 ± 0,7	56,0 ± 12,9	31,6 ± 2,9	174,3 ± 17,5	147,2 ± 11,4	145,4 ± 10,7	n.d. ± n.d.	1176,1 ± 90,6	n.d. ± n.d.	365,4 ± 23,7	n.d. ± n.d.	226,9 ± 16,5	13,0 ± 0,8	4457,5	563,1	1768,4
10	(a)	border	5063,4 ± 367,8	10,0 ± 1,0	53,3 ± 12,2	32,5 ± 3,1	185,8 ± 18,7	169,3 ± 13,3	173,5 ± 12,9	n.d. ± n.d.	1118,9 ± 88,5	n.d. ± n.d.	344,6 ± 23,3	n.d. ± n.d.	245,2 ± 18,3	12,8 ± 0,9	5067,0	624,4	1708,7
2'	(b)	border	4867,3 ± 483,6	7,8 ± 1,0	38,7 ± 9,7	23,8 ± 3,3	136,9 ± 20,1	118,7 ± 17,7	110,9 ± 16,3	114,7 ± 14,4	780,5 ± 107,8	133,2 ± 18,2	230,6 ± 32,1	32,4 ± 4,6	112,2 ± 21,0	6,5 ± 1,0	1995,0	436,8	1123,3
11	(a)	LAZ	8523,5 ± 658,2	33,0 ± 2,9	143,0 ± 33,1	85,3 ± 8,2	469,1 ± 48,1	271,8 ± 21,8	237,4 ± 18,4	n.d. ± n.d.	1403,3 ± 115,2	n.d. ± n.d.	513,7 ± 36,5	n.d. ± n.d.	322,0 ± 24,9	14,1 ± 0,9	7804,9	1239,5	2239,0
12	(a)	LAZ	8729,8 ± 698,6	22,1 ± 2,0	150,4 ± 35,0	82,5 ± 8,0	440,0 ± 45,6	238,2 ± 19,5	214,9 ± 17,0	n.d. ± n.d.	1299,3 ± 108,9	n.d. ± n.d.	493,7 ± 36,0	n.d. ± n.d.	299,5 ± 23,5	12,4 ± 0,8	7853,7	1148,2	2092,6
13	(a)	LAZ	7374,5 ± 587,8	41,6 ± 3,8	128,4 ± 29,9	65,1 ± 6,3	348,6 ± 36,6	226,0 ± 18,6	190,9 ± 15,2	n.d. ± n.d.	1234,5 ± 103,8	n.d. ± n.d.	453,0 ± 33,3	n.d. ± n.d.	284,8 ± 22,7	11,8 ± 0,8	7899,9	1000,6	1972,4
H393-134.6																			
1	(a)		3625,5 ± 1375,4	55,1 ± 7,4	87,8 ± 23,6	22,9 ± 2,6	96,8 ± 11,9	108,9 ± 9,9	112,5 ± 9,9	n.d. ± n.d.	1061,9 ± 97,7	n.d. ± n.d.	293,1 ± 25,1	n.d. ± n.d.	196,2 ± 19,6	23,5 ± 2,3	2940,5	484,1	1551,1
2	(a)		4240,0 ± 355,4	177,2 ± 22,4	282,4 ± 69,3	52,6 ± 6,1	167,5 ± 22,2	141,0 ± 11,9	134,1 ± 11,0	n.d. ± n.d.	1161,0 ± 99,8	n.d. ± n.d.	327,2 ± 25,4	n.d. ± n.d.	198,1 ± 17,4	20,3 ± 1,7	3894,4	954,7	1686,3
3	(a)		4096,1 ± 365,1	170,5 ± 13,8	254,8 ± 59,5	45,8 ± 4,8	149,7 ± 16,5	139,0 ± 12,0	146,7 ± 12,4	n.d. ± n.d.	1138,4 ± 101,9	n.d. ± n.d.	327,9 ± 26,7	n.d. ± n.d.	204,9 ± 19,3	23,4 ± 2,3	3742,1	906,6	1671,3
4	(a)		4399,3 ± 403,6	63,6 ± 5,7	114,1 ± 26,6	26,4 ± 2,8	117,4 ± 12,8	127,2 ± 11,0	133,4 ± 11,0	n.d. ± n.d.	1203,5 ± 103,0	n.d. ± n.d.	342,4 ± 26,5	n.d. ± n.d.	191,7 ± 16,7	18,9 ± 1,6	3529,9	582,0	1737,6
5	(a)		4105,3 ± 340,4	237,9 ± 22,3	352,8 ± 82,2	62,3 ± 6,3	182,8 ± 20,4	137,2 ± 12,3	134,7 ± 11,1	n.d. ± n.d.	1129,2 ± 95,1	n.d. ± n.d.	319,1 ± 24,8	n.d. ± n.d.	192,1 ± 16,3	18,5 ± 1,6	4154,6	1107,7	1640,4
6	(a)		3907,1 ± 344,2	93,6 ± 9,7	147,8 ± 34,9	26,0 ± 3,1	105,4 ± 13,2	93,3 ± 9,5	98,0 ± 9,0	n.d. ± n.d.	964,6 ± 84,7	n.d. ± n.d.	272,7 ± 22,8	n.d. ± n.d.	175,2 ± 16,3	17,5 ± 1,7	2883,1	564,2	1412,5
H347-76.3																			
1	(a)		4819,4 ± 525,0	18,6 ± 1,9	76,9 ± 18,7	38,9 ± 4,9	201,9 ± 23,4	173,6 ± 16,6	130,3 ± 12,9	n.d. ± n.d.	1392,9 ± 146,6	n.d. ± n.d.	416,8 ± 42,2	n.d. ± n.d.	233,9 ± 28,8	31,2 ± 4,0	3708,6	640,2	2043,6
2	(a)		4201,4 ± 469,9	30,8 ± 5,4	74,7 ± 18,5	29,3 ± 3,2	141,8 ± 16,0	132,1 ± 13,1	101,7 ± 10,4	n.d. ± n.d.	1169,1 ± 123,8	n.d. ± n.d.	347,4 ± 35,3	n.d. ± n.d.	192,0 ± 23,6	25,3 ± 3,3	3040,6	510,3	1708,5
3	(a)		4746,8 ± 613,0	8,5 ± 1,3	68,8 ± 16,9	40,7 ± 5,1	218,9 ± 27,3	187,4 ± 19,7	142,0 ± 15,9	n.d. ± n.d.	1413,0 ± 170,5	n.d. ± n.d.	412,9 ± 50,3	n.d. ± n.d.	235,4 ± 36,1	36,4 ± 6,1	3665,1	666,4	2061,3
4	(a)		4651,5 ± 1183,6	8,9 ± 2,2	68,7 ± 20,6	38,8 ± 10,5	223,4 ± 40,8	184,0 ± 30,7	136,8 ± 26,2	n.d. ± n.d.	1499,9 ± 229,8	n.d. ± n.d.	442,3 ± 65,3	n.d. ± n.d.	266,4 ± 40,2	39,5 ± 6,8	3911,4	660,6	2208,5
1'	(b)		4791,2 ± 632,6	121,5 ± 21,9	103,8 ± 28,4	46,7 ± 8,5	234,6 ± 44,2	187,3 ± 37,6	117,1 ± 23,6	148,4 ± 27,4	852,0 ± 161,1	140,7 ± 26,5	223,0 ± 44,1	28,9 ± 6,0	124,3 ± 35,0	8,1 ± 1,9	2843,9	811,0	1199,3
Mo221-79.8																			
1	(b)		1818,2 ± 277,2	21,7 ± 4,1	37,2 ± 10,5	13,2 ± 2,6	67,8 ± 13,8	83,0 ± 18,8	73,9 ± 17,4	122,4 ± 27,3	763,3 ± 168,4	120,0 ± 26,6	181,7 ± 42,7	25,7 ± 6,5	129,0 ± 24,5	9,8 ± 2,8	1949,6	296,9	1074,0
H785-74.6																			
1	(b)		6756,8 ± 658,4	42,4 ± 6,5	39,2 ± 9,8	20,6 ± 2,8	134,8 ± 19,8	143,3 ± 21,4	128,0 ± 18,9	123,9 ± 15,3	792,7 ± 109,9	132,8 ± 17,9	200,9 ± 28,0	24,4 ± 3,4	87,6 ± 16,0	6,7 ± 1,0	2083,3	508,2	1081,2
2	(b)		6683,4 ± 638,7	14,3 ± 1,9	22,3 ± 5,6	15,6 ± 2,1	117,0 ± 17,0	137,0 ± 20,1	123,2 ± 17,8	128,7 ± 15,5	814,0 ± 110,5	139,4 ± 18,2	225,1 ± 30,6	26,9 ± 3,6	94,6 ± 16,8	6,8 ± 1,0	2067,4	429,5	1133,7
3	(b)		6822,8 ± 697,0	6,8 ± 1,1	17,5 ± 4,5	14,0 ± 2,1	106,6 ± 16,9	130,1 ± 21,1	119,3 ± 19,4	124,6 ± 18,5	784,9 ± 119,1	135,4 ± 20,6	214,0 ± 33,1	25,3 ± 4,1	104,7 ± 21,3	6,9 ± 1,2	1995,2	394,2	1103,6
4	(b)		6882,5 ± 680,0	7,7 ± 1,0	18,3 ± 4,6	14,6 ± 2,0	115,4 ± 17,1	141,0 ± 21,5	128,8 ± 19,5	132,0 ± 16,8	832,6 ± 118,1	142,2 ± 19,5	230,6 ± 33,0	28,0 ± 3,9	95,5 ± 18,0	7,1 ± 1,1	2112,2	425,9	1158,7
5	(b)		6988,3 ± 697,3	8,8 ± 1,5	19,5 ± 8,3	15,1 ± 2,1	116,0 ± 43,1	141,0 ± 21,8	128,0 ± 19,6	134,0 ± 17,3	839,4 ± 120,4	145,2 ± 20,1	233,0 ± 33,7	28,3 ± 4,0	101,9 ± 19,4	7,2 ± 1,1	2143,2	428,4	1174,3
6	(b)	pitchblende	463,3 ± 56,0	85,7 ± 13,1	60,4 ± 16,1	15,7 ± 2,6	54,0 ± 9,5	52,3 ± 10,1	30,0 ± 5,7	21,7 ± 3,7	122,7 ± 21,7	18,0 ± 3,2	29,7 ± 5,5	4,2 ± 0,8	14,6 ± 3,7	1,2 ± 0,2	618,0	298,1	167,0
9079-29																			
1.1	(b)		1801,1 ± 1,0	13,0 ± 1,0	38,0 ± 1,0	12,9 ± 1,0	50,0 ± 0,9	26,3 ± 0,8	30,4 ± 0,7	44,3 ± 1,1	280,4 ± 0,6	43,2 ± 1,1	61,9 ± 0,7	7,8 ± 1,4	252,0 ± 0,7	2,8 ± 1,0	863,0	170,7	576,7
1	(b)		905,1 ± 1,0	4,9 ± 1,0	3,8 ± 1,0	1,2 ± 1,0	6,0 ± 0,9	24,6 ± 0,9	13,8 ± 0,7	27,4 ± 1,0	170,5 ± 0,6	28,2 ± 1,0	42,6 ± 0,6	5,8 ± 1,0	121,2 ± 1,0	1,8 ± 1,0	452,1	54,5	319,2
2	(b)		939,2 ± 1,0	15,8 ± 1,0	11,2 ± 1,0	1,9 ± 1,0	8,7 ± 1,1	27,7 ± 1,0	14,0 ± 0,7	23,8 ± 1,0	156,0 ± 0,6	23,9 ± 1,0	35,4 ± 0,6	3,8 ± 1,3	341,7 ± 1,2	1,1 ± 1,0	665,2	79,3	521,6
3	(b)		963,3 ± 1,0	17,4 ± 1,0	13,4 ± 1,0	1,6 ± 1,0	5,5 ± 1,5	21,4 ± 1,0	12,0 ± 0,7	24,8 ± 1,0	163,3 ± 0,6	25,0 ± 1,0	39,6 ± 0,6	5,4 ± 1,0	76,7 ± 3,2	1,3 ± 1,0	407,5	71,3	264,9
4	(b)		956,0 ± 1,0	46,7 ± 1,0	22,5 ± 1,0	1,5 ± 1,0	6,7 ± 1,9	17,7 ± 1,0	12,7 ± 0,7	25,2 ± 1,0	166,8 ± 0,6	25,5 ± 1,0	41,6 ± 0,6	5,6 ± 1,0	434,0 ± 1,3	1,2 ± 1,0	807,7	107,7	626,0

Notes:
HAZ : zones of High Average Atomic number appearing in light grey on BSE images
LAZ : zones of Low Average Atomic number appearing in dark grey on BSE images
nd : no data
REE = Total REE content
HREE = Dy + Tb + Yb
LREE = La + Ce + Pr + Nd + Sm + Eu
(a) January 2004 analytical session ; (b) April 2004 analytical session
All uncertainties are 95%confidence limits. Tb, Ho and Tm were only analysed during the April 2004 session. Gd could not be analtyically determined (see annexe).

However, a more detailed analysis of the REE patterns obtained during the present work, using the same methodology and standard, reveal some significant differences:

(i) REE absolute abundance and fractionation pattern is well reproducible within a single generation of non of weakly altered uranium oxide,

(ii) REE absolute abundance and intermediate and Heavy REE fractionation pattern are similar for HAZ zones from different samples giving the same U-Pb ages as exemplified by the She Creek samples dated at about 1275 Ma (SHE 100-1/7-59.2; SHE 94-1-742.4; SHE 99-2-704.7) and by the McArthur samples dated at about 1330 Ma (H393-143.6; H347-76.3; MO221.79.8),

(iii) REE absolute abundance can varies by more than one order of magnitude from the earliest dated uranium oxide generation compared to a later deposited one in the same deposit, as observed in the McArthur River deposit (sample H293-93-3);

(iv) LREE content may increase tremendously in altered uranium oxides as exemplified by the analyses performed on the HLZ and LAZ zones of the same generation of uranium oxide in the Shea Creek deposit (sample SHE 99-2, 704.7), but more moderately in others (SHE 94-1-742.4), but heavy REE distribution and abundance are preserved. The HREE fractionation pattern are also well preserved in HAZ and LAZ zones of recristallized uraninite generations giving young uranium lead isotopic ages of 400 down to 130 Ma in sample She 100-1-717.8. Therefore, according to the results obtained during the present investigation, the REE patterns from unconformity type deposits presented as typical of sandstone hosted unconformity related deposits, with high abundance of LREE [5], should in fact correspond to an altered uranium oxide phase.

(v) LREE tend to be less fractioned in the Shea Creek deposit than in the McArthur River deposit. However, considering that LREE are more mobile than HREE in uraninite, variations in LREE are not characteristic of the origin, but mainly indicate the degree of alteration of the uranium oxides.

(vi) Pitchblende deposited much later (at about 130 Ma) in sample She 100-1-717.8, still present a bell shaped pattern, but with much lower REE contents, possibly in relation with the lower temperature of deposition of this generation of uranium oxide. Pitchblende show also an abnormal enrichment in LREE like the altered uraninite of older age of deposition.

The McArthur River and LAZ areas of She 99-2,707.7 and She 100-1,717.8 samples exhibit a W-tetrad effect for the lightest REE (La, Ce, Pr, Nd) while there is a slight M-tetrad effect for the rest of the pattern. The light REE appear to be more mobile than the heavy REE, and show typically here with the W tetras effect the signature of a fluid which has circulated after the mineral deposition and then has modified the original signature of the light REE pattern without altering significantly the distribution of the HREE.

4. REE signatures of uranium oxides from the Pen Ar Ran deposit (France).

4.1. Geological setting

The Pen Ar Ran uranium deposit (Vendée, France) is related to an East-West fault which affects metamorphic formations at the northern margin of the Guérande Variscan peraluminous leucogranite. It occurs as veins essentially composed of massive pitchblende crosscutting felsic gneisses, called “porphyroids” and presumed to be of arkosic or acidic volcanic (ignimbrites) origin, in the vicinity of the contact with graphitic schists and quartzites [19]. The uranium oxides are very homogenous and have given a concordant dated U-Pb isotopic age at 320±9 Ma [20] determined from in situ measurement with an ion microprobe.

4.2. Results

REE patterns of the Pen Ar Ran uranium oxide are well reproducible in accordance with the homogeneity of the sample in optical microscopy and BSEM images. They show only a slight variation of REE contents but with an excellent preservation of the pattern shape. The REE patterns are strongly fractionated from the LREE to the HREE, but the REE of the second tetrad (Sm, Eu and Gd) define a strong positive anomaly (Table V). Compared to all patterns available from the literature or determined in our laboratory, the REE distribution obtained for the Pen Ar Ran deposit is the closest to the pattern obtained from pitchblende from one of the deposits of the largest uranium district in the world related to the volcanic Streltsovka caldera (Transbaikalia, Russia) (Fig.1). It strongly differs from the REE patterns of uranium oxides from intragranitic vein-type deposits (Kruth, Beaverlodge), which are characterized by a regular fractionation of their patterns from the LREE to HREE without any particular anomaly, except sometime the classical europium anomaly. The similarity of the REE patterns of the uranium oxides between the Pen Ar Ran and the Streltsovka deposits suggest a volcanic origin of the uranium for the Pen Ar Ran deposit. Such an interpretation is in accordance with one of the hypothesis for the origin of the porphyroids as being of ignimbritic origin. Hence, in the Pen Ar Ran deposit, the hydrothermal fluids would have leached the uranium from metamorphosed rhyolitic ignimbrites. The age of this deposit being close to that of the emplacement of the leucogranites (310±20 Ma) [19], and the temperatures of pitchblende deposition obtained from fluid inclusions studies being relatively high (300-350°C) [19], compared to Variscan intragranitic uranium deposits. Uranium leaching from the porphyroids probably occurred during hydrothermal circulations occurring in the contact metamorphism induced by the Guérande peraluminous leucogranites. Uranium deposition has occurred in the neighborhood of the redox barrier represented by graphitic schists and quartzites.

5. Conclusions

A methodology has been set up for in situ analysis of REE in uranium oxides by in situ isotopic U-Pb analysis using Secondary Ion Mass Spectrometry (SIMS) on a CAMECA IMS-3f.

Uranium oxides from unconformity-related uranium deposits seems to be characterized by a bell shape REE pattern, centered on Tb or Dy, but the variations in the total REE abundance may vary over more than one order of magnitude according to the uranium oxide generation. The younger generations tend to present higher REE abundances than the oldest, except for the latest botryoidal pitchblende deposition. Alteration of the U-oxides leads to a very strong increase of the LREE together with silica, but preserves the intermediate and heavy REE signature which can be used to characterize primary ore deposition. REE patterns with high LREE content presented as typical of sandstone hosted unconformity related deposits, should in fact correspond to altered uranium oxides. The bell shape of the REE pattern centered on Tb or Dy which have the closest ionic radii to tetravalent uranium in eightfold coordination [21], suggest a strong crystal-chemical control of the partitioning of the REE into the uranium oxide structure from the uranium ore forming fluid for unconformity related deposits rather than an effect of the type of REE complexing in the fluid or a signature of the source lithologies. The conditions controlling the increase of REE partitioning into the uranium oxides from the earlier to the later uraninite generations are unknown.

The uranium oxide from the Pen Ar Ran deposit (Vendée, France) with its strong enrichment in REE from the second tetrad, presents a very different pattern compared to unconformity related deposits or to already published pattern from granite related vein type deposits. The pattern obtained on a typical volcanic related uranium deposit from the largest volcanic related deposit uranium district of the world (Streltsovka, Russia) has the most comparable pattern with the Pen Ar Ran deposit. Such an analogy first confirms that the so called “porphyroids” which enclose the Pen Ar Ran uranium deposit correspond to acidic ignimbrites metamorphosed during the Variscan orogeny, and they probably represent the source of the uranium for the deposit rather than the nearby Guérande two micas peraluminous leucogranite, and second that the REE patterns of the uranium oxides from volcanic related deposits are probably characterized by a strong REE enrichment of the second tetrad. However, more systematic determinations on a series of other volcanic related uranium deposits (work in

progress) are necessary to confirm these first conclusions. It is also not possible for this type of deposit to know what is the mechanism controlling the fractionation of the REE between the ore forming fluid and the uranium oxides.

Thermodynamic calculations and experimental studies are now necessary to identify the possible mechanisms and/or key parameters which have been responsible for the specific REE signature which seems to characterize each type of uranium deposits.

Table V. REE abundances in uraninite (ppm) from Pen Ar Ran samples

sample	Y	La	Ce	Pr	Nd	Sm	Eu	Tb	Dy	Ho	Er	Tm	Yb	Lu	REE	LREE	HREE
PAR																	
1.1	121,72 ± 0,08	57,26 ± 0,06	23,73 ± 0,12	4,78 ± 0,06	14,78 ± 0,08	52,52 ± 0,15	13,94 ± 0,07	0,77 ± 0,23	5,30 ± 0,08	1,35 ± 0,07	2,97 ± 0,06	0,40 ± 0,09	11,54 ± 0,26	0,06 ± 0,06	189,42	167,03	17,61
1	147,73 ± 0,08	66,82 ± 0,06	27,19 ± 0,12	5,53 ± 0,06	17,26 ± 0,06	61,06 ± 0,06	15,55 ± 0,06	1,39 ± 0,08	6,27 ± 0,08	1,53 ± 0,07	3,60 ± 0,07	0,56 ± 0,07	17,02 ± 0,31	0,06 ± 0,07	223,84	193,41	24,68
3	134,70 ± 0,13	64,45 ± 0,14	27,61 ± 0,15	5,74 ± 0,11	18,84 ± 0,12	59,89 ± 0,16	19,75 ± 0,07	1,32 ± 0,09	6,91 ± 0,09	1,72 ± 0,11	3,95 ± 0,08	0,61 ± 0,12	6,00 ± 0,23	0,08 ± 0,10	216,87	196,28	14,23
4	143,04 ± 0,08	68,88 ± 0,07	27,79 ± 0,12	5,53 ± 0,06	16,66 ± 0,07	60,28 ± 0,06	15,03 ± 0,06	1,33 ± 0,08	6,32 ± 0,07	1,50 ± 0,10	3,56 ± 0,07	0,57 ± 0,07	6,70 ± 0,28	0,06 ± 0,08	214,21	194,16	14,35
5	175,69 ± 0,09	89,16 ± 0,07	30,19 ± 0,16	7,00 ± 0,06	23,02 ± 0,08	92,89 ± 0,07	22,97 ± 0,07	1,44 ± 0,10	8,11 ± 0,08	1,97 ± 0,07	4,79 ± 0,08	0,65 ± 0,09	8,18 ± 0,19	0,12 ± 0,09	290,48	265,22	17,73
6	136,20 ± 0,07	66,62 ± 0,06	27,93 ± 0,12	5,70 ± 0,06	17,87 ± 0,06	92,00 ± 0,06	21,54 ± 0,06	1,22 ± 0,08	6,73 ± 0,07	1,58 ± 0,07	3,71 ± 0,07	0,52 ± 0,08	12,97 ± 0,28	0,06 ± 0,07	258,46	231,66	20,92
7	159,48 ± 0,08	79,11 ± 0,07	32,87 ± 0,12	6,35 ± 0,06	18,41 ± 0,14	78,84 ± 0,06	18,86 ± 0,06	1,40 ± 0,09	7,51 ± 0,07	1,84 ± 0,07	4,31 ± 0,07	0,61 ± 0,11	13,82 ± 0,29	0,07 ± 0,08	263,99	234,43	22,72
8	176,37 ± 0,08	89,21 ± 0,07	37,08 ± 0,12	7,30 ± 0,07	23,55 ± 0,07	85,05 ± 0,07	20,18 ± 0,07	1,54 ± 0,16	8,42 ± 0,08	1,99 ± 0,06	4,94 ± 0,06	0,66 ± 0,07	11,47 ± 0,39	0,08 ± 0,07	291,47	262,38	21,43

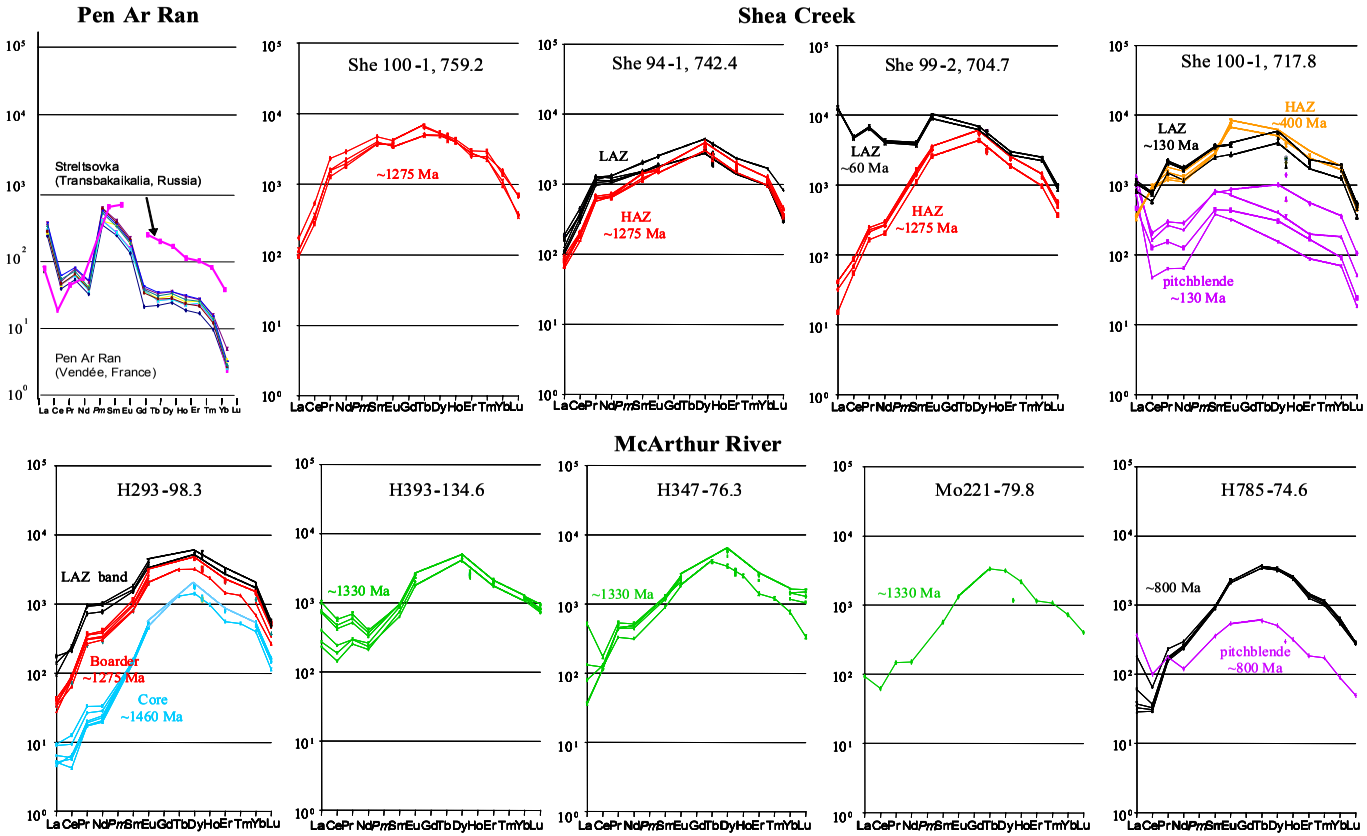

FIG. 1. Chondrite normalised REE patterns of uraninite from the Pen Ar Ran (first top left), Shea Creek (four top right) and McArthur deposits (bottom).

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Alminium Phosphate Sulfate (APS) minerals
Some markers of paleoconditions in unconformity related uranium deposits

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Abstract. In the framework of unconformity uranium deposits knowledge, aluminium phosphate minerals (APS) are considered for markers of paleoconditions of formation of ore deposits. APS minerals are ubiquitous and occur as disseminated crystals in a wide range of geological environments near the Earth surface. Their general formula is $AB_3(XO_4)_2OH_6$. These minerals are well known to incorporate a great number of chemical elements in their lattice and form complex solid solution series which are controlled by the physico-chemical conditions of their formation (Eh, pH, elements activities). These minerals are particularly widespread and spatially related to hydrothermal clay parageneses in the surrounding of unconformity related uranium deposits (URUD). Several APS-bearing clay assemblages and APS crystals-chemistry have been distinguished as a function of the distance from the uranium ore-bodies.

A thermodynamic study on the stability domains of the APS minerals solid solution series associated with clay parageneses has been investigated in the thermal conditions prevailing during the U ore deposition in order to correlate their crystal-chemistry according to pH, Eh or elements activities like strontium or cerium and then to precise the origin of strontium and the conditions of formation of the three different identified APS minerals.

A first simulation has been done to illustrate diagenetic environments far away from the uranium deposits in a barren sandstone area. This study has been realized with the KINDIS software which simulate the dissolution of minerals in a given solution and calculate the mass balance versus the reaction progress.

A second one illustrates the paleoconditions of precipitation of APS minerals associated with the clay halo of alteration encounter in the vicinity of uranium deposits.

1. Introduction

Aluminium Phosphate Sulfate minerals (APS) are ubiquitous and occur as disseminated crystals in a wide range of geological environments near the Earth surface, including weathering, sedimentary, diagenetic, hydrothermal, metamorphic and post magmatic systems. APS minerals belong to the alunite supergroup and crystallize most often in the rhombohedral crystal system. Their general formula is $AB_3(XO_4)_2OH_6$ in which A, B and X represent three different crystallographic sites. A are 12-fold coordinated sites, occupied by monovalent, divalent, trivalent and more rarely tetravalent cations; B consist of 6-fold coordinated sites, occupied by trivalent cations and X are 4-fold coordinated sites, occupied by anions. These minerals are well known to incorporate a great number of chemical elements in their lattice and to form complex solid solution series which are controlled by the physico-chemical conditions of their formation (Eh, pH, elements activities).

APS minerals are particularly abundant in the clay assemblages associated with some unconformity uranium deposits in Proterozoic basins in Australia (Kombolgie basin) and in Canada (Athabsca basin). No systematic investigations have been performed on the APS minerals in these deposits, and no data are available on their compositional variations in relation to the uranium deposits, though it is well known that their emplacement was controlled by physicochemical conditions (Eh, pH, activities of constituent metals, P and T). Also, petrographic, mineralogical and crystal-chemical studies have

and Athabasca (Saskatchewan, Canada). Several APS-bearing clay assemblages and APS crystal-chemistry have been distinguished as a function of the distance from the uranium ore-bodies and the structural discontinuities which have drained the solutions during the mineralization events.

The major crystal-chemistry variations of the APS solid solution series mainly consist in the relative proportions of svanbergite ($SrAl_3[PO_4,SO_4]OH_6$), florencite ($REEAl_3(PO_4)_2OH_6$) and goyazite ($SrAl_3[PO_3{\cdot}(O_{0.5}(OH)_{0.5})]_2(OH)_6$) end members. APS from proximal zones of alteration associated to uranium deposits are LREE and P-rich, in opposition to APS from zone of distal alteration where they are Sr and S-rich. To explain the chemical trend exhibited by APS from barren sandstones (Sr, S-rich APS) to uranium deposits (LREE, P-rich APS) thermodynamic calculations have been undertaken with kindis software to simulate fluids-host rocks interactions at different scale and understand the precipitation of the various chemical compositions of APS and clay minerals.

The goal of the present study is to estimate the paleoconditions of formation (pH, Eh, Log) prevailing during the formation of the APS and clay minerals according to the variations of the crystal chemistry of APS minerals and the nature of clays.

2. Unconformity related uranium deposits (URUD)

Unconformity type deposits represent the most significant high grade, low cost uranium reserves and resources in the world. The deposits are spatially related to an unconformity between the Early Proterozoic basement and the overlying Middle Proterozoic sandstone and structurally controled by graphitic faults. Several theories on the genesis of unconformity deposits have been proposed in the last twenty years and the origin of these ore formation is still debated in literature. The most commonly accepted genetic model; termed the diagenetic-hydrothermal model requires the mixing of a basement-derived, relatively reduced fluid, and more oxidized, high salinity, intraformational fluid circulating within the sandstone [2][3][4]. Favorable mixing occurs at temperature of approximately 200°C and results in precipitation of uranium at structural and physicochemical traps, developped near the sandstone-basement unconformity. Zones of fluids are characterized by well developped alteration halos containing illite, kaolinite, dravite, Mg chlorite, euhedral quartz and locally, Ni-Co, As-Cu sulfides [4].

3. Association APS-clay minerals in the surrounding of URUD

3.1. Clay minerals

Clay minerals are major constituents of the alteration halos in unconformity-type uranium deposits. Their crystal structures and crystal chemistry changes according to the distance of ore deposits and discontinuities which have drained the fluids. Kaolinite group minerals and illite characterized the barren sandstone far from any massive alteration areas and discontinuities. Close to the discordnace, on each side, illite is finelly mixed with variable amount of sudoite and dravite which composed the clay halos in the surrounding of most of the major deposits in the Athabasca basin. Deeper in the metamorphic basement, massive trioctahedral chlorite, associated with some ore deposits in Australia, have replaced the preexistant minerals. Illite has been systematically identified in distal drill holes as well as in proximal and mineralized ones. It occurs both in sandstones and basement rocks and result of several crystallization processing operating during diagenesis or related to the syn-ore alteration events.

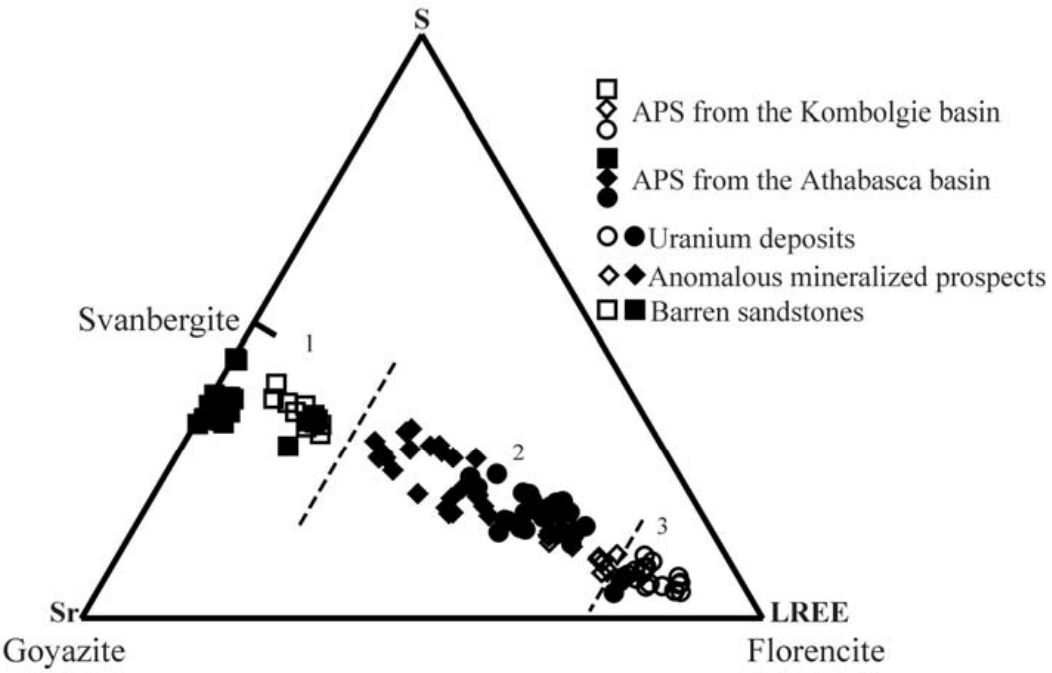

FIG. 1. Projection in S-Sr-LREE coordinates of the microprobe analyses of the different APS minerals encountered in the Kombolgie and Athabasca basins.(1-APS_1; 2-APS_2; 3-APS_3).

3.2. Crystal chemistry of APS minerals

The crystal chemistry of APS minerals as clays depends on their situation according to the discordance and the different discontinuities. In the barren sandstones, APS are Sr, S-rich (APS_1). Close to the anomal zone APS analyzed present an enrichement in P and LREE (APS_2), to have composition close to florencite ($REEAl_3(PO_4)_2OH_6$) in the vicinity of U-deposits (APS_3). The chemical trend exhibited by the APS (Fig.1) suggests that their compositional variation is controlled by large-scale variations in their physico-chemical conditions of formation [1]. There is too some differences of APS compositions between the two basins. In the mineralized and anomalous zones, APS from the Athabasca basin are LREE poorer than APS from the Kombolgie basin. Conversely, in barren areas, APS from the Athabasca basin are closer to the svanbergite pole than APS from the Kombolgie basin.

The mean composition of APS from each alteration can be characterized as follows:

- $Sr_{0.74}Ca_{0.26}Al_3[(PO_3{\cdot}(O_{0.71}(OH)_{0.29}))_{1.41}(SO_4)_{0.59}](OH)_6$, in zones of distal alteration (APS_1).
- $Sr_{0.20}Ca_{0.17}Ce_{0.63}Al_3[(PO_3{\cdot}(O_{0.86}(OH)_{0.14}))_{1.89}(SO_4)_{0.11}](OH)_6$, in zones of intermediate alteration (APS_2)
- $Sr_{0.12}Ca_{0.13}Ce_{0.75}Al_3[(PO_3{\cdot}(O_{0.89}(OH)_{0.11}))_{1.96}(SO_4)_{0.04}](OH)_6$ in zones of proximal alteration (APS_3).

These compositions correspond to solid solutions between svanbergite ($SrAl_3[PO_4,SO_4]OH_6$), florencite ($REEAl_3(PO_4)_2OH_6$), goyazite ($SrAl_3[PO_3{\cdot}(O_{0.5}(OH)_{0.5})]_2(OH)_6$), crandallite ($CaAl_3[PO_3{\cdot}(O_{0.5}(OH)_{0.5})]_2(OH)_6$), and woodhouseite ($CaAl_3[PO_4,SO_4]OH_6$) end-members. The overall variation of APS compositions determined above indicate an overall depletion in sulfates in the aqueous solutions, and conversely, a general enrichment in phosphate with increasing proximity to the uranium deposits [1]. Also, three different assemblages are considered as a function of the distance to the structures that drained the solutions and probably controlled the uranium deposition in these areas.

In this study, three mineralogical association are considered in order to schematize the different zones of alteration associated with the unconformity uranium deposits:

- illite + (Sr, S)-rich APS (APS_1) ± hematite, in the sandstone, several tens of meters far away above the unconformity.

- illite + sudoite + APS_2 ± hematite, on both sides of the unconformity and close to the regional faults that reworked both sandstone and the basement rocks above and below the unconformity.
- massive trioctahedral chlorite ± (LREE, P)-rich APS (APS_3) ± apatite ± uraninite, close to the uranium deposits.

The chemical compositions considered in this study for the APS minerals represent mean based on chemical analyses, representative of the three differents zones distinguished above. The compositions have been simplified to lighten the calculations. Ce represents all the light rare earth elements incorporated in the structure of APS. Fe encountered in the B sites [1] has been neglected.

4. Thermodynamic model

A thermodynamic study on the stability domains of the APS minerals solid solution series has been investigated in the thermal conditions prevailing during the U ore deposition in order to correlate their crystal-chemistry according to pH, Eh or elements activities like strontium or

cerium and then to precise the origin of strontium and the conditions of formation of the three different identified APS minerals.

Gibbs free energies of the APS are estimated by [5]. Entropy, heat capacity are estimated by the Helgeson's algorithm from measured values of alunite. Solubility products of these APS are then calculated by the Johnson's code SUPCRT92 [6] at 200°C and 600 bars.

This study has been realized with the KINDIS software [7][8][9] which simulate the dissolution of minerals in a given solution [10][11] and calculate the mass balance versus the reaction progress. Kinetic processes, which may be important in defining the molar fraction of reactant minerals, is not taken into account in the Kindis software.

Table I. Composition of the sandstone-derived fluid

	Initial fluid moles/kg H_2O	APS_1 equilibrium fluid moles/kg H_2O
Al	$1.2\cdot10^{-07a}$	$1.2\cdot10^{-04}$
K	$2.0\cdot10^{-04a}$	$2.7\cdot10^{-02}$
Na	$1.0\cdot10^{-02b}$	$8.0\cdot10^{-03}$
Sr	$1.0\cdot10^{-09c}$	$6.9\cdot10^{-03}$
Fe	$3.0\cdot10^{-06}$ (pyrite saturation)	$1.2\cdot10^{-05}$
Ca	$3.5\cdot10^{-04b}$	$2.8\cdot10^{-03}$
Mg	$2.1\cdot10^{-02a}$	$1.8\cdot10^{-03}$
Si	$4.0\cdot10^{-04a}$	$4.1\cdot10^{-03}$
PO_4	$1.9\cdot10^{-08a}$	$2.8\cdot10^{-03}$
C	$7.9\cdot10^{-04a}$	$1.1\cdot10^{-03}$
SO_4	$2.0\cdot10^{-05}$ (pyrite saturation)	$2.1\cdot10^{-05}$
Cl	$2.0\cdot10^{-03a}$	$5.4\cdot10^{-02}$
Ce	$1.0\cdot10^{-09c}$	$1.6\cdot10^{-11}$
B	$1.0\cdot10^{-09c}$	$1.0\cdot10^{-09}$
Log fO_2	-35.3	-35.5
pH	3	4.47

[a] [11] [b] [10] [c] value by default

Such models provide a quantitative understanding of complex, multicomponent speciation in the aqueous phase, as well as precipitation dissolution equilibria for a wide variety of solid phases involved in the formation of ore deposits [12][13][14][15][16]. The large thermodynamic databases incorporated in the computer codes can lead to the most realistic reconstruction of the reactions taking place during rock alteration and ore formation. In order to simulate the precipation of APS minerals, the database has been completed with the aqueous species of Ce and Sr. The use of solid solutions permits the direct comparison of the predicted mineral compositions with the analyzed compositions

of these minerals and to test hypotheses for several important characteristic features of unconformity-type uranium deposits [11].

A first simulation has been done to illustrate diagenetic environments far away from the uranium deposits in a barren sandstone area. The modal composition of the rocks has been chosen in agreement with the mineralogy of a sandstone only affected by an early diagenesis (95% quartz, 2% kaolinite, 2% K-feldspar, pyrite and hematite, monazite, apatite <1%) which represent the reactant minerals. Various hypothetical minerals (in weak amounts), Sr-carbonates, Sr-phosphates, aluminous minerals wiht trace of Sr in their structure, have been tested in order to provide the required elements to the formation of (Sr, S)-rich APS. Only the presence of Sr-apatite and Sr-feldspar as reactant minerals led to the formation of APS_1. The initial fluid composition (Table. I) has been proposed from data given by [11] and [10]. Data on Ce, Sr and B are still not available in the literature, consequently the default values considering are very weak (10^{-9} moles/kg H_2O, Table. I). Figure 2 displays the evolution of saturation index (Log Q/K) for the selected minerals versus the reaction progress. The diagram, reactant minerals versus the reaction progress, show the dissolution of the component minerals of the sandstone up to they are in equilibrium with the fluid. The diagram, product minerals versus the reaction progress, show the precipitation of illite and APS_1. The late occurrences of illite and Ca-apatite contribute to the precipitation APS_1 at low pH (4,5) and oxidizing conditions, (Eh=-150 mV).

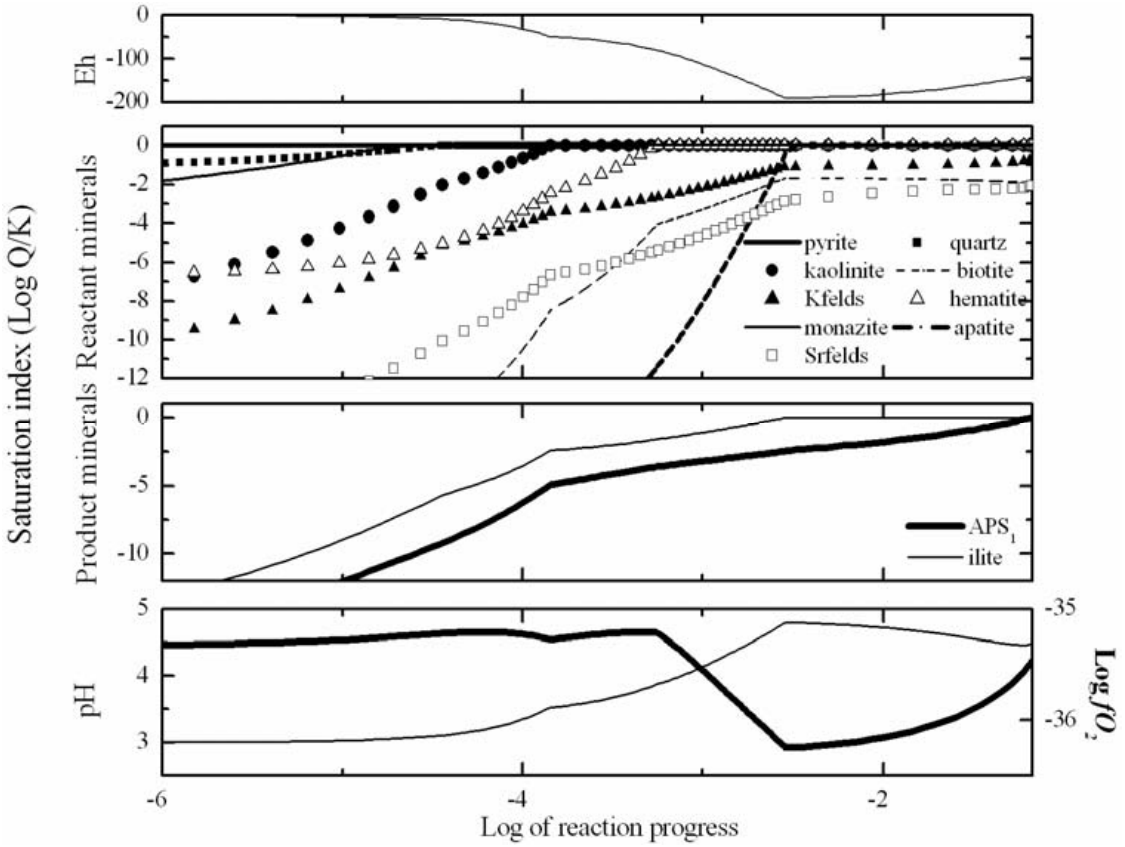

FIG. 2. Simulation of dissolution of a sandstone in a given solution with the KINDIS software.

In order to determine the conditions of formation of the two others APS minerals (APS_2 and APS_3) observed close to the unconformity and in the basement rocks, in anomalous and mineralized areas, a second simulation has been done. The system proposed in this model is assumed to be an interaction between the metamorphic rocks and a fluid initially in equilibrium with APS_1. On this assumption, the fluid in equilibrium with the APS_1 interacts with the mineralogy of the basement rocks and contribute to the formation of APS_2, APS_3 and the clay assemblages, observed in the different anomal and deposit areas of the Kombolgie and Athabasca basins, and to the evolution of paleoconditions.

The modal composition of the rocks has been chosen to represent an overall mineralogy of metamorphic rocks (34% biotite, 31% quartz, 10% orthose, 10% anorthite, 7% albite, pyrite, hematite,

monazite, tourmaline ≤ 1%) characterizing the reactant minerals. The chemical composition of the fluid, reacting with the minerals of the basement rocks, is given in Table I. Figure 3 displays the evolution of saturation index (Log Q/K) for the selected minerals versus the reaction progress. The diagram reactant minerals versus the reaction progress shows the dissolution of the primary minerals of the metamorphic rocks up to their equilibrium with the solution. The diagram products minerals versus the reaction progress shows the precipitation of the APS_2, APS_3 and the clay assemblages (illite + sudoite) associated in the surrounding of U deposits and anomalous areas. These formations are in agreement with the petrographic observations described before. The preliminary observations show that the formation of the APS_2 and APS_3 occur in different reducing conditions and pH. The conditions of formation of APS_2, characterizing the anomalous areas, and APS_3, associated with U deposits are respectively: -270.0 mV, pH equal to 4.87 and -390.0 mV and pH equal to 5.32

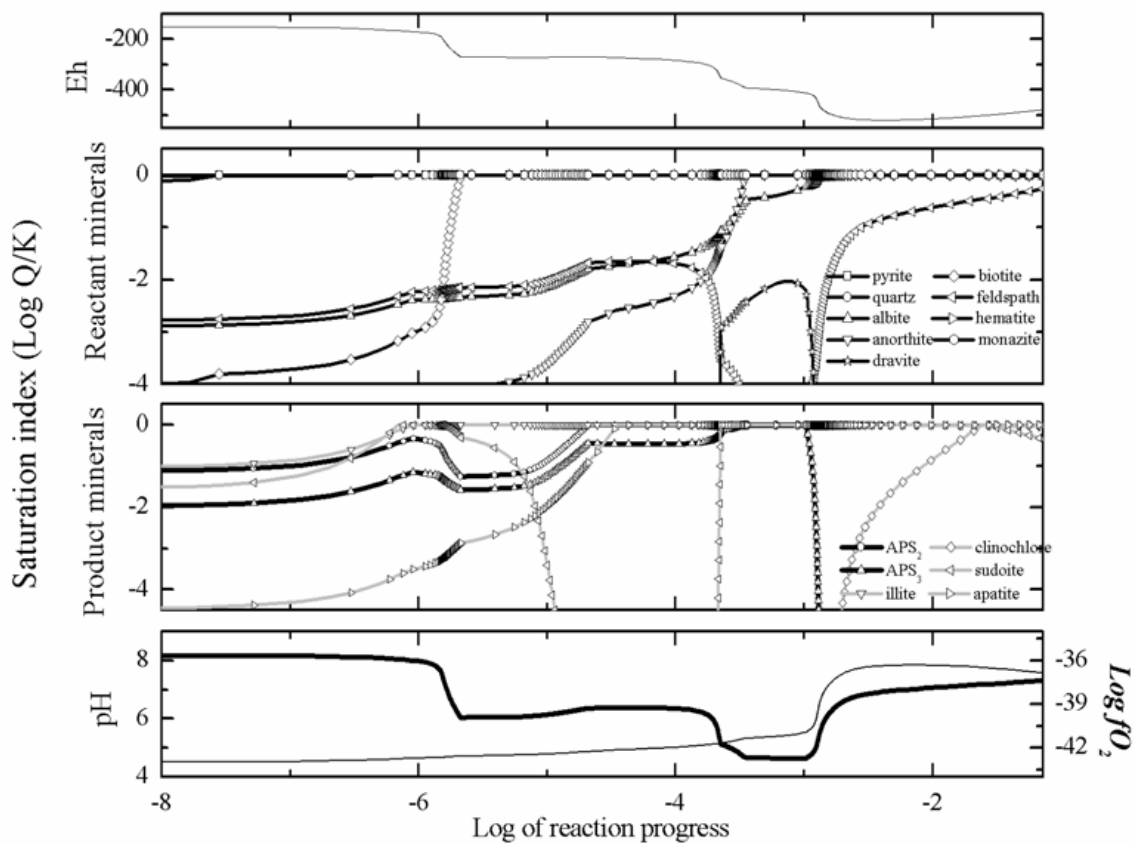

FIG. 3: simulation of dissolution of metamorphic rocks environment at the unconformity in a given solutions with the Kindis software.

This model is a preliminary work supposed to show the paleoconditions of formation of APS minerals analyzed in anomalous and U areas. These results are not definitive and just represent the tendency of the conditions of precipitation of APS minerals in the surrounding of uranium deposits. The choice of the mineralogy of the basement rocks as well the conditions of work (P and T) are not definitive and can vary in order to draw nearer to the conditions and the compositions given by the fluids analyzed in the vicinity of U deposits [10].

5. Conclusions and perspectives

Alteration haloes associated with unconformity related uranium deposit (URUD) are still debated in literature, however, most authors agree on the fact that they took place in response

to structurally-controlled infiltration of basement rocks by the diagenetic solutions from the sedimentary basin. This study works in this way of this hypothesis and reveal that the main factor which controlled the sequential evolution of APS_1 to APS_3 are the same ones that control the deposition of uranium [17] i.e. Eh, pH and the fluid chemistry (ratio Sr/Ce). The APS1 associated with

illite, which characterized barren areas, precipitate in oxidizing conditions and low pH (pH ≈ 4.5) and the different assemblages APS_2, APS_3 and illite + sudoite, which characterize anomal and U deposits, precipitate in more reducing conditions and a pH close to the neutrality (pH ≈ 5,3).

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Geochemical modelling for the unconformity-related uranium mineralization
A case study from Baskati area, Madhya Pradesh, India

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Abstract. Signatures of concealed unconformity-related uranium mineralization at the contact of Chhotanagpur Granite Gneissic Complex (CGGC)/Mahakoshal and Lower Vindhyan Semri sequence have come to light at Baskati, in Vindhyan-Mahakoshal Basin, following a multipronged exploratory efforts. Systematic lithogeochemical sampling brought out uranium halos with concentration sufficiently above the normal background along reactivated faults/fractures occurring parallel and oblique to the unconformity contact. Alteration features like haematitization, chloritization and illitization have also been observed in surroundings of these reactivated faults/fractures. Geochemical modelling indicates a hypogene source for mineralizing fluids. Based on geochemical modelling supported by geology, structure and lithogeochemistry, unconformity-related U mineralization model has been envisaged and the target area has been narrowed down for sub-surface exploration.

1. Introduction

The area under investigation forms a part of Chhotanagpur Granite Gneissic Complex (CGGC, 3.7–2.9 Ga), over which development of volcano-sedimentary sequence of Mahakoshal Group (2.6–1.9 Ga) took place, followed by deposition of Vindhyan Super Group (1.4–0.6 Ga). The CGGC/Mahakoshal-Vindhyan contact represents a favourable locale, for hosting unconformity -related uranium mineralization, as far as the geological time domain is concerned. The highly evolved nature of CGGC, multistage evolutionary history of Mahakoshal – Vindhyan basin, deep-seated nature of marginal faults and signature of reactivation (late Archaean to post Vindhyan) enhance the importance of the area for uranium mineralization. Mahakoshal volcano-sedimentary sequence around Sidhi, has been established as representing an ensialic rift zone [1]. Mineral zoning, characteristic of rift-related environment, have been recognized in Mahakoshal sequence with signature of Co, Ni, Zn, Cu, and Au mineralization in various litho units of this sequence [2]. CGGC during its evolutionary history underwent various stages of magmatism and deformation. The area, therefore, holds significance for mobilization and remobilization of various metals, including uranium with distinct development of metallogenic phases during successive stages of magmatism and deformation. Hence, the basin has been identified as target area for exploration of unconformity-related uranium mineralization.

Based on favourability criteria, aeroradiometric surveys were taken up between 1991 and 1995 to narrow down the target area. After deciphering the favorable uranium zones, thorough interpretation of aeroradiometric data, ground surveys were taken up in selected areas. As a part of the radiometric surveys, several anomalies such as Baran (1 490 ppm U_3O_8), Guleria (700 ppm), Meraraich (13 900 ppm U_3O_8) [3], etc., were located in the cataclasites associated with the CGGC, while anomalies associated with the late intrusives (rhyodacite and syenite) of Mahakoshal were located at Bari (10 700 ppm U_3O_8), Ainti (8 400 ppm U_3O_8) and several other localites [4]. The Bari syenites have been dated 1360±30 Ma [5]. Besides, association of uraninite with quartz stringers within dolomites of Lower Vindhyans was also identified [6]. Till 1998-99, numerous occurrences with high

uranium content were brought to light but none of them could emerge significant during follow-up detailed work, except the discovery of radioactivity associated with ferruginous phosphatic breccia emplaced along reactivated basement fractures at Baskati [7].

The study area falls 7 km ENE of Sidhi town in the state of Madhya Pradesh (Fig. 1). The present paper deals with the development of Baskati uranium zone, utilizing lithochemistry-based geochemical modelling.

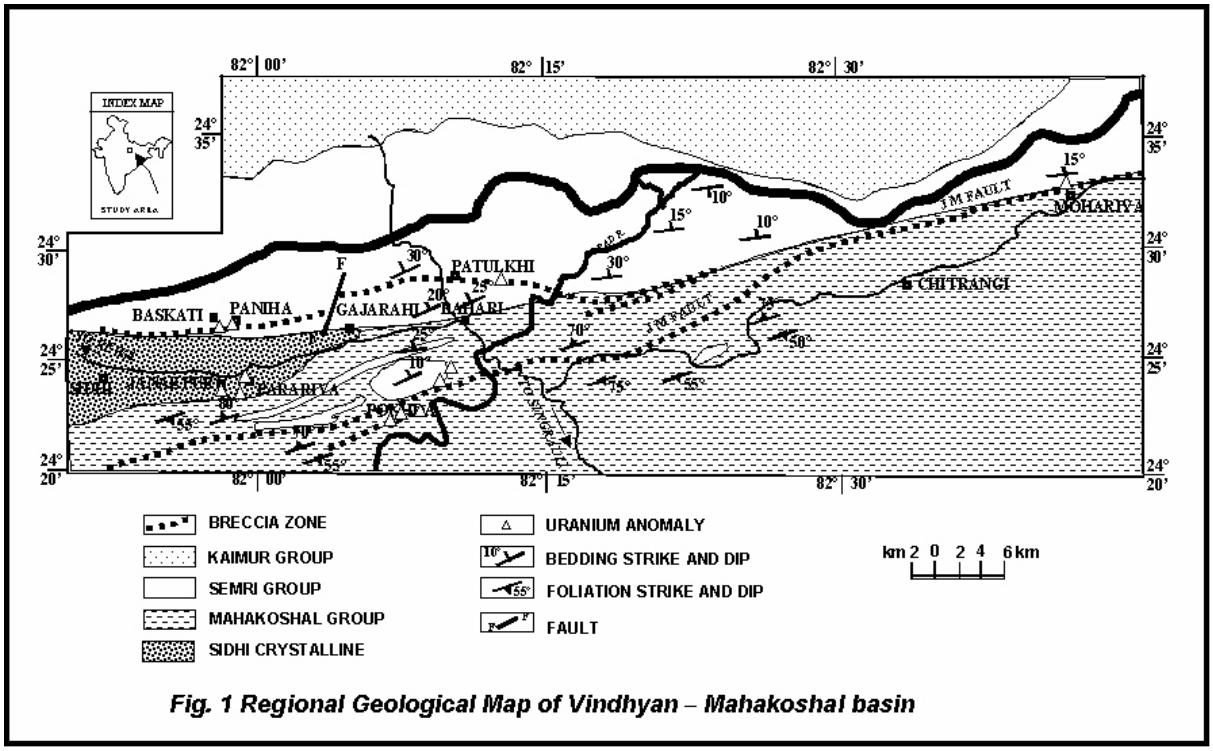

Fig. 1 Regional Geological Map of Vindhyan – Mahakoshal basin

FIG. 1. Regional geological map of Vindhyan-Mahakoshal Basin.

Regional geology

The study area forms part of Son-Narmada-Tapti lineament zone which lies north of the major ductile shear zone, i.e., Central Indian Suture (CIS) [1]. Sidhi area exposes the oldest rock units of tonalite - trondjhemite series, formed during proto-continental stage (3.7 to 2.9 Ga), representing ancient sialic crust. The evolution of CGGC resulted in development of magmatic suites represented by migmatites, rhyodacite, alkaline intrusives and highly felspathized gneisses. Fundamental faults tapping the mantle, developed on the pre-existing sialic crust and formed rift basin in which sedimentation of Mahakoshal Group (2.6 to 1.9 Ga) took place, which is classified as Greenstone Belt. The end of sedimentation witnessed post-tectonic intrusion of granitic plutons (2.0 to 1.8 Ga). Further reactivation of faults is indicated by various intrusive rocks of alkaline suite (1.8 to 1.6 Ga).

Deposition of Vindhyans started around 1.4 Ga over CGGC/Mahakoshal, with a prominent hiatus (Fig. 1). Geophysical studies indicated a number of basement highs within the basin suggesting rugged paleosurface of Vindhyan [8]. After deposition of basal Vindhyan sequence there was reactivation of basin-marginal faults as indicated by the presence of pyroclastic units and felsites in Vindhyan sequence of the Mahakoshal–Vindhyan Basin [9].

Post depositional tectonism affected the Vindhyan sediments along Son–Narmada North Fault resulting in intense structural deformation. Post Vindhyan reactivation of basin-margin faults is indicated by the presence of ultrabasic/alkaline intrusives. The contact between CGGC-Mahakoshal and CGGC/Mahakoshal-Vindhyans, are unconformable but faulted along majority of length. The boundary faults of Mahakoshal Group are named as Son-Narmada North Fault and Son-Narmada

South Fault, delimiting the deposition of Vindhyan and Gondwana in north and south respectively (Fig. 2). The contacts are poorly exposed and obliterated due to later intrusive phases. Physiography of Mahakoshal basin is controlled by ENE–WSW trending anticlinal and synclinal structures forming valleys and hills respectively. Besides, there are later cross-faults which trend either NNW-SSE or NNE-SSW displacing the boundary of the Mahakoshal belt [9]. The presence of Mahakoshal under the Vindhyans suggests that the Vindhyan basin was initiated on a crust which had undergone a stage of stretching and rifting. Heating of the crust, underlying the Vindhyan is evident from the occurrences of magmatic bodies. Thermal cooling and contraction has been responsible for the reactivation of marginal faults and continual subsidence during initiation of Vindhyan basin. Thus, it can be envisaged that the greater tectonic and magmatic activities were operative in the Semris as compared to the overlying units [10].

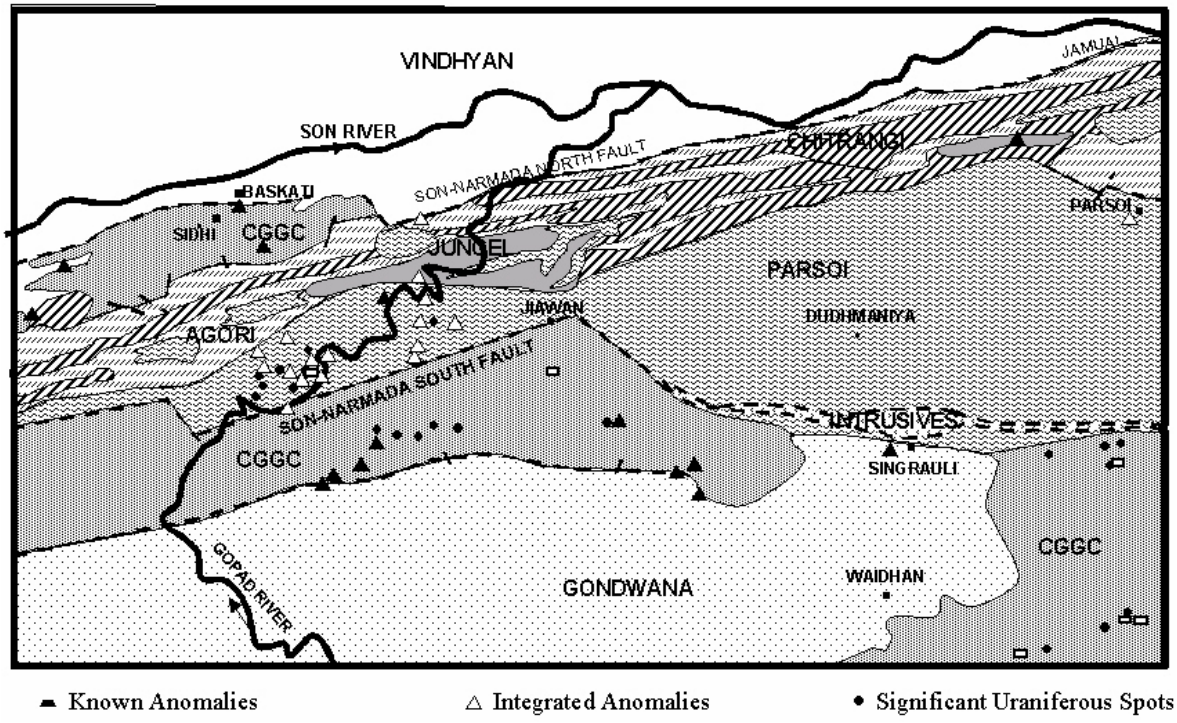

FIG.2. Disposition of known Ground and AGRS anomalies in Mahakoshal-Vindhyan Basin.

2. Exploration stages

2.1. Airborne gamma-ray spectrometry/gravity/magnetic

Airborne Gamma-Ray Spectrometric (AGRS) surveys were carried out between 1991 and 1995, in parts of Mahakoshal–Vindhyan Basin. Based on integrated studies of AGRS data, known ground anomalies, satellite/geological map, literature survey, U, Th, K, U/Th & U/K contour maps; lithostructural maps and aero-radiogeochemical images were produced [11]. Based on interpretative studies on these maps, the best definition of radiometric anomalies was obtained which led to identification of significant uranium favourable zones in parts of Mahakoshal and its environs (Fig. 2).

Anomaly priorities were established for subsequent ground radiometric survey. Regional geophysical gravity surveys brought to light prominent basement high around Baskati and further east [2]. Aeromagnetic data outlined broad compositional and structural features of CGGC/Mahakoshal and defined basin boundaries. A prominent aeromagnetic lineament running approximately in ENE-WSW direction has been inferred, besides a number of significant NNW-SSE, N-S and NNE-SSW oriented magnetic breaks. These interpretations suggest the presence of a large number of faults, fractures, shear zones and other structural and tectonic features in the region [12]. Baskati falls at the junction of

magnetic low and magnetic high attributable to Vindhyan sediments having faulted contact with Mahakoshal/CGGC.

2.2. Reconnaissance prospecting

Though several anomalies were earlier established in CGGC and Mahakoshal, the emphasis was laid on locating anomalies in the unconformity region of Vindhyans with Mahakoshal/CGGC. Reconnaissance prospecting was taken up in 1997-98 to locate point source radiometric anomalies on the ground which could not be picked up in airborne survey and to cover favourable areas in more detail. As a result, several uranium anomalies of significance were located in the vicinity of CGGC/Mahakoshal–Vindhyan contact [7]. The most significant signals are associated with the breccias developed along major faults, close to the unconformity contact (Figs 1 and 3, Table I) [13]. These breccias are steeply inclined and vary abruptly in thickness both along strike and down dip, depending upon the degree of tectonic control. They follow abrasion caused by faults and fractures and probably originated due to escape of gases during younger intrusive activity in the basin by the process of tufficitic brecciation [14].

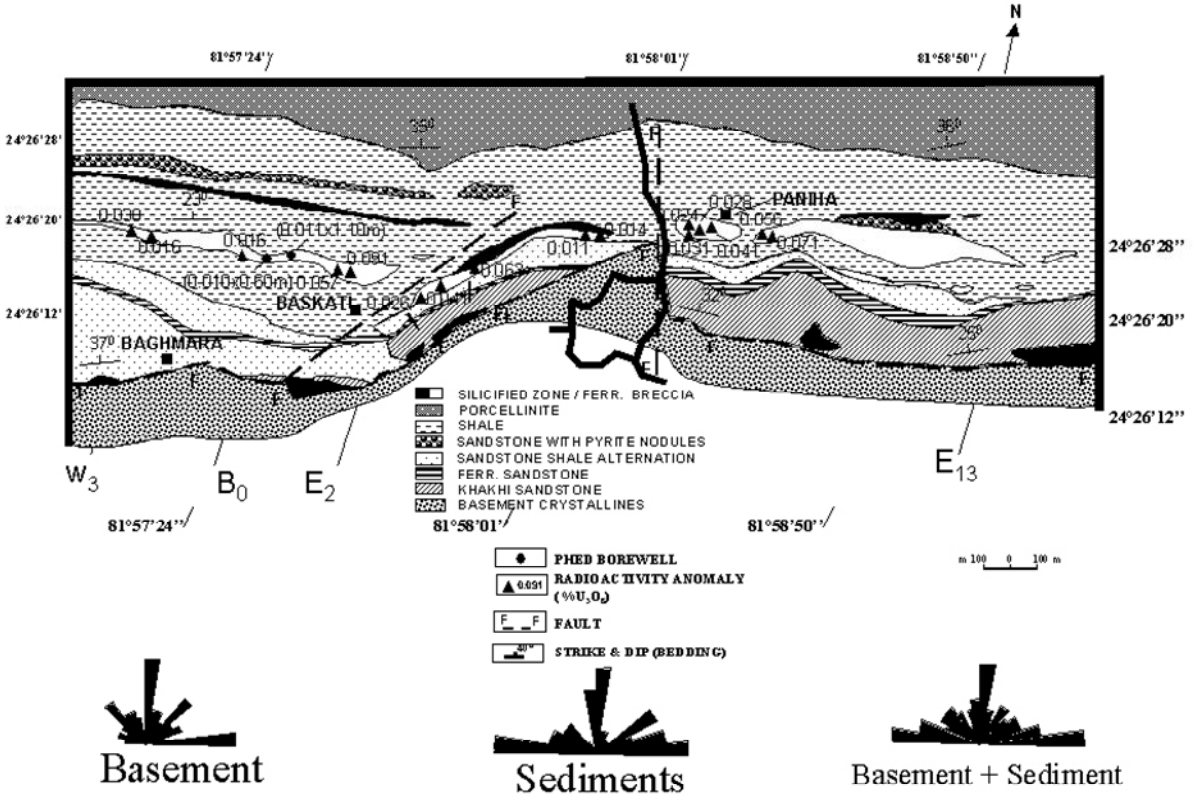

FIG.3. Geological map of Baskati-Paniha uranium occurrence, Sidhi District, M.P. TS No 63 H/15.

The breccia comprises angular to sub angular fragments embedded in a fine-grained matrix displaying layered structures produced by solution activity. Wall rock alterations like silicification, haematitization, chloritization and illitization occurring in these breccias and adjoining litho-units, indicate association of hydrothermal activity. Surface manifestation of uranium mineralization is displayed in breccia [13] and one such radioactive zone has been delineated at Baskati (Latitude: 24°26'25", Longitude: 81°58'00"), (Table I, Fig. 3). This zone assumes importance since it occurs along reactivated basement fractures transgressing the cover rocks.

Table I. Uranium anomaly details in Baskati area

Name of Anomaly	Extent m×m	Assay Results (range) $\%U_3O_8$	Rock Type
Baskati–Paniha	2500 × 3–5 (intermittent)	0.010 – 0.091 $\%U_3O_8$	Along reactivated basement fracture occurring in Vindhyan.
Parariya	3×1	0.018 – 0.039 $\%U_3O_8$	Intrusives in CGGC
Chowrah	1×1	0.042% U_3O_8	
Parariya	5 × 2	0.013 – 0.21 $\%U_3O_8$	Epidote-chlorite-magnetite-quartz rock
Pokhra	100×5	0.012 – 0.045 $\%U_3O_8$	Along reactivated fracture occurring in Mahakhoshal.

All samples analyse less than 50 ppm ThO_2

Geological studies revealed that the contact between CGGC/Mahakoshal and Vindhyans is unconformable but often faulted. The contact did not appear in low land areas but represented by harder lithological units such as silicified zones (schrol rock) along the faulted segments. Several fractures parallel to this basement fracture were mapped within the Vindhyan basin represented by silicified zones or breccia. Besides, cross-faults/fractures trending N-S and NE-SW displacing the marginal faults were also mapped. Alteration features and mineralisation associated with these fractures indicate their repeated reactivation. Fracture pattern reflect three major trends, i.e., ENE-WSW, N-S and NE-SW, which are in conformity with the major trends. The litho-units encountered in the cover sequence include sandstones, shales, ferruginous phosphatic breccia and porcellanite which show various stages of alteration. Carbonaceous shale, though not exposed at surface, is encountered only in wells and probably forms basement for these rocks besides other units of Mahakoshal group (Fig.3) [15]. In contrast to the non-mineralized sector all the rock types in the area surrounding mineralized zone show various degree of alteration such as sericitization, kaolinization, chloritization, illitization and hematitization.

2.3. Geochemical characterization

An area of 150 km^2, encompassing various radioactive zones and covering segments of CGGC, Mahakoshal and Vindhyan sediments has been sampled in a systematic grid and samples were analyzed for major oxides and trace elements. Table II shows range of different oxides and trace elements in various rocks. The entire area is characterized by anomalous concentration of Cu, Ni, Co, Cr, Zn and various other metals, which clearly indicates that all the lithological units have been affected by hydrothermal activity associated with different episodes of reactivations. Binary plots and contour maps of different elements/oxides were prepared to visualize pattern of distribution and correlation.

2.4. Geophysical investigation

Regional and detailed geophysical surveys viz., Gravity, Magnetic, TEM and IP, have revealed basement configuration, concealed intrusives/structures and conductors. The geophysical studies indicated depth persistency of fractures by recording gravity low over the fracture zones and also indicated the existence of two parallel faults, coinciding with the fracture zones observed at surface. Weak TEM anomalies along E-W and NE-SW fractures have been attributed to low intensity sulfide dissemination along NE-SW trend and presence of carbonaceous horizon along E-W trend.

3. Geochemical modelling

Lithogeochemical data have been interpreted through statistical calculation, preparation of contour maps in respect of uranium, major oxides and trace elements and binary plots along the sampling grids.

Table II. Range of different oxide and trace elements in various rocks

	GRANITE(n=51)			MAHAKOSHAL(n=31)			QTZ. BRECCIA(n=19)			FERR. BRECCIA (n=20)			SHALE-SAND STONE(n=31)			SAND STONE(n=49)			PORCELLINITE (n=13)		
	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.	Max.	Min.	Avg.
SiO2	91.6	50	68.9	97	85.57	92.89	98.24	69.5	91.02	75.49	4.43	36.4	95.88	45.58	72.68	96.84	21.7	77.53	90.88	15.44	76.05
TiO2	1.97	<0.01	0.72	0.96	0.14	0.515	1.1	0.02	0.17	0.3	<0.01	0.155	1.21	0.005	0.67	1.29	0.02	0.397	0.42	0.06	0.146
Al2O3	19.2	1	13.1	7.59	0.33	4.007	16.69	0.07	3.84	6.79	0.5	3.518	17.9	0.58	10.74	13.87	0.34	5.606	13.93	3.79	9.198
Fe2O3	5.83	<0.01	3.24	0.83	0.26	0.568	2.79	0.05	0.99	79.6	14	46.469	14.9	0.05	4.38	59.18	0.03	9.47	1.76	0.03	0.493
FeO	3.96	<0.01	0.77	0.94	0.42	0.725	1.6	0.28	0.8	0.14	0.1	0.059	1.37	0.25	68%	5.06	0.05	0.783	2.27	0.4	0.916
MgO	24.8	<0.01	2.25	0.35	0.03	0.183	1.7	0.03	0.77	2.27	0.1	0.84	30.56	0.19	2.26	5.02	0.01	0.925	13.73	0.05	1.458
MnO	0.2	<0.01	0.09	0.01	0.01	0.01	0.06	0.01	0.016	5.4	0.1	1.57	0.75	0.005	0.12	5.61	0.005	0.443	0.65	0.005	0.099
CaO	16.4	<0.01	2.29	1.36	0.03	0.487	1.42	0.01	0.11	8.6	<0.01	0.33	40.12	0.005	3.05	17.73	0.005	0.887	24.84	0.005	2.295
Na2O	7.09	<0.01	1.54	0.16	0.03	0.088	7.41	0.01	0.44	1.44	<0.01	0.327	2.11	0.005	0.46	0.78	0.005	0.155	5.46	0.05	2.497
K2O	8.789	<0.01	2.74	3.35	0.03	1.58	8.81	0.04	1.04	1.57	0.3	0.88	6.5	0.26	2.9	7.47	0.05	2.134	6.66	0.83	2.757
P2O5	0.74	<0.01	0.15	0.98	0.03	0.388	0.22	0.01	0.09	6.4	<0.01	1.97	1.51	0.01	0.22	1.57	0.005	0.208	0.21	0.02	0.081
V	110	9	56.1	15	15	15	235	12	56.42	885	12	269.15	857	2	118.3	545	2	58.31	61	2	18.692
Cr	2787	2	174	251	87	193	285	2	105.36	167	2	64	298	28	119.6	280	15	122.18	308	53	123.76
Co	38	2	14	5	5	5	25	2	8.21	143	2	38.7	32	2	14.35	85	5	16.46	14	5	7
Ni	133	2	92	193	50	135	227	2	85.05	320	2	126	172	2	70.06	667	28	101.49	249	45	109.53
Cu	45	2	24	44	5	25	94	2	24.47	66	2	13	275	5	36.96	1125	5	52.89	26	5	15.53
Zn	460	5	76	14	5	9	32	2	13.26	632	24	236	515	5	77.74	205	5	37.32	485	5	67.3
Ga	24	9	19	<0.01	<0.01	<0.01	17	5	10	15	7	11	25	11	17	17	7	12.16	22	18	19.75
As	17	5	7	<0.01	<0.01	<0.01	304	5	43	52	5	17	19	5	6.8	12	5	5.58	5	5	5
Rb	180	15	86	87	15	43	136	12	41.21	55	12	25	175	15	95.6	128	15	48.42	130	15	81.3
Sr	512	5	137	29	5	18	262	5	135.94	415	12	121	170	5	63.45	120	5	25.24	47	2	21.15
Y	40	9	27	<0.01	<0.01	<0.01	25	2	7.37	44	11	24	39	2	25.5	27	2	10.16	38	26	31
Zr	412	17	266	<0.01	<0.01	<0.01	129	35	67.37	54	33	43	404	38	217.6	263	41	122.41	282	122	180.25
Nb	21	2	13	<0.01	<0.01	<0.01	13	2	3.37	6	2	3	63	2	18.4	55	2	12.58	116	15	47
Ba	1896	15	511	252	28	154	675	12	127.79	3244	75	511	3869	15	480.4	918	15	272.12	1505	52	666.92
Ce	269	20	90	<0.01	<0.01	<0.01	252	25	90.5	91	25	35	356	20	108.9	96	20	36.75	106	25	45.25
Pb	45	50	29	<0.01	<0.01	<0.01	84	12	31.41	55	12	35	47	15	29.07	43	15	22.81	42	15	29.333
Th	49	2	19	20	20	20	25	2	16.1	25	2	16	39	2	16.9	33	2	16.95	38	9	24.23
U	53	1	6.7	2	1	1.33	40	0.85	6.807	96	1	26	39	1	5.7	14	1	2	29	1	4.307
U/Th	1.08	1	0.36	0.1	0.05	0.067	1.6	0.43	0.43	3.84	0.5	1.63	1	0.5	0.338	0.424	0.5	0.118	0.763	0.111	0.177

3.1. It is observed that the granites in the surroundings of Baskati area are of highly evolved nature (K_2O/Na_2O ratio up to 15), with anomalous uranium content (avg. 10 ppm) and high U/Th ratio (up to 17.67) in the vicinity of unconformity contact, indicating geochemical partition of uranium and thorium and presence of labile uranium in the system. Granites near Baskati area analyzed 15 ppm of uranium, which is considerably higher than granites in surrounding area.

3.2. Silicified zone developed along the contact of basement granite and Vindhyan sediments also have elevated U content (av.15 ppm) and high U/Th ratio (up to 13.33), indicating concentration of uranium.

3.3. Comparative study of anomalous and background values of uranium in mineralized and non-mineralized sectors respectively, indicate enrichment of uranium by a factor of more than 4 in the major litho-units of mineralized sector (Table III).

3.4. Regional uranium contour map indicates several patchy rings of uranium halos of the order of >20 ppm in a general pattern of 10 ppm, distributed over a strike length of 17 km along the unconformity contact as well as in the sediments occurring in the vicinity of reactivated fractures (Fig. 4). It is pertinent to mention here that uranium values up to 3 ppm occurring in cover sediments lying above the concealed ore bodies have been considered as anomalies in Athabasca basin, Canada [16].

3.5. Elevated concentration of uranium is evidenced along two cross fracture trends i.e., NE-SW and N-S, indicating remobilization of uranium (Fig.4).

Table III. Comparison of U ppm in various litho-units of mineralized and non-mineralized sector, Baskati area

Litho units	Mineralized sector				Non – mineralized sector			
	(n)	Avg. U	Avg. Th	Th/U	(n)	Avg. U	Avg. Th	Th/U
Porcellinite	5	8	19	2.40	10	2	23	11.5
Shale	11	13	16	1.23	15	2	33	16.5
Ferruginous – Breccia	10	43	7	0.16	9	4	30	7.5
Sandstone	16	5	10	2.00	23	1	26	26
Silicified zone	8	15	5	0.34	13	1	20	20
Granite	18	15	17	1.13	29	2	15	7.5

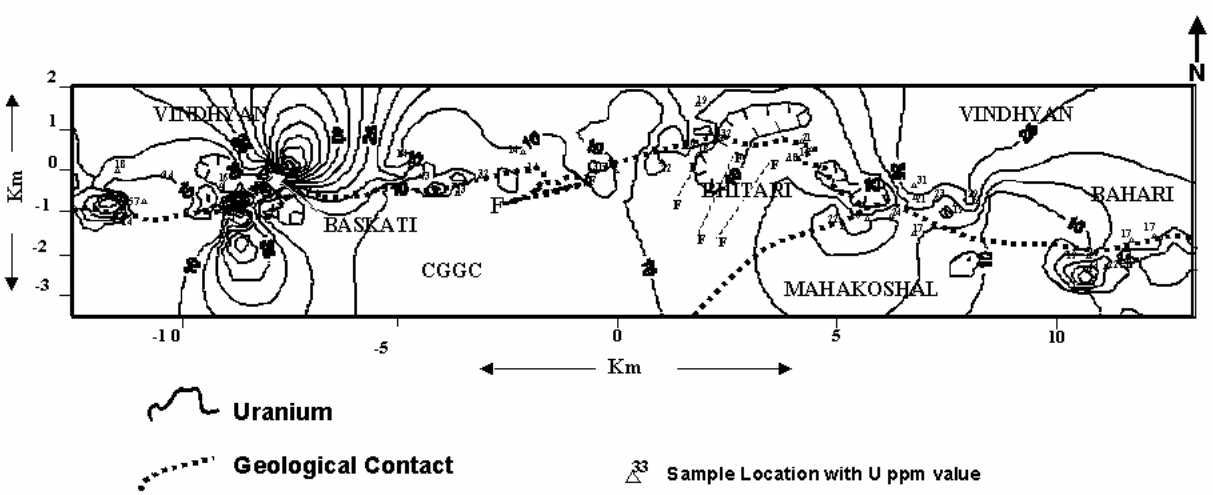

FIG.4. Regional U ppm contour map of Kothar-Baskati-Sarda-Bhitari-Garaha tract, Sidhi district, MP.

3.6. As compared to broad spectrum of uranium halos (more than 200 m wide at places), higher P_2O_5 halos (> 2% P_2O_5) are narrow and spotty and confined only to breccia occurring along one fracture, indicating that all the uranium activity is not associated with P_2O_5. Thus it is inferred that association of P_2O_5 with uranium is incidental. It is pertinent to mention here that P_2O_5 rich outcrops particularly

occurring in sandstone & breccia near the faults have been taken as indicators of unconformity-related uranium mineralisation in known unconformity-related deposits. In many deposits of Rum-Jungle area of South Alligator Valley, Australia, concentration upto 17 to 38 wt % P_2O_5 has been recorded in the vicinity of such faults [17].

3.7. Besides uranium, plots for ratios like K_2O/Al_2O_3, MgO/Al_2O_3, Fe_2O_3/MgO and Fe_2O_3/FeO were made to decipher the alteration associated with uranium mineralisation. These ratios have been chosen for better resolution of alteration features like illitization/sericitization, argillic alteration and haematitization, respectively and to ascertain their causative factor due to hydrothermal activity. Fe_2O_3/FeO ratio also helps in deciphering the role of oxidation of iron in reduction of uranium. The overlay of the ratio contours clearly depicts the correlation among all parameters indicating association of halos with zones of uranium localization (Fig. 5). Anomalies of moderate intensity have also been depicted for V and Ni, poorly correlating with uranium implying that U and Ni/V were not emplaced together but in subsequent phases pointing towards hypogene hydrothermal placement [18].

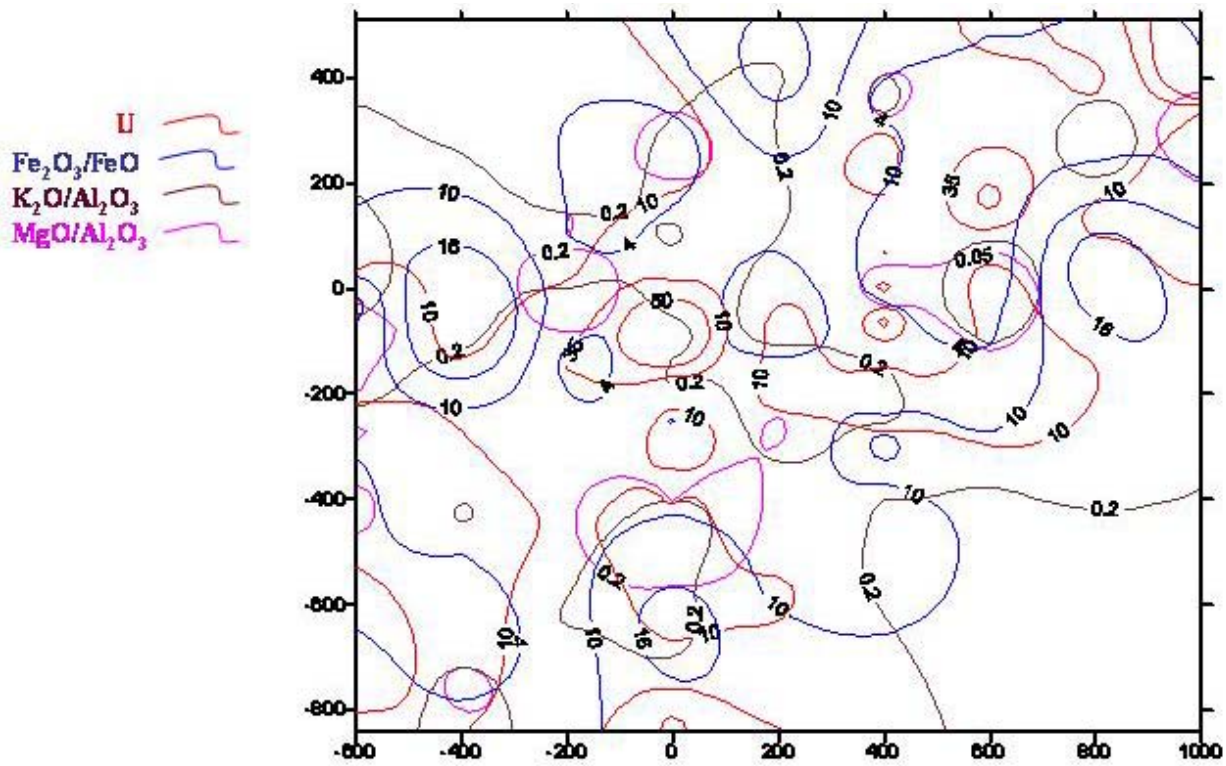

FIG. 5. Overlay of different oxide countours of Baskati.

3.8. In binary plots, distribution pattern of major oxides and trace elements depicts correlation of uranium with K_2O/Al_2O_3, MgO/Al_2O_3, Fe_2O_3/MgO and Fe_2O_3/FeO (Fig. 6), along the major fracture represented by ferruginous breccia, and it suggests that the uranium halos created in the area are probably due to hydrothermal activity. A fair correlation of uranium with some of these parameters can also be seen along two other fractures represented by rejuvenated quartzite and silicified zone in some profiles, suggesting the presence of parallel zones of fracturing and alteration.

3.9. Some bore-wells in the area have indicated uranium mineralization associated with carbonaceous shale which occurs below the cover of Vindhyans. Mineralized zones (upto 110 ppm U) have been encountered in initial attempts.

4. Evolution of concept and discussion

At Baskati, radioactivity was first recorded in ferruginous phosphatic breccia occurring along fractures well within Vindhyan basin close to CGGC-Vindhyan contact. While making analogy with established unconformity related uranium deposits it was observed that association of P_2O_5 -rich outcrops in

breccias occurring at structurally higher level is a common feature in various unconformity- related deposits of Rum Jungle Field, South Alligator Valley, Australia [17]. Besides, identification of carbonaceous shale in the borewell cuttings adjacent to radioactive breccia horizon, which is otherwise not exposed at surface, has been a striking feature. These shales, with intense degree of brecciation and abundant pyrite, besides sericite and calcite, probably provide basement, with Vindhyans as cover sediments.

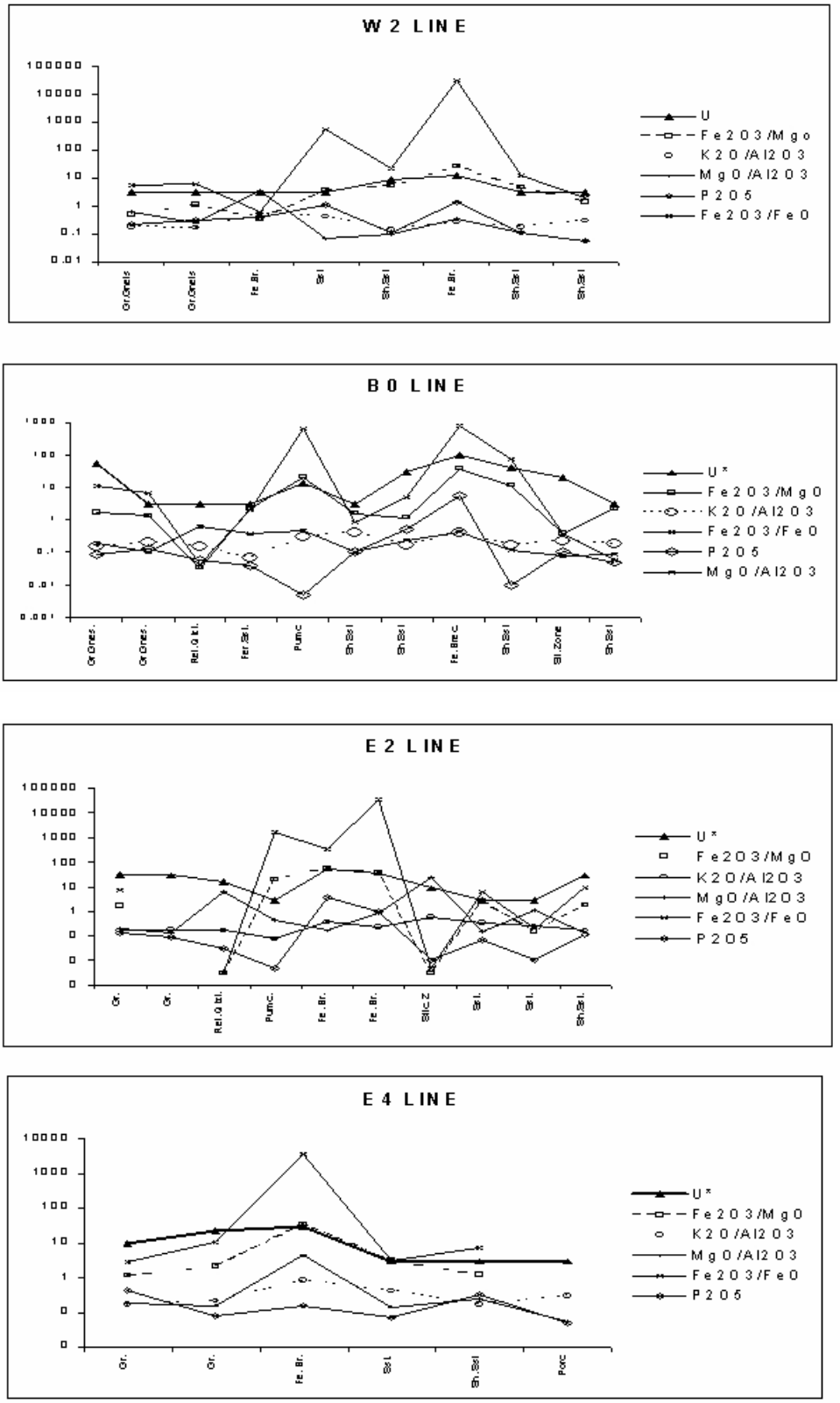

FIG. 6. Binary plots showing distribution pattern of uranium and major oxides.

The geological concept has evolved by orientation surveys, lithogeochemical sampling and review of data. The CGGC/Mahakhoshal – Vindhyan basin is charaterised by a complex evolutionary history. More than five magmatic phases have been recognized during the evolutionary process. The first stage included intrusion of granites at around 2.4 Ga, followed by injection of alkaline rocks of syenitic affinity (1.3 Ga) into the CGGC. This phase has been responsible for formation of small uranium zones such as at Bari [4]. This was followed by acidic intrusives represented by younger granite which have been responsible for mineralisation such as at Meraraich [3]. The fourth phase of intrusive activity is marked by ultra–basic/basic rocks represented by gabbro and dolerite. It is pertinent to mention here that boundary faults of Mahakhoshal are inferred as fundamental faults in the crust which controlled the intrusives and were reactivated during post–Vindhyan times resulting into development of felsites, silicified zones, pyritiferous and siliceous veins. Gases escaping along such faults and fractures probably produced breccia zones along them. Such parallel breccia zones have been commonly mapped in Mahakhoshal – Vindhyan basin. Uranium mineralization has been evident in each stage of magmatism. Uranium mineralization of moderate to high intensity has been reported in migmatites, syenites, rhyolites and alteration zones along reactivated fractures at various localities in CGGC with spots and zones analysing up to 13 000 ppm U [3, 4].

During different episodes of igneous activity and tectonism, CGGC has undergone large scale K-metasomatism in Sidhi sector, resulting into development of migmatites. The renewed activity along the crustal faults/fractures occurring in basement and cover rocks, through various geological periods, has influenced the sedimentary and tectonic history of the area. Syngenetic concentration of uranium is generally high in different rocks which became available for mobilization during successive episodes of deformation. Signatures of uranium mineralization above Precambrian paleosurface which was subsequently covered by Vindhyans are significant since there are strong chances of enrichment of uranium along this paleosurface during later phases of remobilization events induced by post–Vindhyan tectonism. The area, therefore, assumes importance for possible mobilization and remobilization of various metals including uranium with distinct development of metallogenic phases.

Uranium mineralization at Baskati and neighbouring areas occurs in breccia zones developed along the reactivated faults/fractures in proximity to CGGC-Vindhyans tectonised unconformity contact. Geochemical distribution of uranium in different rocks of Baskati area (Table II) indicates high intrinsic uranium content of major litho units which was available for mobilization during different episodes of deformation. Linear network of fractures produced during deformation acted as channelways for transport of fluids. During younger igneous activity in the basin, breccia zones were developed along major faults and fractures. Reactivation of these faults up to post–Vindhyan times is indicated by the presence of alkaline/ultrabasic suites in basement rocks and pyroclastic units and felsites in Vindhyan sequence. In such a situation, mobilization and remobilization of various metals including uranium becomes inevitable. Uranium enriched in the lower part, i.e. at the unconformity surface, which was subsequently covered by Vindhyans would also be prone for redistribution at the time of pre-Vindhyan rifting and post-Vindhyan reactivation of faults. Such episodes of deformation would generate high temperature gradients and facilitate further mobilization of uranium both from basement and cover sequence rocks. Thus the areas concealed under the cover of Vindhyans are potential sectors for uranium accumulation and preservation. Post Vindhyan activity along such sectors would further help in enrichment of uranium along unconformity surface.

Review of geological and geochemical information in conjunction with detailed surface radiometric characters and structural data analysis, reveal that radioactivity occurs along reactivated basement fractures along a favourable geological contact. Keeping in view the factors like parallelism of deep-seated fractures tapping up to mantle, signtures of repeated reactivation, occurrences of several mineralized zones, strong evidences of hydrothermal activity and alteration features along fractures, favourable basement having labile uranium, lithologies with reducing agents and presence of suitable cover rocks, a unconformity-related uranium mineralization model has been envisaged. The results of reconnaissance, follow-up geological and detailed geochemical studies provided insight into uranium dispersion mechanisms and distribution of uranium in the basin. Based on geochemical modelling, not only presence of uranium in the basin has been ascertained but the processes operative for localization / concentration of uranium have also been recognised. This approach has narrowed down the target area for systematic exploration by drilling.

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Sandstone type uranium deposits in NW China

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Abstract. Northwest China, containing most of known sandstone type uranium deposits in the country, comprises seven Mesozoic-Cenozoic basin-forming domains. Meanwhile, four types of host depositional environments have been identified, including cratonic, intra-continental down-faulted, and compressive intermountain flexural basins and erosive gully. It is also indicated that known deposits/occurrences/showings were formed under three tectonic regimes, such as slight arching, sub-orogenic and orogenic regimes. Benefiting the exploration, both roll and basal channel sub-types deposits are further divided into classes that are titled according to the name of typical or first discovered deposits/ ore-fields. Finally, which classes deposits and where are more promising for the exploration in Northwest China are tentatively discussed.

1. Introduction

Northwest China named here indicates the territory of China north of Kunlun-Qilian-Qingling mountain systems and west of Great Higgan Range. The territory, some 2 500 km long, in average about 650 km wide and about 2.86×10^6 km^2 in area, covers Xinjiang Autonomous Region, Gansu Province, Qinghai Province, Shanxi Province, Ningxia Autonomous Region and Inner Mongolia Autonomous Region. It hosts most of significant sandstone type uranium deposits in China, including Kuji'ertai, Wukuerqi, Zajistan and Shihongtan deposits in N. Xinjiang; Nuheting, Subeng, Bayantala deposits and Donsheng mineralized area in Inner Mongolia. The Northwest China is also considered to be the east extension of a giant uranium super-province stretching from Central Asia eastwards, and remains highly perspective, having minor exploration in the past [1].

2. Regional geologic background

Northwest China covers three tectonic elements, the SE portion of Kazakhstan plate and the south portion of Siberia Plate to the north, southwards thereof the Tarimu-N. China Plate (Fig.1). The Tarimu-N. China Plate is a composite plate connected of Tarimu sub-plate and N. China sub-plate by Caledonian orogeny [2]. The Siberia Plate and the Tarimu-N. China Plate are of the "continental type" cored by the Siberia, the Tarimu and the N. China continental blocks respectively while the Kazakhstan plate is of the "intercontinental type" comprising a series of pre-Cambrian terrains amalgamated by Palaeozoic fold zones [3]. In the Northwest China 7 Mesozoic-Cenozoic basin-forming domains were outlined (Fig.1).

- Tianshan-Junggar domain occurs in SE Kazakhstan plate. It includes relatively large-sized Junggar Basin and Tianshan intermountain basin group; the latter contains Yili and Turpan-Hami uraniferous basins where Kuji'ertai and Shihongtan deposits are situated respectively.

- Tarimu domain occurs in the Tarimu sub-plate and developed upon the basis of the Tarimu continental block. It represents the biggest Phanerozoic basin in China where no U deposit has been discovered so far but promising.

- Altun Domain stretches along Altun strike-slip zone, occupying the contact between Kazakhstan plate and Tarimu sub-plate eastwards, including Dunhuan strike-slip compressive

basin, Beishan and Badain Jaran strike-slip extensional basins. Both Beishan and Badain Jaran basins contain a number of secondary order depressions.

- Alxan-Corridor domain occurs in the Tarimu-N. China Plate between the Tarimu and the N. China continental blocks. It includes Alxan, Corridor and Central Qilian basin groups.

- Qaidam domain occurs in the south margin of Tarimu-N. China Plate. It contains only the Qaidam basin.

- Eren-Hailar domain extends across the Siberia Plate and the N. China sub-plate, and the Wendu'ermiao-Xilamulun Fault is the boundary between them. It includes Yinshan intermountain basin group, Eren and Hailar down-faulted basin groups and some uraniferous depressions are known in Eren basin.

- Ordos domain occurs in the east portion of the N. China continental block developed on the basis of the Ordos continental nucleus. It contains only large-sized basin of the same name where Dongsheng uranium mineralized was discovered in latest years where a considerable amount of uranium resources/reserves have been explored [4].

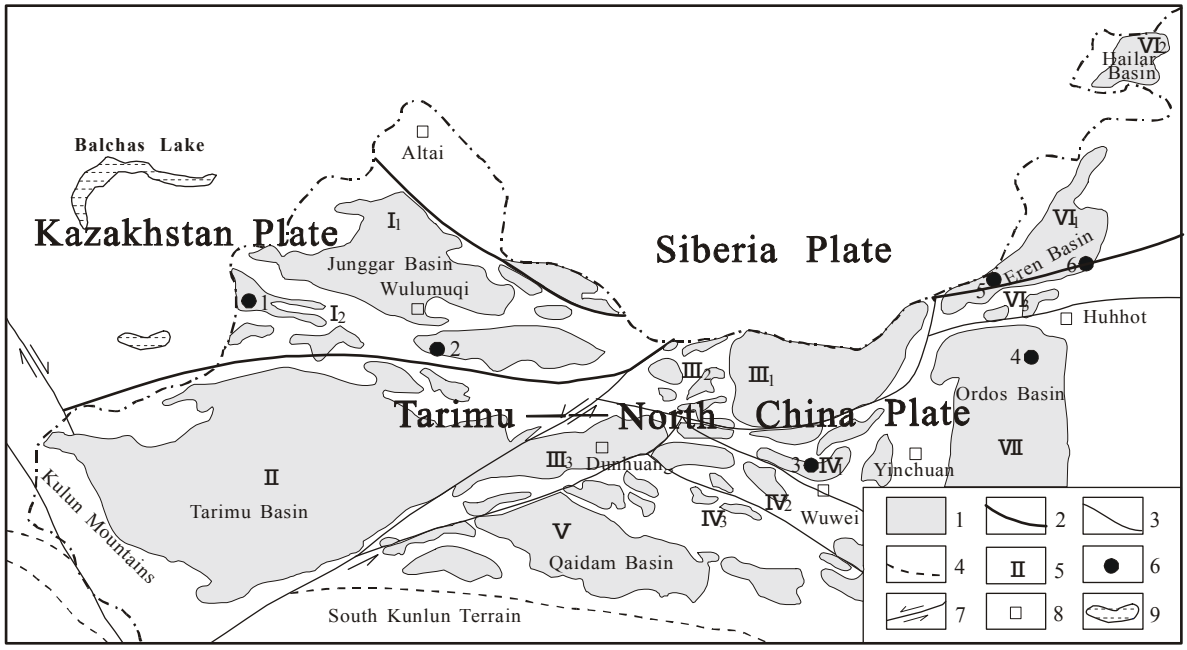

FIG. 1. Mesozoic---Cenozoic basin domains in Northwest China.

(Legenda: 1.Sedimentary basin; 2. Boundary between plates; 3. Boundary between basin domains and sub-domains; 4. Boundary between terrains; 5. Numbers of basin domains and sub-domains; 6. Ore deposit/occurrences; 7. Strike-slip fault; 8. City; 9. Lake; Basin domains and sub-domains: I Junggar-Tianshan Domain: I-1-Junggar sub-domain; I-2-Tianshan sub-domain; II Tarimu Domain. III Altun Domain: III-1- Badain Jaran sub-domain; III- 2-Beishan sub-domain; III-3-Dunhuan sub-domain; IV Alxan-Corridor Domain: IV-1-Alxan sub-domain; IV-2-Corridor sub-domain; IV-3-Central Qilian sub-domain;V Qaidam Domain; VIEren-Hailar Domain: VI-1-Eren sub-domain; VI-2-Hailar sub-domain; VI-3-Yingshan sub-domain; VII Ordos Domain; Deposits and their number: 1. Kuji'ertai, Wukuerqi & Zajistan deposits; 2. Tangjiagou occurrence; 3. Dongsheng mineralized area; 4. Subeng & Nuheting deposits; 5. Saihantala deposit.)

Some basins are well known as oil- and natural gas- bearing, including the Junggar, the Tarimu, the Qaidam and the Ordos basins; the Ordos is the biggest coal- and natural gas-bearing basin in China.

3. Host depositing environments and ore-forming regimes

Summarizing known uranium deposits, occurrences and perspective prospects in NW China, four types of host depositing environment have been identified (Table I): 1) the **cratonic basin**, open and wide, developed on rigid metamorphosed block or terrain and characterised with shallow water depth and low subsidence rate; 2) the **intra-continental down-faulted basin**, usually divided by uplifts into second order depressions and even third order sags, characterised with deeper water depth, higher subsidence rate and development of volcanic activity locally, and each depression or sag representing itself as an independent depositional unit having own provenance area; 3) the **compressive intermountain flexural basin**, mostly of medium/small in size and narrow-elongated in shape, occupying the intermediate position between cratonic basins and the intra-continental down-faulted basins in water depth and subsidence rate; and 4) the **erosive gully**, formed on the hillside fields in stream head area and filled with alluvium, colluvium and elluvium, and evolving from rill to gully and cleugh while erosion is expanding the rill range laterally but declining in intensity.

Table I. Host deposition environments & tectonic regimes of ore formation in Northwest China and its environs (Uranium deposit/ore-field in bracket)

Host deposition environments	Tectonic regimes of ore formation in Northwest China and its environs		
	Slight arching	Sub-orogenic	Orogenic
Cratonic basin	Ordos (Dongsheng),W. Siberia (Trans-Baikal)	Chu Saryssu-Syr Darya (Chu Saryssu, Syr Darya)	
Down-faulted basin	Eren (Nuheting, Subeng)		Eren (Bayantala), Sainshanda (Nars)
Inter-mountain flexural basin			Yili (Ku'jiertai Sulucheken, Turfan-Hami (Shihongtan)
Erosive gully	Vitim (Khiagda), Long chuanjiang (Chenzishan)		

Russian and Kazakhstan geologists had paid much attention to the tectonic regime during ore formation [5][6][7]. Incorporating their ideas with the investigation in NW China, three regimes of tectonic regimes have been distinguished, the slight arching, the sub-orogenic and the orogenic regime. The slight arching regime is characterized by the deformation mainly in shape of dome, placanticline and nose with vertical displacement of 50-200 m. It occurs either in plain of pre-Cambrian block or on highland formed from consolidated fold-belts. The sub-orogeny as a tectonic term was suggested to describe the orogeny occurred at the periphery of main orogenic zone [5][6]. The regime was firstly identified in S. Kazakhstan and demonstrated by the deformation mainly in form of monocline, wide-drape anticline and syncline, and mildly folding or faulting structure with vertical displacement of 500-700 m. The orogenic regime manifests itself as uplifting of mountain range with a number of intermountain basins, characterized by comparatively intense deformation with vertical displacement of more than 1 000 m, reaching 3 000 m and even more, with thick molasses sediments as depositional response. However, displacement of such regime observed in uranium region/area usually ranges from 1 000 m to 2 000 m.

The Ordos, Tarimu and Junggar basins represent cratonic type depositing environment. Besides, the W. Siberia, the Chu Sarys-Syr Darya basins in the neighbouring regions, the type includes the basins in Colorado Plateau as well. The existed data manifest that both roll and basal channel sub-types deposits were formed in the intra-cratonic basins. In the Chu Sarys-Syr Darya basin, host sandstone deposited in K_2-E but roll-shaped ore bodies occurred in Neogene with obvious "time span" and the "tectonic inversion" from intra-cratonic subsidence into **sub-orogenic** uplift. In the W. Siberia basin, the stable **slight arching** regime existed continuously from host deposition till ore emplacement within the range without obvious time-span. The Crownpoint and Churchrock deposits of Colorado, W. US demonstrate a litter complicated ore-forming process that original tabular ore bodies were formed immediately after the deposition of host sandstone followed by re-distribution of original ore bodies into roll-front under some **sub-orogenic** regime due to the re-raise of Zuni uplift. Similar

phenomena are observed in the Dongsheng uranium mineralised area where uranium was weakly enriched in Middle Jurassic basal channel sediments (lower Zhiluo Fm.), immediately after their deposition. The **sub-orogenic** regime due to raise of northern uplift in J_3-K_1 was responsible for the ore emplacement by re-distribution of primary weak mineralization into redox front through stratum oxidation (Fig.2).

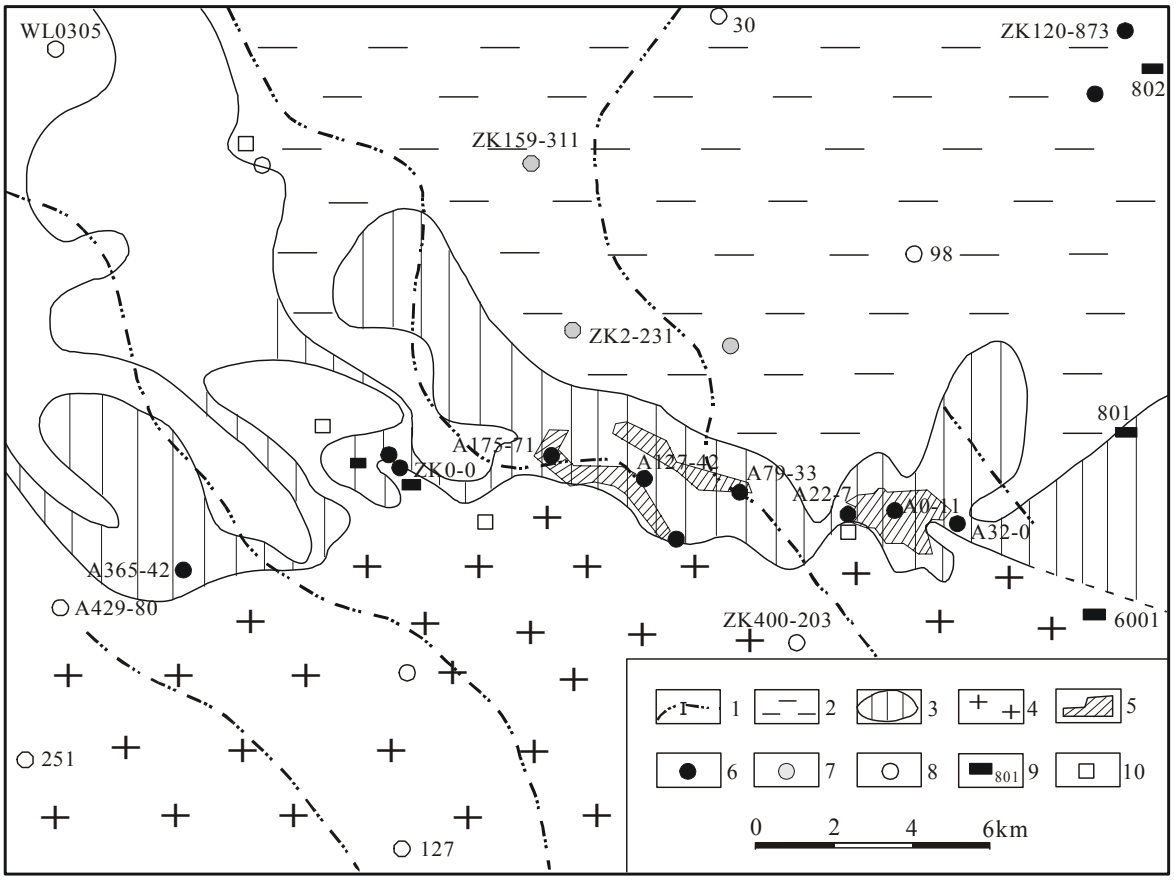

FIG. 2. Schematic regional redox interface in Dongsheng uranium mineralised area (after Chen Anping, 2004[4] with some modifications).

(Legenda: 1. Axial line of braided channel; 2. Oxidized host sandstone; 3. Redox interface; 4. Unaltered sandstone. 5. Ore body; 6. Mineralized hole; 7. Non-economic mineralized hole; 8. Barren hole; 9. Mineralized outcrop; 10. Town or village.)

Among known down-faulted type uraniferous basins, Eren basin is of more importance. The basin covers an area of 110 000 km^2, including 53 depressions and 53 sags. The incised valleys were basically filled by K1 coal-bearing or carbonaceous braided stream sediments at the active stage (orogenic), and covered by K2 red/variegated fine-grained sediments with marl to fill up the gaps at the decline stage (slight arching). As a result, a number of basal channel sub-type deposits occur in K1 carbonaceous braided stream sediments, as the Bayantala deposit in the sag of the same name [8] and the tabular sub-type deposits, as the Nuheting and the Subeng, are hosted in K2 siltstone, fine-grained sandstone, and mudstone of meandering stream facies [1].

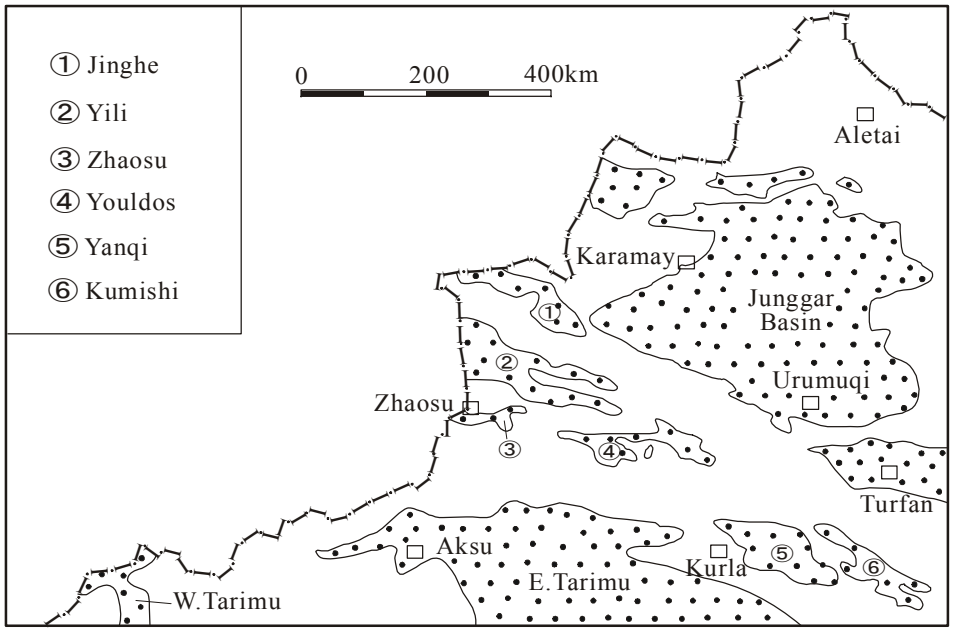

FIG. 3. Mesozoic-Cenozic residual basins in Tianshan Mountains and environs [9].

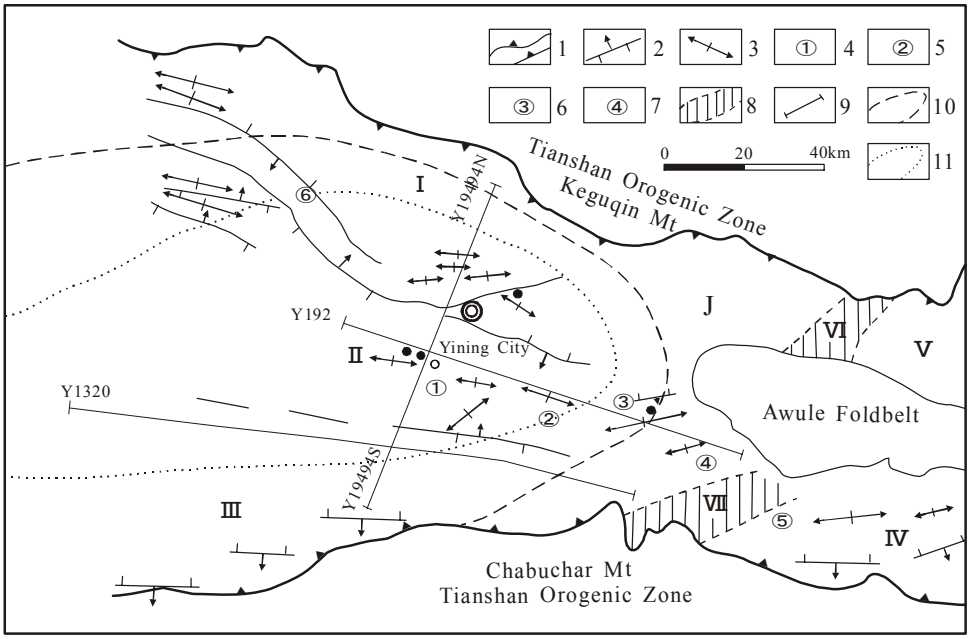

FIG. 4. Simplified structural map of Yili Basin [10].

(Legenda:1. Basin boundary; 2. Thrust; 3. Anticline; 4. Chabuchar structure; 5. Kanbei structure, 6. Kashihe structure; 7. Bashituohai structure; 8. Intra-basin low-uplifted zone, 9. Seismic measuring line; 10. Jurassic depositional centre; 11. Permian depositional centre. I. North thrust zone; II. Central buried uplift zone; III. South slope; IV. Gongliu depression; V. Nilek depression; VI. Kalasu uplift; VII. Yabei uplift.)

The compressive intermountain flexural basins are well developed in Northwest China with J1-2 coaly clastic strata as main uraniferous sequences. The Yili basin where much exploration has been conducted represents a typical example. As shown by the distribution of Early-Middle Jurassic residual sediments the host sandstone was deposited in a Pan-Yili basin, remaining the basic framework of a post-Hercynian Paleo-Tianshan intermountain basin.

The basin contained two depressions and a central buried uplift between them. Besides the Yili, its range covers recent Jinghe, Zhaosu, and Youldos basins [9] and even Yanqi and Kumishi basins [10]

(Fig.3). The Pan-Yili basin disintegrated by the end of Jurassic period as the central buried uplift was back thrusted. Ore bodies were formed even late in Neogene when Himalayan orogeny resulted in the production of the recent Yili basin, having quite complicated structure (Figs 4 and 5). The South Slope where uranium deposits are intensely distributed is actually a structural plane, not a depositional boundary.

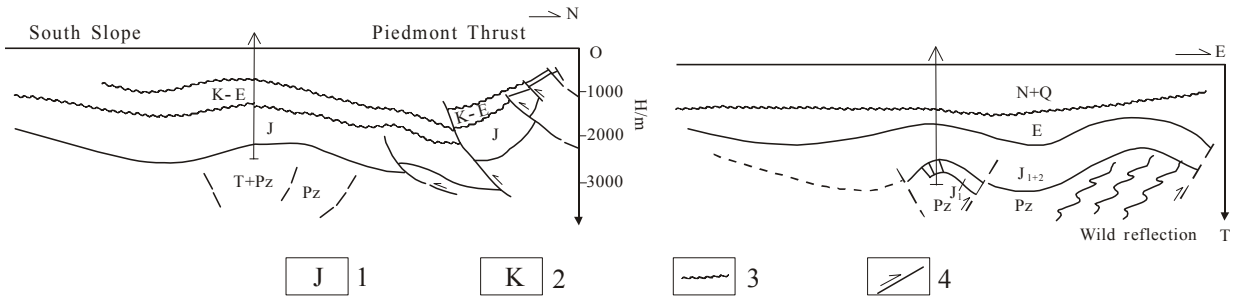

FIG. 5. Schematic geological interpretive seismic profiles of Yili Basin [10].

(Legenda: 1. Jurassic; 2. Cretaceous; 3. Unconformity; 4. Thrust)

The erosive gullies were firstly known as uraniferous depositional environments in Longchuanjiang, West Yun'nan, China, and Khiagda, Trans-Baikal, Russia separately where both host deposition and ore formation occurred under the **slight arching** regime as a continuous process. It is indicated that recently observed gullies are all of Neogene period because earlier formed gully deposits were mostly or even entirely eroded during subsequent uplifting process. A series of such depositional environments occur in NW China and more promising area might be the north slope of Yinshan Mountains with a nimber of erosive gullies on the piedmonts of highlands between Aibugai River and Tabu River, Inner Mongolia.

4. Typology and classification

According to IAEA classification [11], Phanerozoic sandstone type uranium deposits include three sub-types, the roll, the tabular and the basal channel. All of them have been discovered in NW China: the Kuji'ertai and Shihongtan deposits of the roll sub-type, the Nuheting and Subeng deposits of the tabular sub-type and the Bayantala of the basal channel sub-type. In addition, the Crownpoint and Churchrock deposits, Colorado, US present a new variety of roll sub-type where the tabular-shaped ore bodies were redistributed or remobilized to roll front [12][13]. However, some deposits, as those in Frome Embayment ore-field, S. Australia, are attributed either to the tabular sub-type or to the basal channel sub-type in different times or by different authors. Similar problem appeared with the Bayantala deposit. Such uncertainty seems resulted from the diversity of classification criteria applied by the IAEA classification: to distinguish the roll sub-type from the tabular one by the shape of ore body/deposit but to "establish" the basal channel sub-type by the depositional environment of host sandstone. Benefiting the exploration, it might be suitable to divide the sub-type, especially the roll and the basal channel sub-type, further into classes titled according to the names of typical ore-fields or deposits.

The roll sub-type may include four classes, including the Chu Saryssu-Syr Darya, the Yili, the Wyoming and the Crownpoint-Churchrock. The Chu Saryssu-Syr Darya (S. Kazakhstan) class represents the deposits where the host rocks deposited in cratonic basins but ore bodies formed under sub-orogenic regime with evident time span and tectonic reversion between them. The Yili class indicates the deposits whose host sandstones deposited in mildly compressive intermountain basin, followed by mineralization under orogenic regime after a calm stage, i.e. time span was evident but obvious tectonic reversion was absent. The Wyoming class stands for such deposits that the host deposition and ore emplacement occurred successively when a comparatively wide foreland basin was evolving into a group of intermountain basins. It shows a continuous process without evident time break. The Crownpoint-Churchrock (Colorado, W. US) class, as mentioned above, is featured by re-distributed roll-shaped deposit from primary tabular ore bodies.

Known basal channel sub-type sandstone-hosted uranium deposits could group into three classes. The Honshu (Japan) class represents the basal channel deposits, as Ningyo-Toge and Tono, formed in down-faulted where the ore bodies are localized in the trough-shaped structure incising the basement or underlying strata. The Trans-Ural (Russian) class is defined that uraniferous basal channel were developed at the margin of intra-cratonic basin and the down cutting of channels was resulted from the decrease of global sea level, independent of orogenic control [7]. The Vitim (Trans-Baikal, Russia) class stands for the deposits formed in Neogene erosive gullies where the host rocks are usually covered by basalt or other confining bed.

5. Discussion and conclusion

Mining practice indicated that the roll-shaped uranium deposits are more amenable to IS leach, and thus of more economic significance than those of basal channel sub-type. So, the Chu Saryssu-Syr Darya class roll-shaped deposits play a leading role in uranium exploration and mining industry in Kazakhstan though some basal channel deposits are known in Kokchetav Uplift, N. Kazakhstan. In contrast, the basal channel sub-type has been selected as the major target for uranium prospecting in Russian, based on the systematical analysis of regional geology. Both Kazakhstan and Russian are neighboring countries to China. Therefore, how to appraise the ore-generating potentiality of various sub-types sandstone-hosted uranium deposits in Northwest China and which one is of more fertility became the problem Chinese geologists have to face.

The roll sub-type still will be one of the main exploration targets in Northwest China. The question had once been asked if possible to search for the Chu Saryssu-Syr Darya class deposits in the Beishan sub-domain (Fig.1) that seems as approximate mirror image to the Chu Saryssu-Syr Darya basin: the Chu Saryssu-Syr Darya at west plunge and the Beishan at the east plunge of the Tianshan Range. The Beishan is, nevertheless impossible, being a portion of an Indo-Sinian (Paleo-Alpine) orogenic zone followed by uplifting and denudation from Late Cretaceous till Pliocene. In contrast, the Yili class should occupy the first place in roll sub-type prospecting in Northwest China and the Chaoshui basin merits further exploration. The Shihongtan deposit located in the WE margin of Turfan-Hami basin resembles those deposits of the Wyoming class in some aspects, including the host sandstone (J_2^1) of proximal braided stream system, the WE margin of Turfan-Hami basin where host sandstone deposited being a foreland depression of Pan-Junggar basin at that time and the absence of obvious time span between host deposition and main stage of ore formation. So the exploration there prefers the Wyoming class model rather than that of the Yili class though the hosts in both the Yili and Turfan-Hami basins are of the same early Middle Jurassic coal-bearing clastic sediments. Besides, the Crownpoint-Churchrock class is also of importance as the prospecting and scientific research works are successfully processing in the Ordos basins. In addition, the Dingshan area of N. Junggar basin might be another perspective prospect where the re-raise of San'gequan uplift might be responsible for the re-mobilization of primarily enriched uranium into roll front. It seems reasonable to pay special attention to the exploration of basal channel sub-type sandstone-hosted uranium deposits that began in Northwest China not too long before. The Bayantala deposit is of the Honshu class. It occurs in the Bayantala sag, Eren down-faulted basin where host sandstone and conglomerate (K_1bs^1)were deposited in the trough-shaped structure originated from the F_2 and F_3 [8]. The exploration is continuing in other depressions/sags in the Eren basin. Although the Tarimu basin is quite mobile, some relatively stable areas in W. Tarimu are still perspective for prospecting for the Trans-Ural class deposits. Milanovski [14] proposed six evident decrease events of global sea level since Middle Jurassic: Middle Jurassic (~162 Ma), Early Cretaceous (~128 Ma), middle Oligocene (28~35Ma), middle Miocene(~12Ma)and late Pliocene (~2 Ma). In the north portion of W. Tarimu, the Keping-Banchu area represents a valuable exploration target for search for uraniferous valleys that had uplifted and denudated with discontinuous down-warp from Miocene till Pliocene. Besides, the stream valley-incision took place the same time at the "Qimgen salient" between Yingjisha sag and Guman-Zepu sag in SW Tarimu. As to the Vitim class, the Khiagda ore-field possesses much more resources/reserves than that of the Longchuanjiang. The comparison between them shows that uplifting is necessary for the production of erosion gully, nevertheless, frequent uplifting hinders the evolution of rill into cleugh; the rill is with tens m to hundreds m long and tens cm to n m in width observed in the Longchuanjiang and the cleugh is n to 10 km long and 1 to 3 km in width observed in

the Khiagda. Moreover, frequent uplifting is unfavorable to preservation of existed mineralization. So, as mentioned above, the north low-angle slope of the EW-trending Yinshan Mountains developed on the basis of a relatively stable "Uplift at north margin of North China continental block" [2] was proposed as a target for regional reconnaissance where a series of erosive gullies are developed on the piedmonts of highlands between Aibugai River and Tabu River, Inner Mongolian Autonomous Region. Both Aibugai River and Tabu River are sourced from north portion of inter- Yinshan mountain basins surrounded by granite with relatively high uranium background value, and discharged northwards in Tengge'er Nor and Huhe Nor in Gobi.

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Australia's uranium
Linking uranium endowment to crustal evolution

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Abstract. Australia has the world's largest resources of uranium, the great bulk being recoverable at low cost. It is the second largest producer of uranium, which it exports to global markets, and recent developments are likely to significantly expand production. Evidence is presented that this considerable uranium endowment reflects the widespread emplacement of uranium-enriched felsic rocks in three main periods of igneous activity. While some uranium deposits appear to have formed during these igneous events, including the giant Olympic Dam deposit, most are considered to have formed by subsequent low temperature processes from uranium-enriched source rocks. There has been limited uranium exploration in Australia since 1980 and considerable potential exists for further discoveries of various types of uranium deposits in favourable geological settings within and beside regions characterised by uranium-enriched igneous rocks.

1. Introduction

Australia has a major uranium sector, based on world class resources and high and increasing production. A review of uranium resources, production and export markets sets the scene for consideration of why Australia has such abundant uranium resources. Particular reference is paid to spatial and temporal relationships between uranium deposits and uranium-enriched igneous rocks, as revealed by Geoscience Australia's national geochemical database (OZCHEM). Finally, exploration trends and uranium potential are summarised.

2. Industry trends

2.1. Resources

Australia has the world's largest resources of low cost uranium (701 000 t U as at April 2005), with roughly 40% of world resources in this category. Some 75 uranium deposits, varying in size from small to very large, are scattered across the Australian continent [1]. Approximately 86% of total uranium resources (1 143 000 t U) occur in two main types of deposits: hematite breccia complexes and unconformity-related deposits:

Hematite breccia complex deposits: some 70% of resources occur in Proterozoic hematite granitic breccias at Olympic Dam in South Australia, which is the world's largest uranium deposit. Broadly similar hematite breccia mineralisation is being evaluated elsewhere in the same geological province, at Prominent Hill. These are examples of 'iron oxide copper gold deposits' with higher uranium contents than most deposits of this type.

Unconformity-related deposits: about 18% of resources are associated with Proterozoic unconformities, mainly in the Alligator Rivers field, Northern Territory (Ranger, Jabiluka, Koongarra).

Other significant resources occur in:

Sandstone uranium deposits: about 6% of resources, mainly in the Frome Embayment field, South Australia (Beverley, Honeymoon) and the Westmoreland area, Queensland.

Surficial (Calcrete) deposits: constitute about 4% of Australia's uranium resources, mostly in the Yeelirrie deposit (Western Australia).

The remaining resources are mainly in metosomatic and volcanic types of deposits.

2.2. Production and export markets

Mining for uranium commenced at Rum Jungle and Radium Hill in 1954 and a second phase of uranium mining commenced at Mary Kathleen in 1976. Since then, Australia's uranium mining industry has grown progressively to become the world's second largest producer (in terms of annual mine production) with approximately 22% of world production – in 2004 Ranger mine produced 5 138 t U_3O_8 (11% of world production), Olympic Dam 4 370 t U_3O_8 (9%) and Beverley 1 084 t U_3O_8 (2%).

All of Australia's mine production of uranium is exported. Tonnages of exports have increased steadily from less than 500 t U_3O_8 in 1976 to a record level of 9648 t U_3O_8 in 2004, valued at A$411 million.

Mining companies supply uranium under long-term contract to electricity utilities in the United States, Japan, European Union (Belgium, Finland, France, Germany, Spain, Sweden, United Kingdom), South Korea and Canada.

Australia has a strong reputation as a reliable and responsible supplier of uranium to world markets for peaceful purposes. It is well positioned to be able to sustain this role because of its very large identified and potential uranium resources, provided the development of these is permitted by future government policies. Most of these resources are amenable to low cost production with minimal long term environmental and social impacts.

2.3. Recent developments

2.3.1. Olympic Dam

WMC Resources is investigating the feasibility of a major expansion of the operations that would increase annual production to 500 000 t copper 15 000 t U_3O_8 and 500 000 ounces gold. This would require mining 40 Mt of ore per year. The study includes:

A major drilling program to better define the resources in the southern part of the deposit;

Assessing alternative mining, treatment and recovery methods for the southern part of the deposit, water and energy supply options; and

Logistics planning that may include linking Olympic Dam to the national rail network.

On-going drilling continues to identify large tonnages of additional resources in the south-eastern portion of the deposit. The total Olympic Dam resources as at December 2004 are almost 30% higher than in December 2003.

2.3.2. Beverley

Heathgate announced the discovery of a new zone of uranium mineralisation approximately 3 km south of the Beverley deposit. This ore zone, referred to as the Deep South zone, was discovered using a range of geophysical surveys followed up by an extensive drilling program comprising more than 120 holes.

2.3.3. Jabiluka

Jabiluka is a world class uranium deposit. Mining was approved in 1999 subject to over 90 environmental conditions, but did not have the consent of the Aboriginal traditional owners at that time. ERA Ltd has announced that further development at Jabiluka would only be conducted after formal support was received from the Aboriginal people, and would be subject to feasibility studies and market conditions. The project site remains on long-term environmental care.

2.3.4. Honeymoon

Following a lengthy environmental impact assessment process which lasted almost two years, Southern Cross Resources received environmental clearances from government to develop the Honeymoon in situ leach project. The company has also been granted a uranium export permit. Following a review of development options for the Honeymoon project, a decision was made to focus on a 400 t U_3O_8/year capacity plant with a mine life of 6-8 years. Development of the project is currently on hold pending an investment decision.

3. Metallogenesis

Why does Australia has such a high proportion of the world's known uranium resources? In an attempt to answer this, we have considered uranium metallogeny by studying the spatial and temporal relationships between deposits and unmineralised uranium-enriched rocks from across the continent. This study was based on Geoscience Australia's extensive OZCHEM database (http://www.ga.gov.au/gda/index.jsp).

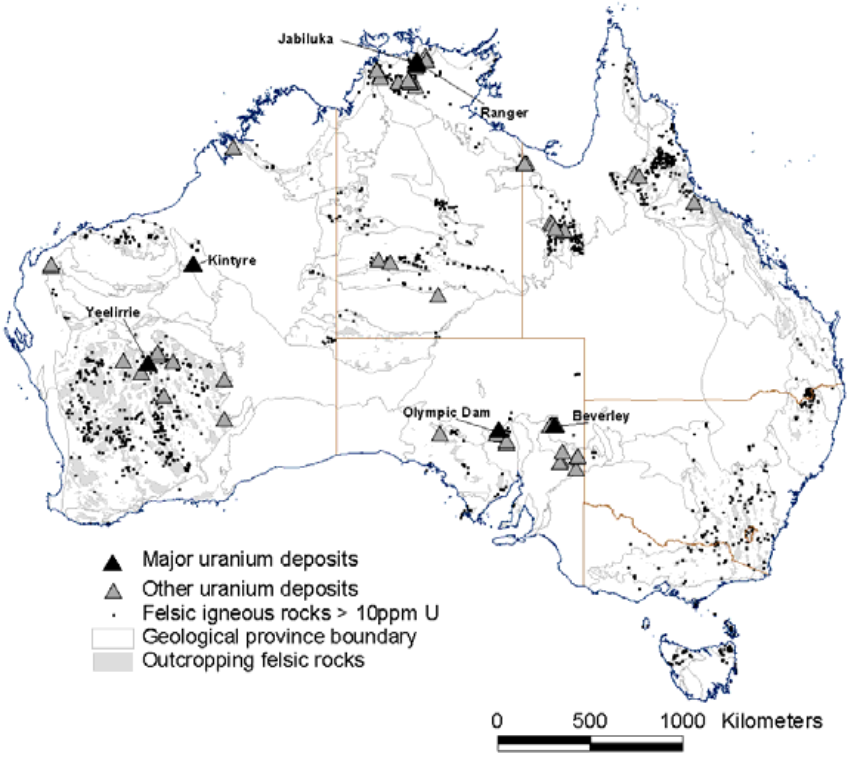

FIG. 1. Australian uranium deposits in relation to occurrences of felsic igneous rocks known to have at least 10 ppm uranium.

3.1. Importance of uranium-rich felsic igneous rocks in Australia

Approximately 22 000 rocks in the OZCHEM database have been analysed for uranium, and over 2 700 of these have 10 ppm U or more (that is at least four times crustal average). These uranium-

enriched samples are mainly granitic and felsic volcanic rocks, but include a small proportion of associated gneisses and sedimentary samples. Their distribution is indicated in Fig. 1. It is a significant observation that all known uranium deposits exhibit clear spatial relationships, at regional scale, with uranium-enriched bedrocks (Fig. 1).

3.2. Relationships between felsic igneous activity and uranium mineralisation

Further investigation indicates that the uranium-enriched felsic igneous rocks are highly fractionated and/or have alkaline affinities, and were emplaced during major magmatic events in the:

- late Archaean (2.69 – 2.65 Ga) [2],
- the Palaeo-Mesoproterozoic. (~1.9 – 1.5 Ga) and,
- in eastern Australia, Silurian to Permian (0.43 – 0.25 Ga).

Of these intervals, the Proterozoic produced the greatest volumes of uraniferous igneous rocks. These are widespread in South Australia, Northern Territory and parts of Western Australia and Queensland, in regions of high geothermal gradients [3, 4]. Figure 2 shows the ages of uranium mineralisation in relation to the ages of the uranium-enriched granitoid intrusives and associated felsic volcanics [1].

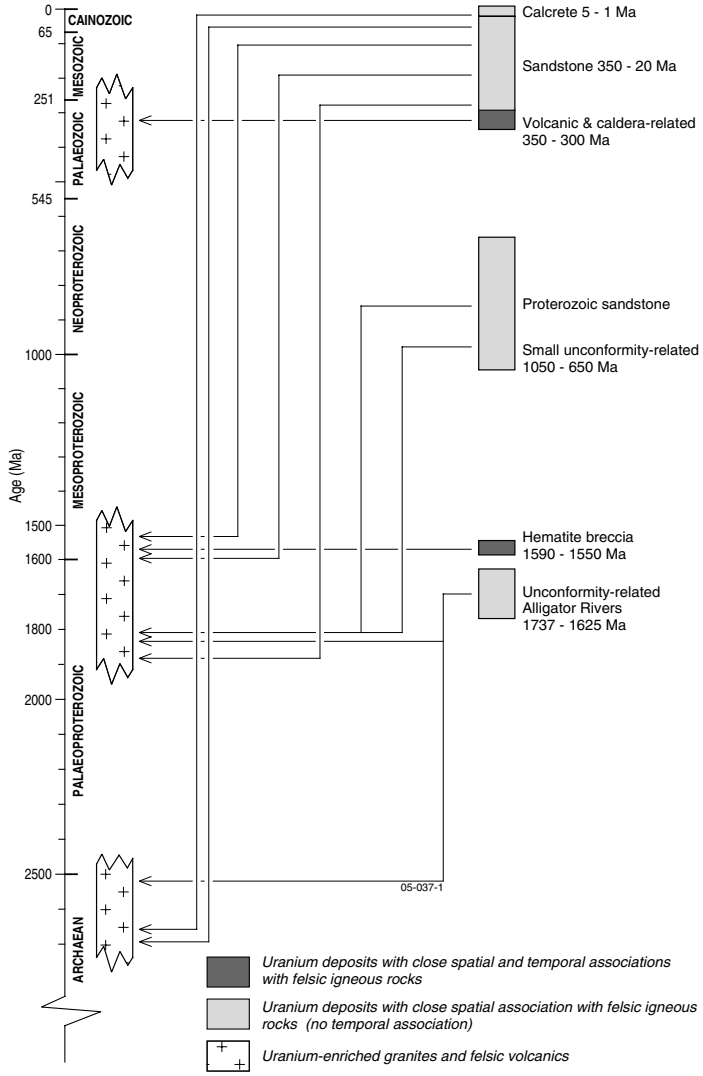

FIG. 2. Ages of uranium deposits and uranium-enriched felsic igneous rocks. Lines link each deposit type to the age of its probable source rocks.

In the case of Olympic Dam, mineralisation is of similar age to felsic igneous activity. Together with the close spatial association, this supports the concept that the uranium was concentrated during associated hydrothermal activity [5]. Some small intrusive and volcanic style uranium deposits also have temporal association with felsic host rocks, including the intrusive style Crocker Well deposit in Mesoproterozoic granitoids in South Australia and the Ben Lomond volcanic style deposit in Carboniferous rhyolitic tuffs in northeastern Queensland [1].

More generally, the uranium mineralisation is considerably younger than the spatially-related igneous rocks. This is the case for the calcrete, sandstone and unconformity-related deposits, which appear to have formed as a result of uranium mobilisation from older uranium-enriched source rocks under low temperature oxidising conditions, and precipitation by redox reactions. In particular:

There is a clear spatial relationship of the Cainozoic calcrete type uranium deposits in the western part of the continent, including the large Yeelirrie deposit, with the uranium-rich Archaean felsic rocks in the northern part of the Yilgarn Craton. The ages of the probable source rocks are approximately 2.6 billion years older than the uranium deposits.

Sandstone uranium deposits are the most widely distributed type of uranium deposit in Australia and range in age from Neoproterozoic for the Westmoreland group of deposits [6] in Queensland to Cainozoic for those of Honeymoon and Beverley in the Frome Embayment, South Australia. The Mulga Rock sandstone deposit in Western Australia, was sourced from uranium in the Archaean basement [7] to the west. Those in the Frome Embayment are derived from the adjacent exceptionally uranium-rich Proterozoic felsic rocks [8].

Unconformity-related uranium deposits, which formed in the late Palaeoproterozoic to late Neoproterozoic, are variably younger than the spatially associated Palaeoproterozoic to late Archaean felsic igneous rocks. In uranium fields such as in the Alligator Rivers–Arnhem Land region, available age determination data provides evidence for several ages of mineralisation. This implies several episodes of transport and deposition of uranium, presumably triggered by tectonic activity.

It is of interest that no significant uraniferous deposits have been found in Late Archaean-Paleoproterozoic conglomerates in Australia, which do not have the high proportions of quartz pebbles that are characteristic of the gold-uranium bearing conglomerates of South Africa.

Further, a lack of exploration in the southeastern part of Australia as a result of state Government policies is a factor in the absence of known uranium deposits in that region.

4. Exploration and uranium potential

Geoscience Australia conducts annual surveys of expenditures on uranium exploration. The results are summarised in Fig. 3, which shows exploration reached a peak in 1980 of US $35.0 million ($A105 million in constant $A2 003). During the period 1968 to 1980, up to 60 companies were exploring for uranium in Australia. The bulk of discoveries were made during this period (Fig. 3).

As market prices fell from 1980 onwards, most companies ceased uranium exploration. By 2003 only 5 companies were actively exploring for uranium and this work was confined to areas adjacent to known deposits, mainly western Arnhem Land (NT), Frome Embayment and Gawler Craton-Stuart Shelf (SA).

Over the last two years, spot market uranium prices have more than doubled from around US $10/lb U_3O_8 in early 2003 to US $26.25/lb U_3O_8 in May 2005. These price rises have resulted in increases in uranium exploration activity – currently there are more than 20 companies exploring for uranium in Australia.

There have only been two notable discoveries since 1980 with the unconformity-related Kintyre deposit in 1985 and the hematite breccia hosted copper-gold-uranium deposit at Prominent Hill in

2001 (which was primarily an outcome of exploration for copper and gold). Despite the lack of discoveries since 1985, Australia's low-cost resources have continued to increase due to the delineation of additional resources at the known deposits, particularly Olympic Dam. Early uranium discoveries relied extensively on airborne radiometric surveys. The 1960s and early 1970s saw extensive testing of surficial radiometric anomalies. This progressed to more sophisticated approaches, often based on conceptual geological modelling, which led to major discoveries at Jabiluka and Olympic Dam. In more recent exploration, airborne electromagnetic surveys have been used to locate palaeo-channels in the vicinity of the Honeymoon sandstone uranium deposit in South Australia.

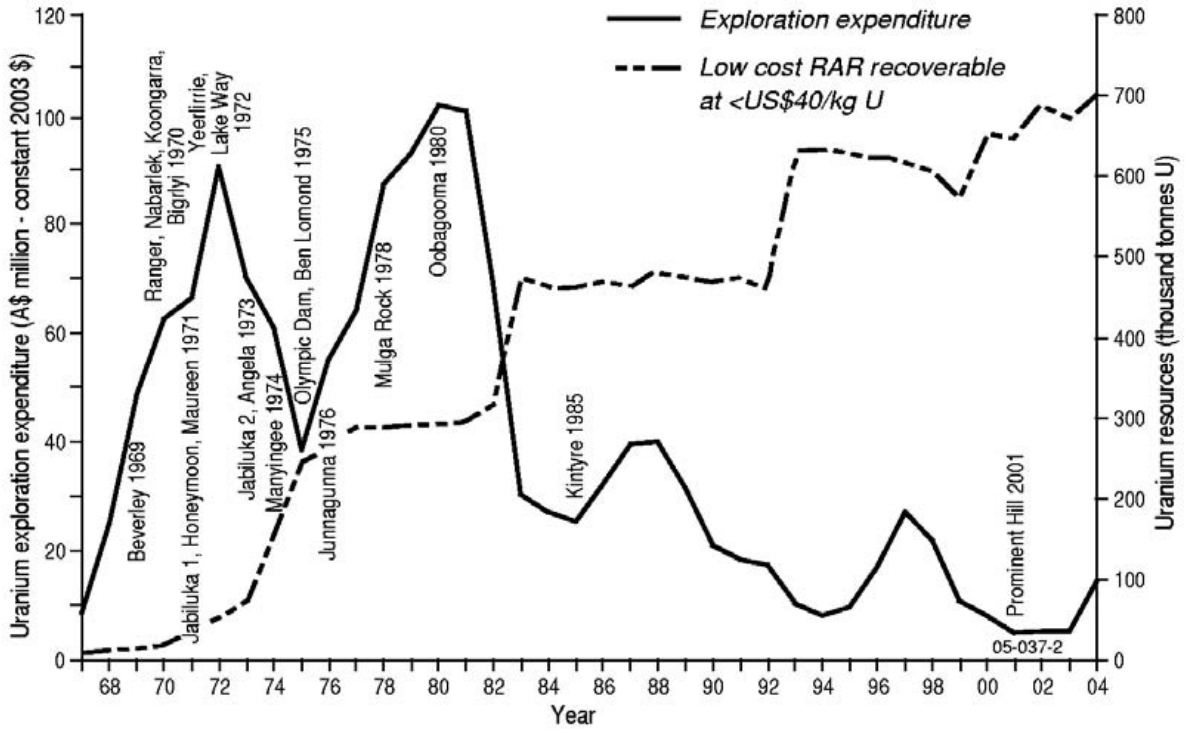

FIG. 3. Trends in uranium exploration expenditures, discovery of deposits and total resources.

Given the paucity of modern exploration, there is significant potential for additional uranium deposits in Australia, including:

- sandstone deposits in sedimentary strata in various regions adjacent to uranium-enriched basement;

- unconformity-related deposits, including relatively high grade deposits at and immediately above the unconformity, particularly in Arnhem Land in the Northern Territory but also in the Granites-Tanami region (Northern Territory-Western Australia), the Paterson Province (Western Australia) and the Gawler Craton (South Australia); and

- hematite breccia deposits, particularly in the Gawler and Curnamona cratons of South Australia.

5. Conclusions

Australia has the world's largest total identified uranium resources and roughly 40% of world low cost uranium resources. Approximately 70% of total identified resources are in the Olympic Dam **hematite breccia complex** deposit, and some 18% of resources are in **unconformity-related** deposits. Other significant resources occur in **sandstone** deposits and a calcrete-type **surficial** deposit.

Of the roughly 22 000 (unmineralised) felsic rocks analysed for uranium across the Australian continent, over 10 percent – mainly granites and felsic volcanics, with some gneisses and sedimentary rocks – have elevated uranium contents of at least 4 times crustal average. Analysis of the distribution

of these uranium-enriched bedrocks shows that known uranium deposits display a marked spatial relationship with them at the regional scale. Further, the uraniferous felsic igneous rocks are mostly highly fractionated and/or have alkaline affinities, and were emplaced during major magmatic events in the late Archaean, the Palaeo-Mesoproterozoic and the Silurian to Permian. Of these intervals, the Proterozoic produced the greatest volumes of uraniferous igneous rocks, which are widespread in regions of high geothermal gradients in South Australia, Northern Territory and parts of Western Australia and Queensland.

These observations support the conclusion that Australia's extensive uranium mineralisation reflects the widespread emplacement of uranium-enriched felsic rocks in three main periods of igneous activity. While some uranium deposits appear to have formed during these igneous events, including the giant Olympic Dam deposit, most formed from uranium-enriched source rocks by subsequent low temperature processes.

There has been limited uranium exploration in Australia since 1980, but this is starting to change as a result of higher uranium prices. There is considerable potential for further discoveries of uranium deposits in regions characterised by uraniferous igneous rocks and associated sedimentary strata and gneisses.

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TOPIC 3 - URANIUM EXPLORATION

Recent innovative applications of geophysics to new uranium discoveries in the Athabasca Basin

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Abstract. In the last five years an innovative and integrated multidisciplinary approach to exploration has significantly improved Cameco's rate of discovery of new uranium occurrences in the eastern Athabasca Basin of northern Saskatchewan, Canada. Some recent advances are: the brownfield (previously well explored area) discovery at zone O2 Next, Eagle Point mine, and the brownfield investigation of historic uranium mineralization at zone A, McArthur River mine; as well as greenfields discoveries of the Millennium deposit, Cree Extension project and Wide Lake, Virgin River project. These advancements were aided by adopting a number of themes, notably: innovation, integration, non-traditional targets, grid format surveys, basement-hosted and brownfield exploration. Zone O2 Next, Eagle Point mine, is a brownfield basement-hosted uranium discovery (2003) that demonstrates the value of grid format Time Domain Electromagnetic (TDEM) surveys to map areas of enhanced conductivity related to structure and alteration in the hanging wall of the graphitic Collins Bay fault. The McArthur River mine unconformity-hosted zone A has become a testing ground for seismic techniques applied to uranium exploration. The Millennium deposit is a greenfield, basement-hosted discovery (2000) that emphasizes the importance of being willing to drill away from the historic conductor axis, and the need to adequately define adjacent conductors and their geological setting. The Wide Lake greenfield, sandstone-hosted and unconformity-hosted discovery (2004) exemplifies innovation and integration toward a more focused approach on a long, wide and deep conductor corridor, by selectively looking for evidence of enhanced structure and alteration along the conductors.

1. Introduction

The Athabasca Basin is a Paleo to Mesoproterozoic quartz arenite basin located in the northern part of the provinces of Saskatchewan and Alberta, in central Canada (Fig. 1). Exploration for uranium began in the mid-1960's, with companies looking for sandstone and/or paleochannel-type uranium deposits. Early discoveries at Rabbit Lake (1968) and Cluff Lake (1970), by airborne and ground radiometric prospecting and systematic drilling, lead eventually to the establishment of a significant uranium resource in the basin and recognition of the unconformity deposit type [1]. The subsequent four decades of exploration have seen the discovery and development of roughly two dozen uranium deposits in the Athabasca Basin spread over six mining centers: 1) Rabbit Lake-Collins Bay-Eagle Point (discoveries 1968-2003), 2) Cluff Lake, Carswell Structure (1972-1984), 3) Key Lake (1975-76), 4) MaClean Lake - Sue (1979-1992), 5) Cigar Lake (1981), and 6) McArthur River (1988).

The discoveries at Key Lake and Cigar Lake led to a growing emphasis on graphitic fault conductors as a key factor in the formation of these deposits. Consequently EM mapping of conductors became an exploration standard for the next quarter century. However, uranium exploration in the basin has witnessed a sharp fall in the discovery rate of new uranium from the peak (46 000 t U/yr average) in the late 1980's. This was likely due to the falling market price of uranium through the 1980's and 1990's, and the ensuing exodus of exploration companies from the basin. The exodus has now reversed itself, resulting hopefully in a significant increase in the discovery rate over the next decade.

The eastern Athabasca Basin has seen most of the historic exploration work and is becoming very much a mature uranium play. There is a limited amount of remaining conductor length left to be tested for conventional unconformity-type deposits, and there is evidence of a diminishing return on this

methodology. While discoveries of less than 20 000 tonnes U continue, it has been seventeen years since the discovery of the world class McArthur River P2 North deposit in 1988. This has led to a realization that a paradigm shift in exploration strategy will be required to sustain longer term production from the basin.

At Cameco, a new defining principle is greater emphasis on employing geophysical techniques to remotely map 1) the ore deposit setting at all scales, 2) the geological conditions that favor uranium deposition and preservation, and 3) the subtle manifestations of the presence of a uranium deposit. This means greater attention to the lithostructural setting of the ore deposit, the fluid pathways, and the ore-fluid processes involved. At present, the preference is a fluid ingress/egress (into/from basement) deposit model producing basement-hosted/unconformity-hosted uranium (Eagle Point / Cigar Lake deposits, for example), as described by [2].

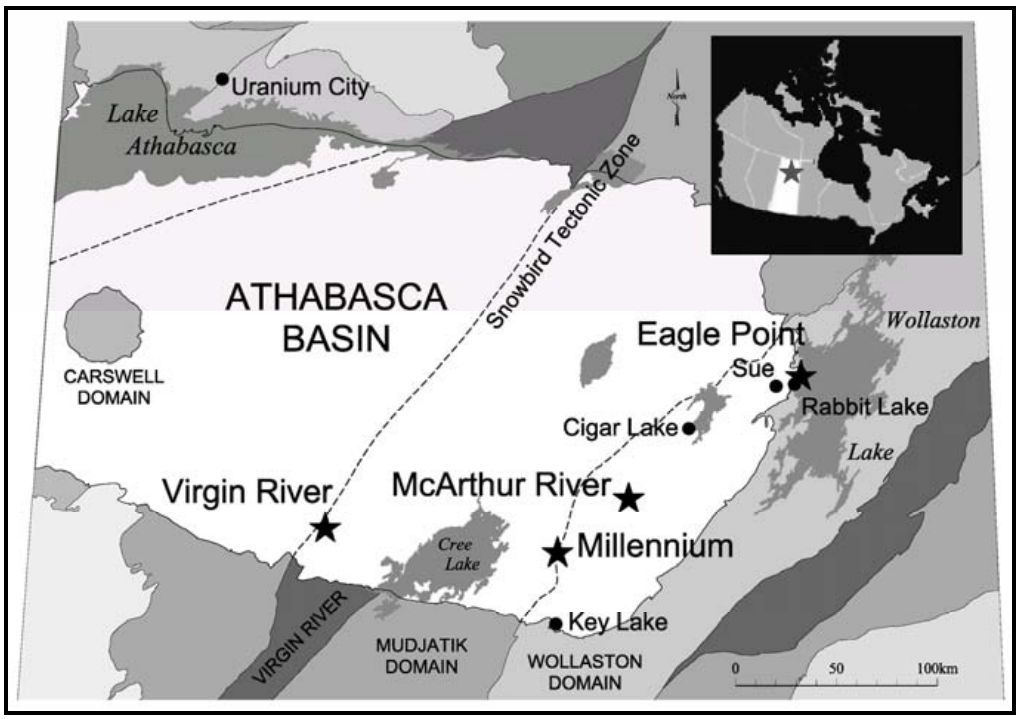

FIG. 1. Location of the Athabasca Basin in northern Saskatchewan, Canada. The discoveries discussed in this paper are indicated with stars, the Eagle Point and McArthur River mines, the Millennium deposit and the Virgin River project.

The exploration themes that Cameco Corporation has embraced in the last five years, in the order of their contribution to new resources, are 1) an emphasis on **innovation** in the application of existing geophysical techniques, 2) better **integration** of the geoscience disciplines through the use of downhole geological, geochemical, and geophysical data in centralized databases and greater use of "common earth" 3D visualization software, 3) greater emphasis on **non-traditional targets**, such as "bright spots" and "breaches" (sections 2 and 5), where indications exist for these, 4) greater use of **grid format surveys** combined with 1D, 2D and/or 3D inversions, as well as greater use of forward models to improve our understanding of the data, 5) greater emphasis on **basement-hosted** deposit models, 6) a renewed focus on **brownfield** to mine-scale exploration through greater collaboration between the mining and exploration groups, 7) greater use of **orientation surveys**, including airborne, surface, underground and downhole, to characterize and predict deposit responses, 8) more use of **Moving Loop** relative to Fixed Loop EM surveys [3, 4] for better conductor resolution and understanding of the host environment, and 9) greater use of **downhole logs**, particularly resistivity, induction and sonic logs.

2. Zone O2 Next, Eagle Point Mine

Based on data compiled from internal and external sources, notably [5, 6], basement-hosted uranium deposits have accounted for 63% of uranium produced from the basin to date, but their share of the resource has fallen from approximately 50% before the Cigar Lake discovery in 1981 to less than 17% today. The decline of the basement-hosted deposit can be explained in terms of the relative success of the classic unconformity-hosted exploration model, along with the higher grades encountered. As a result, relatively few historic holes were drilled more than a few tens of metres into basement, and/or away from the defined EM conductor axes. Basement-hosted deposits, on the other hand, can occur hundreds of metres below the unconformity and/or off the conductor axes.

The brownfield, basement-hosted discovery of the O2 Next zone in 2003 embodies all of the exploration themes mentioned above. This deposit lies 400 metres to the north of the Eagle Point mine (Figs 1, 2) and about 225 metres southeast of the graphitic Collins Bay fault/conductor, at depths ranging from 150 to 350 metres under Wollaston Lake, and probably comparable depths below the now-eroded sandstone-basement unconformity. The host rocks are tightly folded graphitic and non-graphitic metasedimentary gneisses of the Paleoproterozoic Wollaston Group, and related anatectic pegmatitic and granitic intrusives. The geology of the Eagle Point mine is described in [7].

Orientation surveys were conducted across zone O2 (Eagle North) in 1997, notably Stepwise Moving Loop [8] and Sounding profiles, using 300 and 100 metres square loops respectively and Geonics Ltd. TDEM equipment. In addition to a system of weak conductors mapped north of the mine, a “bright spot” (positive, mid- to late-time channel, in-loop anomaly) was also defined directly over zone O2, which was previously thought to be unresponsive. A conductive zone approximately 200 metres in vertical and horizontal dimensions, was defined at zone O2 on a conductivity depth image (CDI) produced by Quantec Geosciences Inc. by direct inversion [9]. Underground tests using a Geonics EM38 conductivity meter confirmed that the host rocks, which are normally quite resistive (> 2 000 ohm-m), were quite conductive (< 100 ohm-m) within 100 metres of the deposit center. Also, a comparison of downhole resistivity logs with the corresponding geological logs of a few drill holes in the area confirmed that moderate to strong argillic alteration of the graphitic host metapelites within and beneath zone O2 could cause the low range of resistivities indicated [10].

The Eagle Point mine was closed from 1999 to 2001, and exploration in the area was suspended during that period due to low uranium prices. In 2001 and 2002, Stepwise Moving Loop coverage north of the Eagle Point mine led to the discovery of other bright spots, notably in the area of zone O2 Next (Fig. 2). A drill test in 2002 targeted the O2 Next bright spot and a prominent bend in the defined conductor system, establishing the presence of sub-economic uraniferous veins and significant argillic alteration. At the same time, relogging of historical drill core in the general vicinity of the bright spot identified favorable argillic alteration similar to that encountered at zone O2.

In 2003 and 2004, grid format TDEM soundings defined the established bright spots in more detail. The CDI produced from the sounding data suggested that they were related to elongate conductive bodies just above the graphitic Collins Bay fault, and oblique to it. A 3D EM model constructed in Emigma V7.8 of the conductive features confirmed their basic configuration (Fig. 3). Additional drilling targeted the defined conductive feature north of zone O2, which led to the definition of a significant uranium resource at zone O2 Next by the end of 2003, approximately 75 metres into the hanging wall of the Collins Bay fault, along an intersecting east-northeast trending secondary structure. Two of the more interesting holes are EPE-059 and EPE-061, which encountered 1.47% U over 14.4 m and 5.82% U over 4 m respectively. Underground development and evaluation of this zone is currently underway from the mine, which reopened in 2002.

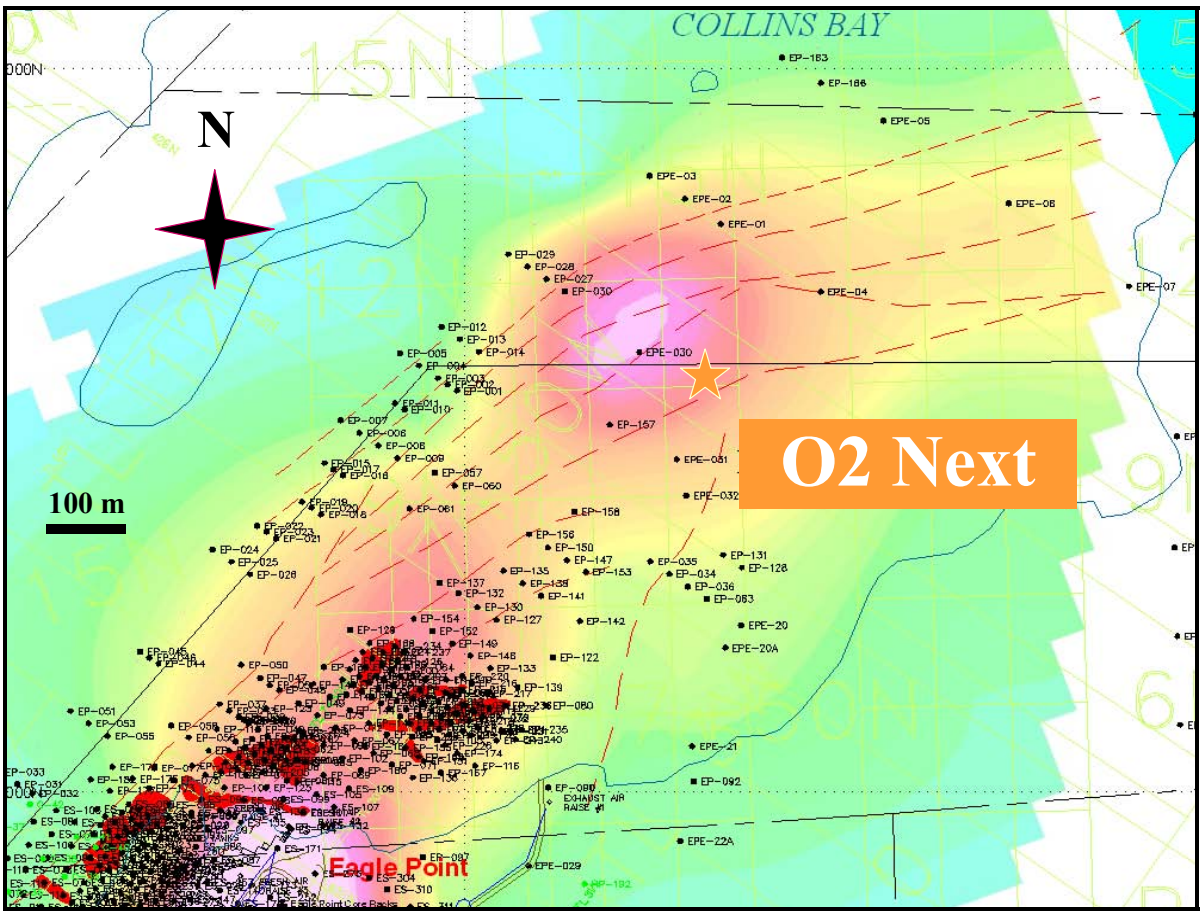

FIG. 2. Image of In-loop channel 7 (of 20), from a compilation of Stepwise Moving Loop profiles in the Eagle North area. The bullseye anomaly in the top center part of the image is the bright spot associated with zone O2 Next (amplitude 130 nV/Am^2).

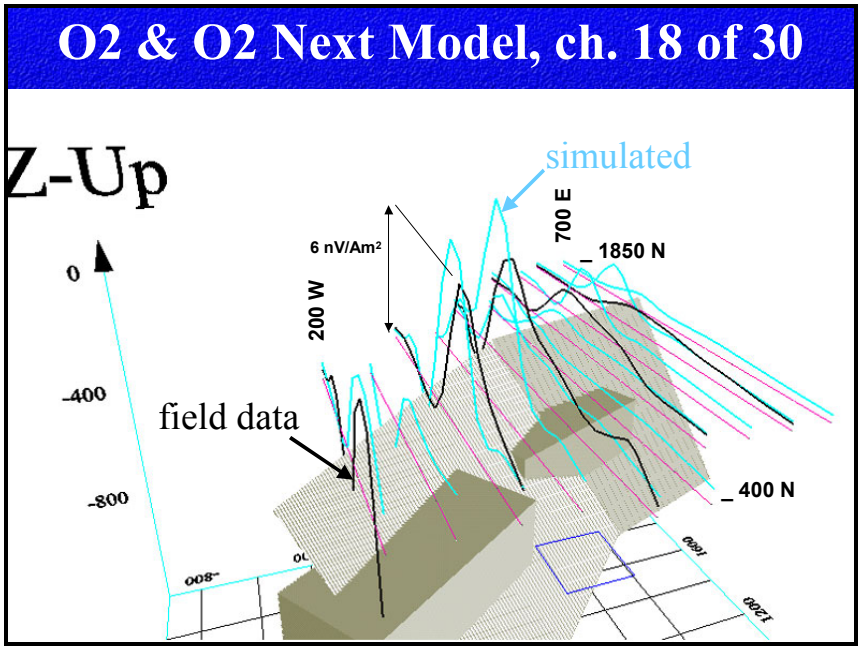

FIG. 3. A 3D forward model in Emigma V7.8 of TDEM sounding data, looking north. The dipping sheet (1 siemen) is the Collins Bay graphitic fault. The zone O2 and O2 Next alteration features (05 siemens/m) are the rectangular prisms in the foreground and background respectively.

3. Zone A, McArthur River Mine

A renewed drilling program was undertaken at zone A in 2004 under a McArthur mine site brownfield exploration program initiated in 2004, following the success at Eagle Point. Drilling focused on the P2 reverse fault and was based on a single historical intersection in this locale in drill hole MAC-204, with sufficient distance remaining between adjacent holes (50 m) for the possibility of an economic deposit. Zone A is located about 250 metres north of the current mine workings along the P2 fault, which constitutes the primary control on the ore zones. Zone A occurs at a depth of approximately 520 m, and is largely restricted to the nose of the upthrusted basement wedge of the P2 fault, which has a throw of about 75 metres in the mine area. The geology of the McArthur River Mine (Fig. 1) is described in [11]. Two of the more interesting intersections at zone A to date are historic MAC-204 and MC-269-3 (2004) which returned average grades of 23.1% U over 9 metres and 15.0% U over 4.1 metres respectively. Underground delineation of this zone will begin in 2005.

Three-dimensional images of the interpreted seismic surfaces indicate that there are good reasons to further test zone A for its economic potential. Figure 4 is a view of the McArthur River mine area, looking south, which shows the seismic-interpreted unconformity and P2 fault surfaces [13]. Use was made of existing drill holes and the processed pseudo-3D seismic data collected under EXTECH IV in 2000 [14]. The 75 metres offset of the unconformity at the P2 fault is readily apparent. Unconformity undulations perpendicular to the P2 reverse fault suggest the presence of related northwest oriented tear faults. Some east west oriented cross faults are also discernible as linear undulations, particularly in the footwall of the P2 fault. These secondary structures tend to correlate well with the endpoints of the ore zones, which are shown as white bodies against the P2 fault surface. Zone A is identifiable as a favorable site from the locations of these secondary structures.

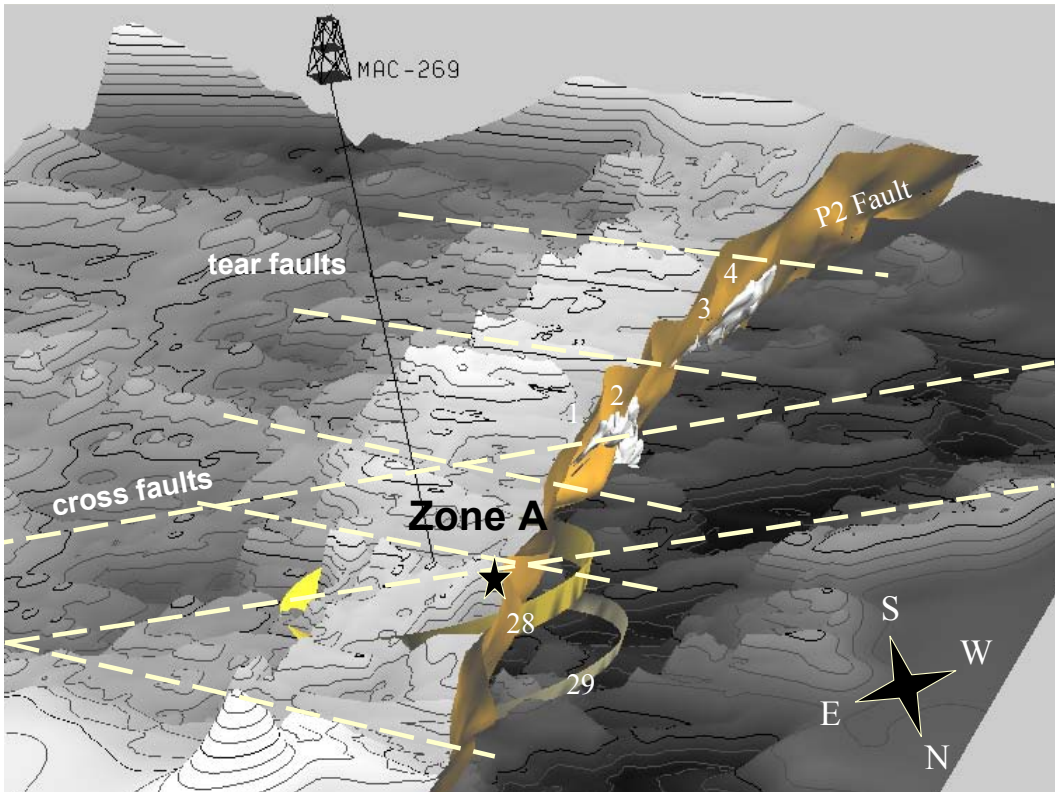

FIG. 4. A 3D image looking south toward zone A. Shown are the unconformity surface interpreted from the EXTECH 3D seismic survey, ore zones 1 - 4, the P2 fault, and drill hole MC-269. The rings are possible locations of interpreted diffraction features 28 and 29.

Preliminary tests of McArthur River ore samples, carried out by the Rock Mechanics Laboratory at the University of Saskatchewan, suggested that high-grade ore could be detectable as a relatively high frequency reflector (> 1 kHz). For example, 4.2% U (p-wave velocity 3.927 km/sec; density 3.391 g/cm^3) in an altered metapelite host would produce a strong reflectivity of as much as 0.3, or 30%. This information could be absent in a surface seismic survey due to significant high frequency losses in the overlying sandstone and glacial till. However, downhole multi-azimuth seismic profiling [12] offers the possibility of accurately defining the controlling structure(s) and detection of ore bodies as seismic diffractors up to 200 metres away from the drill hole using high frequency seismic waves.

Also shown in Fig. 4 is the pilot hole MC-269, used to target the area of the P2 fault that is now referred to as zone A. Downhole multi-azimuth seismic surveys were performed in this hole and another in this area (MAC 204) by contractor-consultant Vibrometric Oy, using an in-hole, piezoelectric, swept-impact source operated at a signal frequency of 1kHz, with a downhole string of 24 receivers at 2 metre intervals. The rings concentric about the drill hole in Fig. 4 represent the full 360º of possible locations of two interpreted seismic diffraction anomalies (labelled #28 and #29 in Fig. 5). The elevations of these correspond to the upper and lower surfaces of the offset unconformity at the P2 fault. The intersections of the rings with the P2 fault represent first priority targets. These points await testing either from surface or underground.

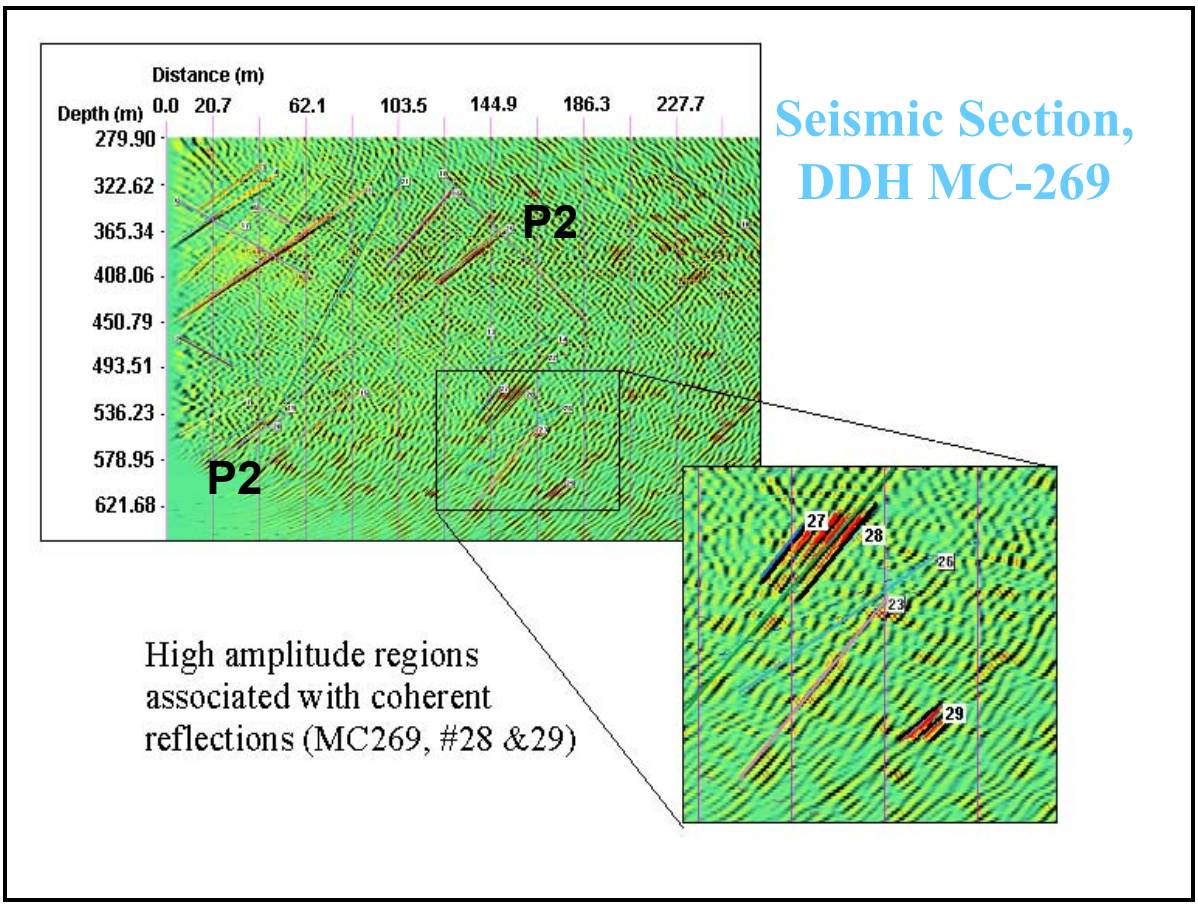

FIG. 5. Downhole seismic image from drill hole MC-269 showing defined faults, notably the P2 and related structures. Features #28 and #29 indicate two coherent reflections with possible diffraction anomalies at depths corresponding to the upper and lower unconformity surfaces at the P2 fault.

4. Millennium deposit, Cree extension project

The greenfield, basement-hosted Millennium deposit (Fig. 1) discovery in 2000 occurs at a depth of 650 metres on a major post-sandstone structural trend mapped historically as the B_1 conductor. It was discovered as a result of progressive drill step outs westward from a north-south segment of the main

B_1 conductor defined initially by Fixed Loop TDEM surveys from 1985 to 1995. Regionally, the B_1 conductive package is hosted in a north to northeast trending magnetic low related to folded Wollaston Group metasedimentary gneisses. The Millennium deposit sits on a significant northwest-southeast magnetic break, a feature that crosscuts the regional northeasterly trending magnetic fabric.

Considerable difficulty was experienced intersecting the B_1 conductor due to the complexity of the setting, notably 1) a significant unconformity relief (75 m) across the B_1 conductor system, 2) presence of additional unresolved discrete conductors in the original EM surveys, and 3) the presence of an eastern Archean granite interpreted to be thrusted over the B_1 conductor system. This led to drill step outs to the west of the conductor with the objective of intersecting the B_1 conductor at the unconformity. This is shown in Fig. 2 of [15], which describes the geology of the Millennium deposit, this volume. Favorable sandstone uranium and boron geochemistry, structure and strong alteration in the bottom of step out drill hole CX-38 provided encouragement to continue step outs to the west, which resulted in the intersection in hole CX-40 of significant uranium centered 85 metres below the sandstone-basement unconformity.

The current drill-defined location of the "Main Zone" occurs at the "Graphitic Marker", the westernmost, thinnest and deepest graphitic unit within the B_1 conductor package (Fig. 4 of [15]). Stratigraphically, the graphitic marker and the mineralization are located approximately 80 to 100 metres grid west of what is referred to as the main B_1 conductor. The Millennium deposit would therefore not have been found through systematic along-strike drilling of the main B_1 stratigraphy alone, if it were not for the recognition of the strong hydrothermal alteration 50 metres into the basement of CX-38 and the potential for a basement-hosted deposit, well off (100 m) the defined B_1 conductor axis.

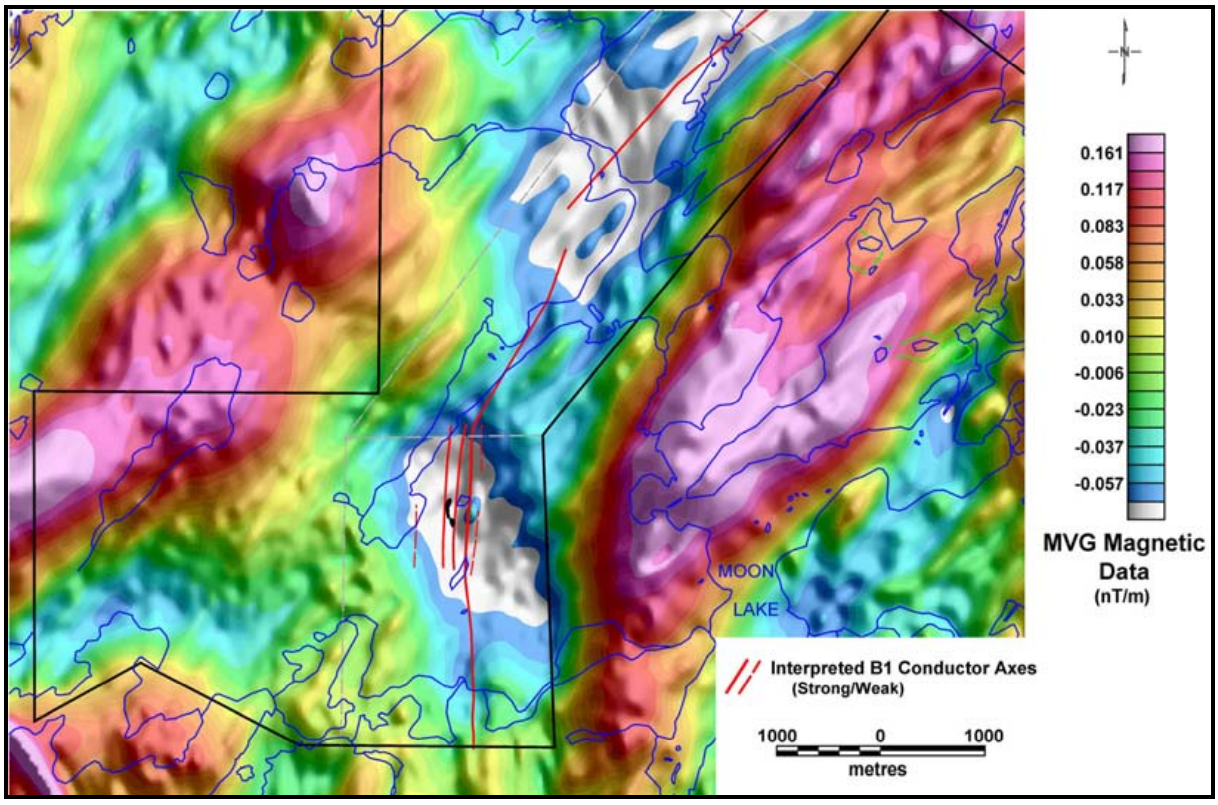

FIG. 6. Magnetic vertical gradient setting of the Millennium deposit and the B1 conductor system.

The deposit, as currently defined, has a minimum strike length of 230 m, a maximum width of 30 metres and a down-dip extent of 70 m. The resource and grade information for this deposit are provided in [15]. Recent geophysical work in the area has included an airborne triaxial magnetic gradiometer survey and MEGATEM test, as well as ground Stepwise Moving Loop and Soundings,

AMT, IP/resistivity and gravity surveys with the objective of adding resources in this area. Based upon the various EM techniques applied to date at Millennium, Stepwise Moving Loop EM methods produced better conductor resolution in the Millennium deposit area (Fig. 6) than the historic Fixed Loop coverage elsewhere along the B_1 trend.

5. Wide Lake Discovery, Virgin River Project

The Wide Lake greenfield, sandstone- and unconformity-hosted discovery (2004) demonstrates innovation and integration toward a more focused approach on a 50 kilometre long, 10 kilometre wide, deep (to 1 km) conductor corridor, by selectively looking for areas of enhanced structure and alteration along the defined conductor axes. The Virgin River project (Fig. 1) is located near the southern margin of the Athabasca Basin along the trans-continental Snowbird Tectonic Zone, and has been explored for uranium since the early 1970's. While there is no published geology for the project area, the geology of the exposed basement to the southwest is described by [16].

In addition to early folding events F_1 and F_2 , responsible for the dome and basin character of the Mudjatik Domain (Fig. 1), there were additional folding events F_3 and F_4 which form the framework for the following description. More recently, it was noticed that significant uranium enrichment occurs along the Virgin River trend at the interpreted intersections of a NNE trending antiform (F_3) with the synforms of WNW trending F_4 folds. These "saddles", occur approximately every 6 to10 kilometres along the F_3 antiformal axis and are recognizable in the detailed vertical gradient magnetic and Bouguer gravity data for the area. The unconformity-hosted uranium mineralization occurs at the graphitic fault/conductor that flanks the west side of the F_3 antiformal fold axis, where it is intersected by crosscutting zones upper-sandstone desilicification. Paragenetic studies indicate that the desilicification was a premineralization event that may have controlled synmineralization fluid flow patterns [17].

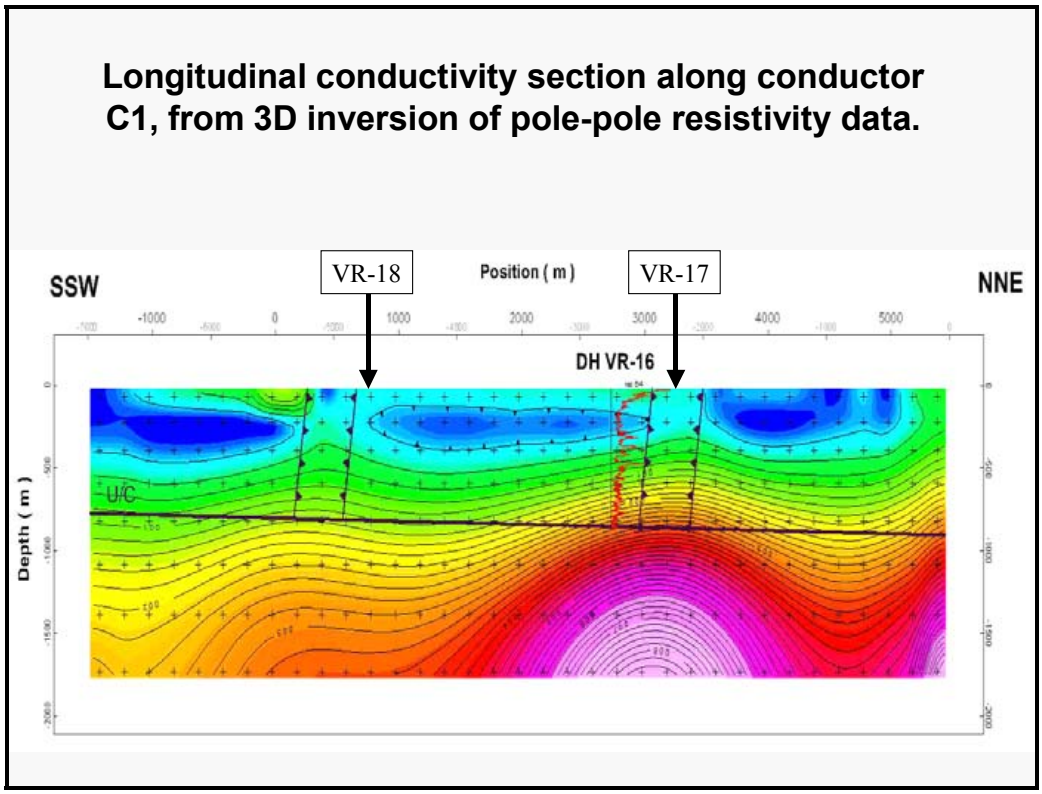

FIG. 7. Inversion section of a three line longitudinal resistivity survey along the C1 conductor. The breach defined south of VR-16 was the target for the discovery hole VR-18 on the north edge of the breach. The conductivity range is 0.0001 to 0.008 S/m. A downhole resistivity log of VR16 is shown for comparison (0 to 10 000 ohm-m plot range).

The desilicification is attributed to hydrothermal fluids channeled in post-Athabasca brittle fractures associated with the F_4 folds. The conductor was outlined in the saddle area on profiles perpendicular to the strike of the F_3 fold axis, using large Moving Loop (1 000 x 1 000 m) TDEM surveys. The sandstone above the conductor was then mapped using galvanic resistivity methods (pole-pole survey, a = 200 m, n = 1 to 10) on profiles parallel to the conductor, followed by 3D resistivity inversion by the method of [18], referred to as longitudinal resistivity (Fig. 7). This successfully mapped the crosscutting zones of desilicification, which form "breaches" of low resistivity in an otherwise very silicified, high-resistivity upper sandstone. The intersection of the basement graphitic conductive fault and the unconformity within, or proximal to, the "breach" was then considered a valid drill target. Two such targets were drill tested in 2004 (Fig. 7). DDH VR-18 is the discovery hole which intersected perched uranium in the sandstone from 710.5 to 711.7 and 752.0 to 762.8 metres and unconformity-hosted uranium from 789.1 to 795.5 metres with average grades of 0.24%, 0.85% and 4.94% U respectively. DDH VR-17 encountered anomalous radioactivity (6 433 cps) and alteration in the lower sandstone.

6. Conclusions

An innovative and integrated multidisciplinary approach to exploration has led to significant new discoveries by Cameco Corporation in the Athabasca Basin. The significance of the Millennium and O2 Next discoveries relates to the presence of a relatively undertested basement-hosted deposit type, in the Athabasca Basin. Their large depths below the unconformity and distances off the dominant conductor bear similarities to other deposits of this type, notably zone O2 (150+ m below the eroded unconformity and 200 metres southeast of the graphitic Collins Bay fault), and the Rabbit Lake deposit (75+ m below the eroded unconformity and 125 metres southeast of the graphitic Rabbit Lake fault). The significance of historic zone A at the McArthur River mine relates to the recognition that considerable potential remains in this area for both unconformity and basement-hosted styles of mineralization. Development of this zone is on-going and seismic techniques are being tested to play a role in future discoveries in this area. The message of the Virgin River greenfield discovery is that considerable efficiencies are achievable by taking a more selective approach to systematic drilling of conductors, particularly under deep sandstone cover.

ACKNOWLEDGEMENTS

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Uranium exploration in Australia
A renewed interest

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Abstract. After many years of declining or static exploration for uranium, exploration companies are again realising the potential for significant uranium discoveries in Australia. Despite the continuing negative appraisal of the nuclear industry by various State Governments and political parties in Australia, many in the industry are adopting a long-term approach and targeting regions throughout the continent. Public sentiment is also showing signs of change. During the past decade, exploration has predominantly targeted unconformity-related mineralisation in western Arnhem Land (Northern Territory), and sediment-hosted mineralisation in the state of South Australia. Many companies are now actively targeting these, and other, mineralisation styles in numerous locations throughout the country.

1. Introduction

Uranium exploration within Australia has been in decline for a number of years, somewhat dissociated from the significant remaining potential for discovering new world-class orebodies (Fig. 1) [1]. Australia contains the world's largest resources in the ≤ US $80/kg U Reasonably Assured Resources (RAR) category [2]. The majority of these resources are contained within diverse mineralized settings, for example IOCG-U, unconformity-related, sandstone and calcrete, indicating the wide variety of world-class targets possible within Australia (Fig. 2).

Recently, interest for uranium in Australia has been piqued, largely as a result of the increase in the world's demand for uranium product. The increase in the uranium price has obvious financial incentives for discovering a new uranium deposit (or re-invigorating a dormant resource) resulting in a number of new uranium explorers recently appearing on the Australian market and the inclusion of the commodity into established companies portfolios.

However, the renewed interest is also as a result of local influences such as a more balanced assessment of the nuclear industry by some legislators, commentators and the public at large. For example, in March 2005 a Parliamentary Committee of the Federal Government sought submissions to assist with its "Inquiry into developing Australia's non-fossil fuel energy industry"; this Inquiry will commence with a case study into the strategic importance of Australia's uranium resources.

Many junior explorers, as well as the larger established uranium explorers, are now spreading into new regions that have either undergone sporadic exploration or none at all.

Notwithstanding this new interest in uranium exploration around Australia, expenditure is still greatest in both South Australia and the Northern Territory, presently the only provinces where uranium production is ongoing and whose respective government's have given approval to the extraction of uranium product[1]. The State of New South Wales enacted legislation in 1986 banning the exploration for, or exploitation of, uranium (the *Uranium Mining and Nuclear Facilities [Prohibitions] Act*) and is the only State in Australia with these legislative restrictions. However, most State governments in

[1] The Australian Federal Government grants export licences.

Australia have policies against the production of uranium, and Western Australia in particular is debating legislation specifically prohibiting uranium extraction.

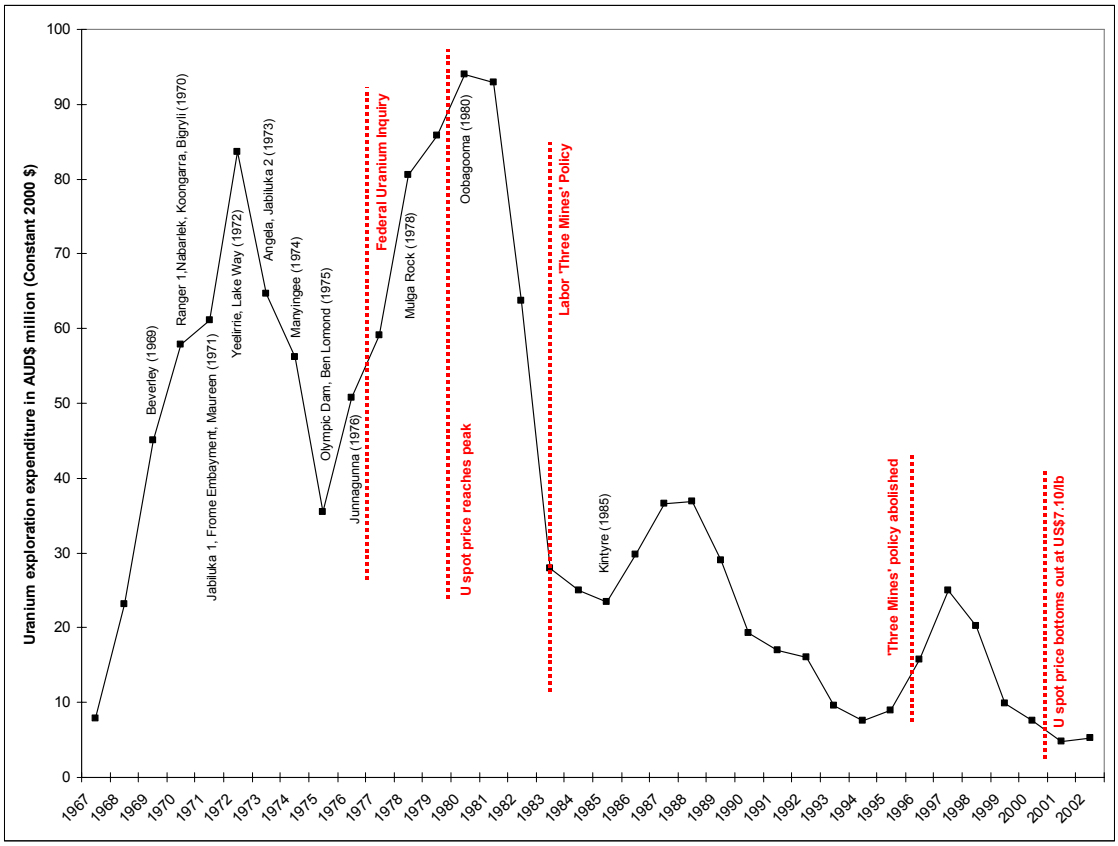

FIG. 1. Annual expenditure on uranium exploration (constant $A2 000), the discovery of important deposits and events that affected uranium exploration in Australia. .

2. Deposit styles

Proterozoic unconformity-related mineralization

During the past decade, a large proportion of annual uranium exploration expenditure has been focussed on discovering Ranger or Jabiluka equivalents. This exploration has been centred on western Arnhem Land in the far north of the Northern Territory. With all of the major deposits of this style being discovered during airborne radiometric surveys during the early 1970's, most of the exploration is concentrated on blind targets beneath substantial thicknesses of sandstone cover. As a result, numerous exploration methods have been employed during the past decade to 'see through' the barren cover and detect the mineralization based upon its inherent electrical conductivity and density properties. Two methods that have greatly assisted exploration teams have been airborne electromagnetic (Tempest™) and airborne gravity gradiometer (Falcon™) surveys. Another regional exploration tool trialled with limited success, but with obvious potential, has been airborne hyperspectral surveying.

Exploration for this style of mineralization has historically been centred on western Arnhem Land. While this area remains a major focus, attention is also shifting towards other Proterozoic basins in South Australia and Western Australia that have experienced limited exploration during the 1970's and 1980's, and where the potential for hosting significant deposits is largely untested.

The Rum Jungle uranium field, approximately 90km south of Darwin, host numerous uranium mineral occurrences, some of which were mined in various stages between 1953 and 1963 [1]. The region is in the process of being re-evaluated, with exploration (in the form of drilling) likely to commence in 2005 [3].

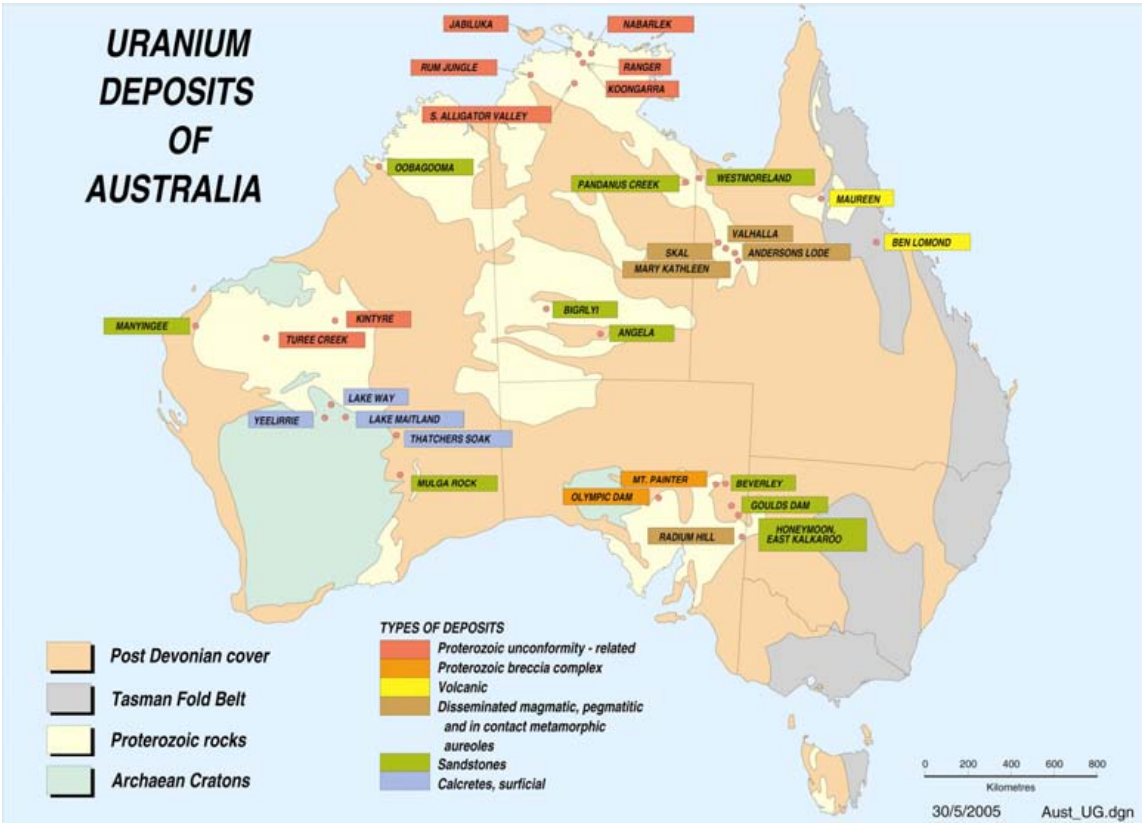

FIG. 2. Locations of major uranium deposits and prospects in Australia identified by mineralization style.

2.1. Sediment-hosted mineralization

The commencement of production at Beverley in 2000 and the feasibility studies at the Honeymoon and Gould's Dam projects has seen a marked increase in exploration activity in the Curnamona Province, eastern South Australia for sediment-hosted uranium deposits amenable to in-situ leaching extraction. The potential for discovering similarly sized orebodies in the Tertiary basins of South Australia and Western Australia remains high. Exploration methods adopted by companies in their search for deposits of this style during recent years includes the use of Tempest™ surveys to delineate buried palaeochannels filled with electrically-conducting hypersaline groundwater [4]. Innovative use of nighttime thermal imagery to detect subtle contrasts in the thermal co-efficient of a district has also been used to some effect in identifying buried palaeochannels in the Eucla Basin [5].

Areas of focus for sediment-hosted mineralization are the Callabonna sub-basin, which contains the Beverley, Honeymoon and Gould's Dam deposits, the Eucla Basin (straddling the states of Western Australia and South Australia), and the Canning and Carnarvon Basins in Western Australia. Applications for new exploration licences in the Carnarvon Basin were submitted early in 2005 with the intention of exploring for Manyingee equivalents [6].

The Westmoreland region, straddling Queensland and the Northern Territory is another area undergoing resurgence. Recent and ongoing exploration in this area is primarily focussed on gaining access to the deposits already delineated with the intention of further progressing the resource calculations [7]. There is a possibility that recommencement of activity here will result in renewed exploration on the Northern Territory side of the border.

2.2. Metamorphic and metasomatic mineralization

This style of mineralization exists throughout the Mt Isa Inlier in northwest Queensland, and has only been historically mined at Mary Kathleen. Significant mineralization exists in numerous other deposits

and prospects throughout the region, one of the largest being Valhalla with total resources of 16 500 t U_3O_8 [8]. Exploration expenditure is expected to increase around the Mt Isa Inlier during 2005. This exploration will mainly be in the form of both regional and development drilling surrounding the Valhalla and Skal deposits north of Mt Isa in Queensland [9].

2.3. Breccia complex mineralization

Exploration for breccia complex, or iron-oxide copper-gold-uranium (IOCG-U) deposits, has been ongoing in the Gawler Craton, central South Australia, for a number of years, especially since the discovery of the Prominent Hill orebody in 2001. It is fair to say that interest in this type of mineralization is not only focussed on uranium, but rather on the polymetallic nature of the mineralization and their sheer size. Nonetheless, this style of deposit is a legitimate target for uranium exploration companies – Olympic Dam is (by far) the world's largest uranium deposit, with current reserves of 380 500 t U_3O_8 (0.05% U_3O_8) [10].

Exploration for IOCG-U orebodies is also increasing in other Proterozoic complexes throughout Australia, most notably in the Curnamona Province. The presence of abundant, albeit small tonnage and low grade, uranium occurrences within the Curnamona Province and adjacent Mt Painter Inlier has seen recent explorers target buried mineralization using a combination of airborne and ground geophysical surveys (including gravity and magnetics).

3. Conclusions

A number of factors, notably the under-explored potential of large parts of Australia, the steadily improving uranium market (underpinned by demand), and an increasing awareness of the benefits of nuclear power have all combined to change the perceptions of mineral explorers. The true test will be whether the renewed interest results in a significant increase in the annual exploration expenditure (especially in drilling) and, eventually, with the discovery of new deposits.

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Uranium explortation in the upper proterozoic Bhima Basin, Karnataka, India
A new target area

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Abstract. The unconformity between the Lower Proterozoic basement granite and overlying Middle-Upper Proterozoic sediments of Purana basin constitute the most important target for locating unconformity related uranium deposit in India. The Upper Proterozoic Bhima basin occurring in the northern part of Karnataka comprising predominantly calcareous and clastic sediments is presently one of the important targets for uranium exploration. Integrated exploration programme along with sub-surface drilling resulted in establishing a medium grade and low tonnage fracture controlled uranium mineralization associated with Shahabad Limestone of Bhima group and basement granite along the EW trending 30 km long Gogi – Kurlagere reverse fault in proximity to the unconformity at Gogi, Karnataka. Several other surface uranium occurrences have been identified in different lithic units viz., phosphatised limestone at Ukinal and Madnal, limestone/cherty breccia at Darshanapur and shale at Kasturpalli. The reverse faulting at the southern margin of the basin has resulted in folding of the sedimentary units and the brecciated - fractured axial zone host rich grade uranium mineralization, which occur as veins and veinlets at Gogi. The mineralized zones have steep to moderate dips proximal to the hangwall sediment-basement granite contact and attain near horizontal dips proximal to the footwall sediment – basement granite contact. The thick mineralized zone formed by the merger of footwall and hangwall lodes resembles a 'nose-like structure', which is probably formed due to reverse faulting. In the sheared basement granite, uranium mineralization occurs about 5 to 20m below the unconformity. Few fractures in hangwall granite are also mineralized but have restricted extent. Pitchblende and coffinite, the main uranium phases are essentially ultrafine (5 to 10 microns), localized in sulphides rich portions and also occurs as dispersed specks in brecciated calcareous and siliceous matter. Notable concentration of SiO_2 in pitchblende, and appreciable amount of REE, Pb, Ag, Au in pyrites have been observed. Significant target areas have been delineated by hydrogeochemical survey and Airborne Gamma-ray Spectrometry. The Bhima basin is currently under active exploration involving an integrated approach to identify large tonnage, high-grade and low-cost uranium deposits.

1. Introduction

Unconformity related uranium deposits and their characteristic geological features were recognized in the early 1970s almost at the same time both in Canada and Australia. Since then the progress made in understanding these deposits are enormous. Nearly one third of the world's "Reasonably Assured Resources" of uranium and more than one half of the annual production are from the Proterozoic unconformity related deposits. These high grade and large tonnage deposits occur at the base of the Middle Proterozoic strata close to the unconformity with the Early Proterozoic basement rocks. In the light of the emerging trend world wide, the Proterozoic basins of India have been viewed with seriousness for uranium exploration. The Middle to Late Proterozoic basins, well known to Indian geologist as "Purana basins" with unmetamorphosed, undeformed and unfossiliferous sediments resting over crystalline complex with a profound unconformity, is now the prime targets for uranium exploration. Prior to this, these basins drew little or no attention for mineral exploration. The exploration efforts for more than a decade led to identify unconformity related deposit at Lambapur [1] and dolostone hosted strata-bound deposit at Tummalapalle [2] in the Mid-Proterozoic Cuddapah basin, Andhra Pradesh. The exploration in the neighbouring Bhima basin has established medium grade – low tonnage deposit at Gogi, which is unique in terms of geological setting hitherto unknown in India. This has given an insight into the favourability of the Bhima basin for uranium exploration and the entire basin is under different stages of active exploration.

2. Geology and structure

2.1. Regional geological setting

Bhima basin occurs in parts of Gulbarga district of northern Karnataka state and Mahboobnagar and Ranga Reddy districts of western Andhra Pradesh state. It is exposed over an area of 5 200 sq km between latitude $16^0$12' - $17^0$35'N and longitude $75^0$35' – $77^0$40'E in a linear stretch for about 160 km in a NE-SW direction with a maximum width of 40 kms (Fig.1). The northern extension of this basin is concealed under the Late Cretaceous – Paleocene Deccan trap volcanic province, while the southern boundary exposes the early Precambrian granite – greenstone terrain of Eastern Dharwar Craton. Limestone and shale are the predominant lithounits of Bhima group with a thin arenite and conglomerate at the base of the sequence exposed at several places marking the unconformity with the basement crystalline rocks [3]. The average stratigraphic thickness of the Bhima sediments is about 300 m observed from surface and subsurface data [4]. Bruce Foote (1876) was the first to study the entire basin and suggested a two fold classification [5]. The latest revised stratigraphy [6][4], is given in Table I:

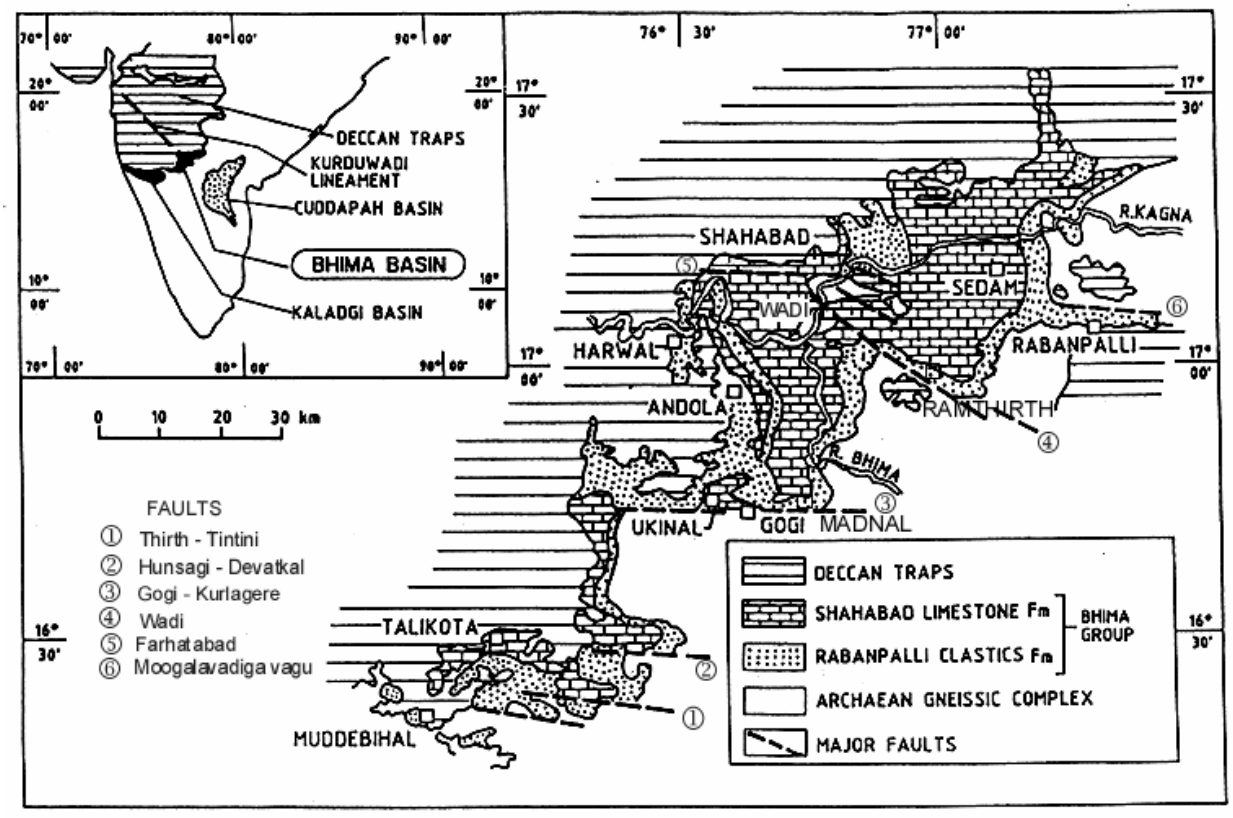

FIG.1 Geological map of Bhima Basin.

Table I. Stratigraphy of Bhima Basin

Jayaprakash A.V. (1999)			Kale V.S (1999)
GROUP	**FORMATION**	**MEMBER**	
	Harwal		B) Shahabad Limestone Formation
	Katama devarahalli		** Grey micritic impure limestone.
	Hulkal		** Dark blue – grey massive limestone.
	Shahabad	Mulkod Limestone	** Variegated, siliceous and cherty
		Gudur Limestone	limestones
			** Flaggy impure (cherty/argillaceous)
BHIMA			limestones
GROUP			-Gradational and transitional
		Sedam Limestone	----- Facies changes---
Total		Wadi Limestone	A) Rabanpalli Clastics Formation
Thickness		Ravoor Limestone	d) Ekmai Shale Member
297m	Rabanpalli	Korla shale	(ferruginous & calcareous shales)
		Kundrapalle Sandstone	c) Kasturpalli Glauconitic Member
		Muddebihal Conglomerate	b) Kundrapalli Quartz-Arenite Member
			a) Adki Hill conglomerate Member.
---------- Unconformity ----------			
BASEMENT CRYSTALLINES		Younger Granites, Peninsular Gneisses, Greenstone Belts	

2.2. Structure

Sediments of the Bhima group generally display horizontal bedding, except in the neighbourhood of faults, where steep dipping, intense brecciation, isoclinal and recumbent folding and over thrusting have been observed. E-W and NW-SE trending faults are the most prominent, penetrative and continue into the basement. In addition, a number of smaller cross faults with NS and NE-SW trends have been identified. The important major faults are the E-W Gogi - Kurlagere fault and NW-SE Wadi fault, which are also boundary faults and the minor faults are Tirth-Tintini fault, Wajjal fault and Farhatabad fault (Fig. 1). The exposure pattern indicates that these faults have exercised control over the configuration of the basin [6].

It was widely believed that the faults in the Bhima basin are strike-slip faults [6], but the work by this Directorate established the EW Gogi – Kurlagere fault as a reverse fault. Slump structures produced due to penecontemporaneous deformation of the semi-consolidated sediments prior to the lithifications have been observed in some sections. They can be distinguished from tectonic breccia as they are limited to particular beds within a sequence, where the beds above and below do not show any deformations.

2.3. Geological setting of Gogi area

Gogi is located at the middle of the E-W trending Gogi – Kurlagere fault along the central part of the southern margin of Bhima basin (Fig.2). This fault finds a special mention in the description of Bhima basin geology by Bruce Foote as early as 1876. The EW trending Gogi – Kurlagere fault takes a NW-SE, then NE-SW and swerve back to EW trend at Gogi. This is due to a NE-SW cross fault at Gogi traceable for nearly 1.5 km. Limestone of Shahabad Formation is the main rock type exposed in this area with minor shale and arenite. Due to thick soil cover, cultivation, water bodies and habitation the geological exposure at Gogi are scanty. Good exposures of brecciated limestone are seen south of Gogi village. Steep dipping of the beds, intense brecciation in limestone and basement granites are the characteristic features of the fault zone indicating the involvement of basement rocks during tectonization. Clasts and fragments of granite, basic rock, limestone, shale and arenite all embedded in grey blocky limestone, characterize the breccia zone along the fault. A thin, but persistent, bed of glauconitic shale serves as a marker along the basin boundary. The beds become horizontal away from the tectonized zone. Sub-surface drilling along this fault zone at Gogi, Darshanapur and Ukinal areas

reveals that the fault is shallow at upper structural level and becomes steep at deeper level, which is characteristic of an up-thrust [7].

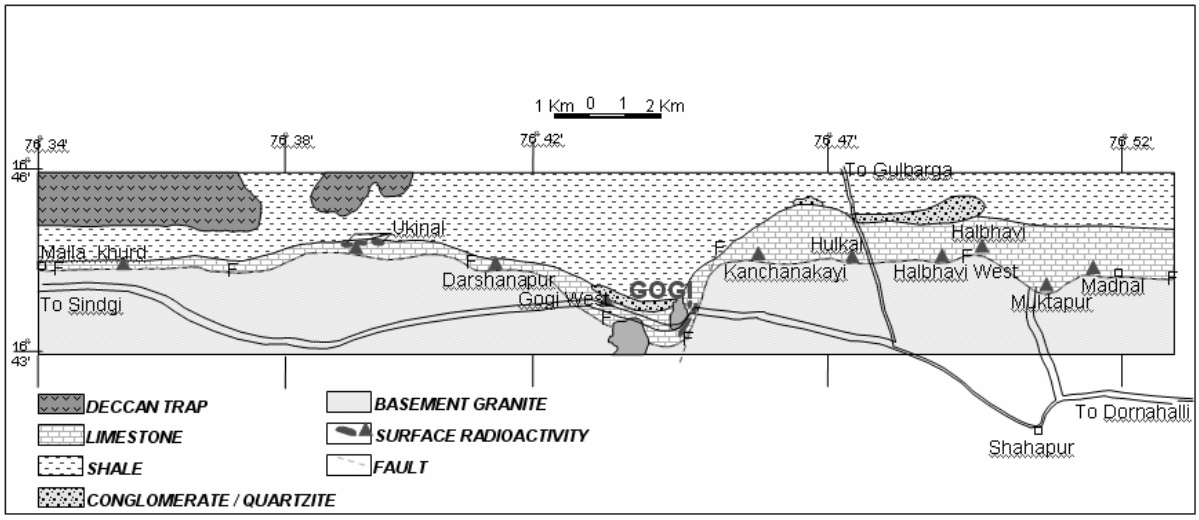

FIG. 2 Regional Geological map of Malla-Gogi-Madnal Sector.

3. History of uranium exploration and methodology

Bhima basin as such was considered least priority area for uranium exploration as limestone and shale constitute 80% by volume of the rock formations without evidence of any major tectonic activity [8]. Considering the Proterozoic age - an epoch characterized by many episodes of uranium mineralization on global scale - and the success of locating uranium deposits in the Proterozoic Cuddapah basin not far away, uranium exploration was taken up in the Proterozoic Bhima basin. Accordingly, an integrated exploration programme was launched involving

(a) satellite image and aerial photo interpretation to identify the structural elements affecting the basement and basin lithology and the intersection of major lineaments, which would be ideal loci for mineralization;

(b) airborne gamma-ray spectrometry and car-borne radiation survey to identify areas of anomalous radio element concentration;

(c) regional hydrogeochemical sampling to identify potential targets in soil covered regions;

(d) foot radiometrics to precisely select areas for subsurface exploration; and

(e) geophysical surveys, such as magnetic, resistivity/IP and EM, in the extension areas of Gogi for identifying the structures and carbonaceous matter, sulphide-rich zones for planning sub-surface drilling.

Initial foot radiometric checking in some selected areas brought out interesting surface uranium occurrences hosted in brecciated cherty phosphatic limestone near Ukinal along the tectonized zone of Gogi – Kurlagere fault. This was followed by a systematic radiometric survey wherein all the prominent fault zones were targeted leading to the discovery of uranium mineralization in various rock formation at a number of places. The uranium mineralization in Bhima basin can be broadly classified into four categories: (i) hosted in phosphatic limestone/cherty limestone e.g., Ukinal, Darshanapur, Ramtirth, (ii) hosted in non-phosphatic limestone e.g., Gogi, Halbhavi, (iii) hosted in granite e.g., Gogi and (iv) hosted in shale/siltstone e.g., Kasturpalli.

Gamma-ray logging of some of the drinking water borewells close to the radioactive outcrops intercepted interesting radioactive zones at depths e.g. 0.136% eU_3O_8 x 6.40 m (BWG-2);

0.052% eU_3O_8 x 12.30 m (BWG-3) [9]. Of the 31 drinking water borewells logged in Gogi area, 12 have intercepted uranium mineralization. Based on the surface information and subsurface data obtained from the gamma-ray logging of domestic borewells, core drilling was taken up at Gogi during summers of 1997. Initially the boreholes were drilled vertically as there was no clue on the nature and control of mineralization. Subsequent boreholes were inclined to intercept the true thickness of the ore bodies. Although the initial exploration was on unconformity model, the deposit at Gogi turned out to be structurally controlled. Accordingly, the sub-surface exploration was reoriented and emphasis was given to the tectonized zones, which are the loci for mineralization.

4. Uranium mineralization in Bhima basin

4.1. Mineralization in phosphatic limestone

Uranium mineralization hosted in phosphatic limestone has been located at Ukinal [10], Darshanapur, and Madnal along the Gogi – Kurlagere fault zone and Ramtirth along the Wadi fault [11]. The mineralized portion of the limestone is completely altered giving rise to kankar like appearance and no proper outcrop seen in any of the area. Petrographically, the host rock has been identified as micritic siliceous limestone, limonite-bearing calcitic phosphorite, phosphatic chert and siliceous phosphorite. Surface samples analysed 0.017 to 0.084% U_3O_8 and 1.66 to 29.5% (av. 14.8%) P_2O_5. The major minerals are collophane and calcite admixed with silica, limonite, clay, glauconite and pyrolusite and other ore minerals present are specular hematite, anatase and pyrite in accessory quantity. No discrete uranium mineral has been identified. Uranium is mostly associated with collophane with minor amount in limonite and clay besides a little labile uranium along the grain boundaries. Rarely ultra fine (1-2 micron) pitchblende occurs as disseminations in pyrrhotite [12].

4.2. Uranium in non-phosphatic limestone

Occurrence of uranium in non-phosphatic limestone is reported from Gogi, Halbhavi and Muktapur areas along the Gogi – Kurlagere fault. The mineralization occurs in the form of veins cutting across bedding plane in the brecciated dark grey Shahabad Limestone Formation as isolated outcrops in the tectonized zone close to the basement-sediment unconformity contact. Surface samples contain 0.02 to 0.27% U_3O_8, and upto 0.28% P_2O_5 and are free of thorium. Coffinite and pitchblende are the main uranium minerals which occur in intimate association with carbonaceous matter and sulphides.

4.3. Mineralization in granite

Incidence of uranium mineralization in the basement granite close to the unconformity has been reported at Gogi along the fault zone. It occurs as two isolated patches in sheared granite. Samples from these outcrops analysed 0.02 to 0.3%U_3O_8. No discrete uranium mineral is identified in these samples except U-Ti complex. In general, the uranium concentrations in the granites bordering the Bhima basin range from 10 to 110 ppm [9]. Spectacular uranium mineralization upto a thickness of 20m and grade > 1% U_3O_8 has been intercepted in one of the boreholes drilled at Gogi. It occurs as fracture fillings and veinlets along the steeply dipping fractures developed in the granite thrusted over the sediments as well as horizontal fractures immediately below the unconformity contact. Some of the core samples analysed upto 20% U_3O_8 with various uranium mineral phases being represented mainly by pitchblende, uraninite and coffinite. The host rock shows higher concentration of Pb, Ag, Y, Ba and REE.

4.4. Mineralization in shale

Uranium mineralization in glauconitic shale and siltstone has been identified near Kasturpalli intermittently over a strike length of 1 km [13]. The samples analysed upto 0.042% U_3O_8 but no distinct uranium mineral has been identified. The radioactivity is contributed by uranium adsorbed in limonite and U-Ti complex. Except this, occurrence of uranium in shale has been observed in some of the boreholes drilled at Gogi.

5. Gogi uranium deposit

This is the most important of all the uranium occurrences in Bhima basin. The success at Gogi was responsible to put the entire basin as a first order target for uranium exploration. Gogi Uranium deposit is located in the middle part of Gogi – Kurlagere fault along the southern margin of Bhima basin (Figs 3, 4). Surface expression of uranium mineralization is in the form of few isolated outcrops, close to the basement granite – sediment contact spread over an area of 400 x 100 m. In one of such outcrop coffinite and pitchblende bearing 3 cms wide vein, cutting across the bedding plane and as fracture filling in brecciated limestone was located. Surface samples from this zone assayed upto 0.12% U_3O_8 and <0.01% ThO_2 with P_2O_5 content of upto 0.28%. Considering all the data, sub-surface exploration by drilling was taken up at Gogi.

5.1. Sub-surface exploration

Initially 1.5 km^2 of area was taken up for sub-surface exploration by core drilling to identify the host rock and sub-surface continuity of uranium mineralization recorded in the domestic borewells and in the surface outcrops. Exploratory vertical drill holes were planned close to the surface occurrences and domestic borewells in which radioactivity was intercepted. After few boreholes it was found that the mineralization is steeply dipping and the fault is reverse in nature and accordingly, inclined boreholes were planned to intercept the true thickness of the mineralized zones at shallow depth. After the exploratory boreholes, 1 km strike length of the favourable area was taken up for systematic drilling. The strike of the reverse fault at Gogi is $N50^0E$-$S50^0W$ dipping due $S40^0E$. Hence all the inclined boreholes were planned at an angle of 50^0 towards $N40^0W$ along predetermined profiles. Besides core drilling, non-core (DTH) drilling and combination drilling (coring and non-coring) was also done for economical and speedy evaluation.

5.2. Structure

The structure at Gogi was not clear due to paucity of geological exposures. The uranium mineralization was thought to be unconformity-proximal type. The initial boreholes drilled close to the unconformity contact intercepted the basement at much deeper level than expected and confirmed that the fault is a reverse fault wherein the basement rocks in the south has moved towards north over the Bhima sediments. The reverse faulting resulted in folding of the sedimentary units and the basement-rocks. Both limestone and granite, have been fractured and brecciated in the axial zone resembling a 'nose-like' structure. Intense and wider fractures have developed in comparatively more competent limestone. The fractures fan out towards the higher level with attitude varying from steep to horizontal dips and die out further away from the tectonized zone. The horizontal fractures have better continuity in the limestone whereas in granite they have limited extent close to the unconformity contact.

5.3. Nature of mineralization

Uranium mineralization at Gogi is hosted in two different rock types viz., limestone and granite. Mineralization occurs in the form of veins and veinlets in the fractures developed due to reverse fault. The key controls of mineralization are (i) fracturing and faulting and (ii) abundance of carbonaceous matter and sulphides. The mineralized zones have steep to moderate dips near the hangwall granite-sediment contact and attain near horizontal dips proximal to the footwall sediment – basement granite contact. The separation between the mineralized zones varies from 5 to 20 m. In some portions of the deposit, the steeply dipping mineralization zone merge with horizontal zones near the axial portions giving rise to a thick mineralized zone. The horizontal mineralized zones have better continuity than the steeply dipping ones. In the sheared granite, uranium mineralization occurs about 5 to 20m below the unconformity. Few fractures in the hangwall granite are also mineralized but have restricted extent.

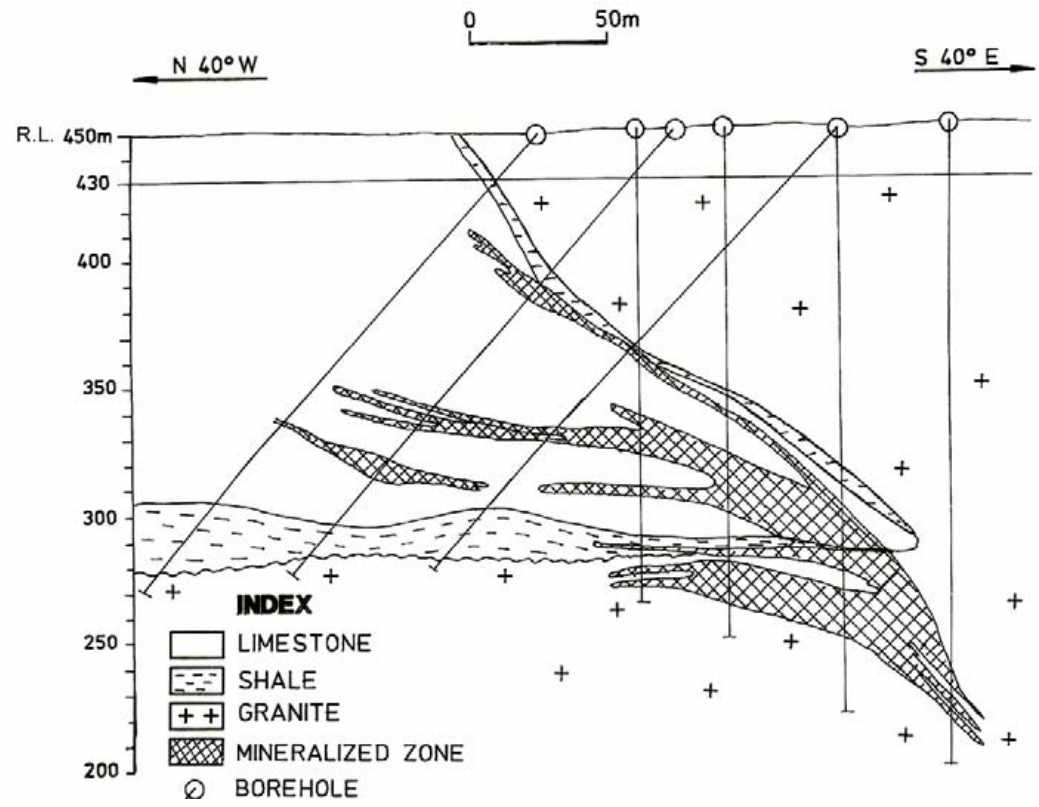

FIG. 3. Idealised cross section across Gogi uranium deposit.

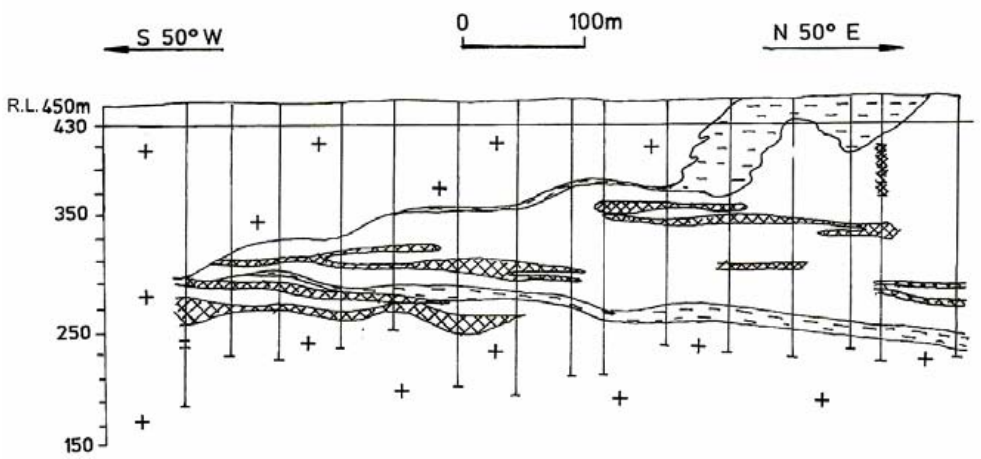

FIG. 4. Longitudinal section along Gogi uranium deposit.

5.4. Host rock petrology and mineralogy

The mineralized limestone is light to dark coloured, fine grained, compact, brecciated and contains calcite, chert, carbonaceous matter, clay (illite and smectite), sulphides and limonite, together with accessory glauconite and barite. The carbonate mineral is ferron calcite that is both primary and secondary. The primary calcite (40-60 vol %) is fractured, mainly micritic. The secondary type occurs as large anhedral and subhedral grains along the fractures of primary calcite. Organic matter is migratory type. Radioactive phases are coffinite and pitchblende occurring as veins, veinlets and fracture fillings intimately associated with carbonaceous matter and sulphides. Two generations of pitchblende have been identified. Among the sulphides pyrite is most dominant with minor amounts of marcasite, chalcopyrite and galena [9]. The whole rock chemistry of the mineralized limestone and the trace element concentration is given in Table II.

The mineralized granite is deformed pink and grey biotite (± hornblende) granite – granodiorite with cataclastic texture, having numerous fractures filled with calcite and occasional fluorite. It comprises mainly of quartz, sodic plagioclase, microcline and microcline perthite with minor to major amount of biotite, minor hornblende and accessory zircon, apatite, allanite, carbonaceous matter and sulphides, besides anatase ilmenite and limonite. Radioactivity is mainly due to coffinite and minor pitchblende with lesser contribution from U-Ti complex. The uranium minerals occur as veins, veinlets and fracture fillings. Sulphides comprise mainly pyrite with minor amount of marcasite arseno-pyrite, chalcopyrite and galena. The major oxide and trace element content of the mineralized granites is given in Table II.

Table II. Whole rock chemistry of mineralized limestone and granite

Sample No.	Mineralized limestone					Mineralized granite				
SiO_2	12.84	10.5	18.28	6.22	17.70	69.78	70.15	70.29	70.68	71.97
TiO_2	0.14	0.16	0.12	0.02	0.16	0.50	0.44	0.46	0.50	0.05
Al_2O_3	2.65	2.45	3.18	1.35	3.48	14.93	14.17	13.97	13.64	13.51
Fe_2O_3	1.14	1.70	0.78	0.30	0.68	-	-	-	-	-
FeO	0.56	0.50	0.65	0.36	0.68	5.12	4.04	4.67	5.21	1.82
MnO	0.18	0.20	0.18	0.10	0.15	0.04	0.04	0.04	0.05	<0.01
MgO	1.30	1.05	1.36	0.56	1.30	2.55	3.17	3.09	3.44	0.46
CaO	43.72	49.40	41.64	50.66	38.86	0.92	0.53	0.47	1.09	0.39
Na_2O	0.26	0.50	0.28	0.68	0.46	4.46	4.79	3.94	4.18	1.28
K_2O	0.78	0.66	0.90	0.32	0.94	2.58	2.71	2.91	1.26	8.70
P_2O_5	0.36	0.35	0.32	0.22	0.42	0.10	0.09	0.10	0.11	0.26
LOI	33.75	33.15	32.50	37.50	32.50	-	-	-	-	-
Ba	N.D	N.D	N.D	N.D	N.D	604	425	566	233	664
Sr	N.D	N.D	N.D	N.D	N.D	151	124	105	132	86
Cu	78	74	52	14	34	27	22	18	31	17
Pb	40	30	53	61	79	29	31	25	27	27
Zn	N.D	N.D	N.D	N.D	N.D	77	39	43	97	35
As	N.D	N.D	N.D	N.D	N.D	5	<5	<5	7	<5
Co	28	26	13	14	<10	11	10	11	11	10
Ni	17	19	18	11	10	54	49	37	47	9
V	58	99	86	131	103	68	70	70	73	<5
Cr	<25	<25	<25	<25	<25	89	84	69	100	28
Y	N.D	N.D	N.D	N.D	N.D	8	10	11	17	18
Ce	N.D	N.D	N.D	N.D	N.D	60	<50	351	<50	123
Zr	39	39	36	<25	58	168	180	198	156	77
Nb	N.D	N.D	N.D	N.D	N.D	6	8	<5	8	<5
Rb/Sr	N.D	N.D	N.D	N.D	N.D	0.69	0.83	1	0.70	3
K/Rb	N.D	N.D	N.D	N.D	N.D	206	218	232	114	280

N.D. : Not determined [Source: Ref.9]

Data of Electron Probe Micro Analysis of the radioactive phases viz., pitchblende, coffinite, U-Ti complex, hosted in brecciated limestone and granite of the Gogi area are given in Table III.

Examination of the data (Table III) indicates the following features in different radioactive phases.

Pitchblende:

(i) Pitchblende in limestone compared to that in granite contains higher UO_2, PbO, Y_2O_3 and FeO and lower SiO_2 and Ln_2O_3, Th is negligible in both.

(ii) The silica value indicates coffinitisation of pitchblende in the granite ore.

(iii) CaO, Al_2O_3 and Ln_2O_3 in the pitchblendes of granite ore closely follow SiO_2. The enrichment might have taken place during coffinitisation of the pitchblende.

Table III. EPMA data for radioactive phase – Gogi area [9]

	PITCHBLENDE		COFFINITE		U-Ti Complex
	In limestone (n=9) Average	In granite (n=14) Average	In limestone (n=16) Average	In granite (n=20) Average	In granite (n=6) Average
SiO_2	2.73	7.28	10.34	15.64	8.36
TiO_2	N.D	0.57	N.D	0.58	42.00
Al_2O_3	0.53	0.63	1.81	1.20	1.55
FeO	1.04	0.24	0.62	0.11	1.86
MnO	0.10	N.D	0.06	N.D	N.D
MgO	N.D	0.13	N.D	0.13	0.09
CaO	1.64	2.32	2.21	1.45	1.81
Na_2O	0.13	N.D	0.28	N.D	N.D
P_2O_5	0.23	0.08	0.53	0.52	0.32
UO_2	83.91	80.24	77.93	71.47	41.35
ThO_2	0.04	0.04	0.02	0.06	0.37
PbO	6.28	2.48	3.20	1.27	0.04
La_2O_3	0.05	0.29	0.03	0.15	0.11
Ce_2O_3	0.22	1.17	0.05	1.54	0.56
Pr_2O_3	0.03	0.04	0.03	0.21	0.20
Nd_2O_3	0.13	0.25	0.05	0.92	1.06
Sm_2O_3	N.D	0.10	N.D	0.18	0.14
Gd_2O_3	N.D	0.12	N.D	0.14	0.22
Er_2O_3	0.10	N.D	0.12	N.D	N.D
Yb_2O_3	N.D	0.09	N.D	0.14	0.09
Y_2O_3	0.13	0.03	0.01	0.52	0.33
Total	**97.28**	**96.09**	**97.30**	**96.23**	**99.94**
Ln_2O_3	0.51	2.05	0.28	3.80	2.39
Chem Age (Ma)	533	226	300	126	7

Coffinite:

(i) Coffinite from limestone compared to that from granite is characterized by higher content of UO_2, PbO, FeO and lower content of SiO_2 and Ln_2O_3 with negligible ThO_2 in both.

(ii) Coffinite from granites contain many orders more of all REEs (LREE > HREE) including Y, in contrast to that in limestone.

U-Ti Complex:

(i) This phase is present only in the granite ore and is marked by wide range in the concentration of major elements U, Ti and Si, indicating that it is a complex of U-Ti-Si rather than brannerite, which has a restricted range of composition.

(ii) The U-Ti complex has very low content of ThO_2 and negligible PbO. The replacement of pitchblende and coffinite by U-Ti Complex support its formations due to Pronto reaction.

(iii) Like pitchblende and coffinite, U-Ti complex contains impurities of Al, Fe, Mn, Ca and P.

(iv) The U-Ti complex also shows notable concentration of REEs with LREE >HREE.

6. Uranium potential of Bhima basin and future targets

Bhima basin has been an important target for uranium exploration among the Proterozoic basins of peninsular India since 1995. Establishment of a medium-grade/low-tonnage, structural/ fracture-controlled uranium deposit at Gogi has enhanced the significance of the basin further. Some of the boreholes drilled in Gogi area intercepted high-grade and thick uranium mineralized zones e.g., 0.25% U_3O_8 x 20.48 m in limestone, 0.48% U_3O_8 x 16.82 m in granite. Besides Gogi, a number of surface uranium occurrences have been reported along the prominent E-W trending Gogi – Kurlagere fault zone which extends over a length of more than 30 km. It has been observed from the present data that the entire Gogi – Kurlagere fault is a reverse fault and forms potential target requiring detailed investigation as only a limited sub-surface drilling has been done at Gogi. The other significant uranium occurrences located as on date is at Ramtirth associated with altered phosphatic limestone and Kasturpalli hosted in glauconitic shale and siltstone. The NW-SE Wadi fault zone, along which the Ramtirth uranium occurrence is located, is the next important target.

Regional hydrogeochemical survey carried out recently over a large area of Bhima basin has indicated several significant hydrouranium anomalous zones of varying dimensions. The important hydrouranium anomalous zones are located in (i) Wadi, (ii) Sedam, (iii) Santi and (iv) Tintini areas (Fig.5). These hydrouranium anomalies are confined to prominent NW-SE, NS and EW structural zones and the samples analysed upto 3 562 ppb uranium [14, 15]. The eastern part of Bhima basin with more number of hydrouranium anomalous zones is important for further investigations.

The uranium occurrence of Tintini hosted in diabase cataclasite along the prominent EW fault is an important segment, as this fault transects the basement rocks as well as the Bhima sediments. Besides, there are a number of minor uranium occurrences in the area between Tirth-Tintini fault and parallel Hunsagi – Devatkal fault in the north [16].

Airborne Gamma-ray Spectrometric (AGRS) and magnetic survey was conducted over Bhima basin covering 16 330 line kms. Most of the known ground anomalies have been registered in the surveys, which were picked up at 5 ppm uranium threshold. Considering all these facts and 5 ppm uranium (mean + 2 SD) as threshold value, 22 targets have been delineated [17, 18]. The priority areas fall near Sedam, Habbal Buzurg, Chitapur and Ramtirth. The integrated study of the data indicates that the eastern part of Bhima basin is more promising. AGRS data interpreted together with hydrogeochemical data, their convergence marks high priority targets.

Apart from the above sectors there are many other prominent structurally disturbed areas which have the favourable factors for uranium exploration. If considered together the metalogeny of this region with a number of gold and copper mines and numerous uranium occurrences in the basement rocks, all the faults/shears reactivated time and again forms potential targets for structurally-controlled uranium mineralization. To sum up, Bhima basin has got immense potential for discovery of new uranium deposit.

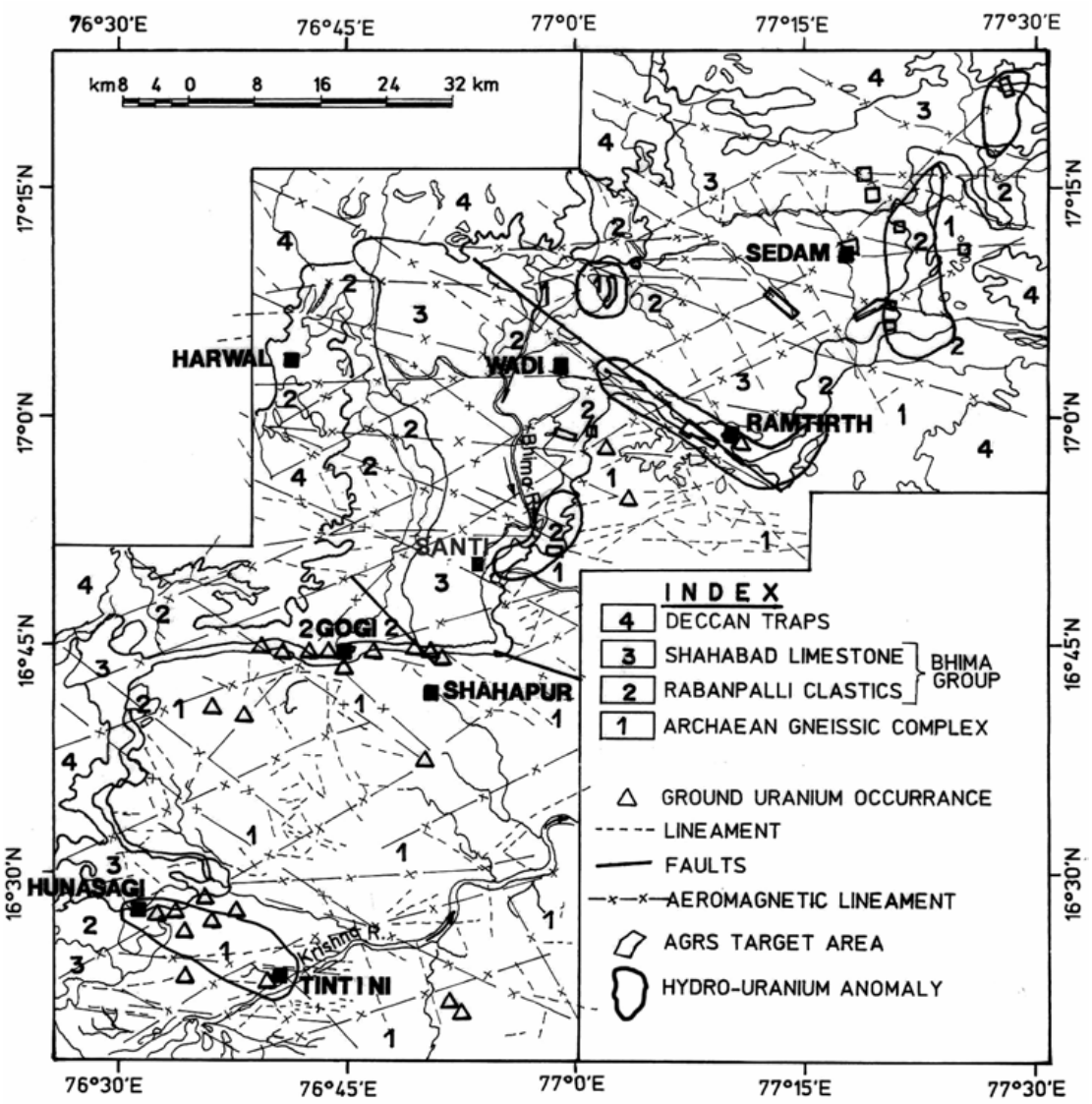

FIG. 5. Integrated thematic map of Bhima Basin showing target areas for uranium exploration.

7. Conclusion

Bhima basin once a least priority area for uranium exploration has secured a place in the uranium map of India. The systematic integrated exploration programme was responsible for the success. Though initially, the exploration was driven by unconformity model, sooner it was realized that the area holds good for structurally-controlled epigenetic mineralization as established at Gogi. Medium-grade, low-tonnage uranium deposit at Gogi is testimony to the uranium mineralization process in the area which will not occur in isolation. Occurrence of all the known surface mineralization, hydrouranium anomalous zones and the target selected by AGRS survey are confined to prominent structural zones. High uranium values recorded in numerous hydrogeochemical samples in the eastern part of Bhima basin is significant and is of great help in an otherwise mainly horizontally disposed undeformed limestone, shale terrain. Hence all the prominent structures in the Bhima basin needs exploration input to bring out more number of uranium deposits.

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A global radioelement baseline for gamma-ray spectrometric data

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Abstract. A global radioelement baseline for gamma-ray spectrometric data requires that all gamma-ray data be acquired and processed in a globally consistent way. This will ensure that all radioelement estimates are tied to (or are consistent with) agreed reference standards. We recommend a set of procedures for the establishment of a global radioelement baseline for gamma-ray spectrometric data based on the reference standards used for laboratory gamma-ray spectrometry issued by the IAEA Seibersdorf Laboratory in Austria. If these procedures are followed, then gamma-ray spectrometric survey data will be both internally consistent and comparable between surveys. This will greatly enhance the usefulness of these data in areas such as environmental management, regulatory requirements and the sustainable development of the earth's resources.

1. Introduction

The existing "global" gamma-ray spectrometry coverage has been acquired over several decades. The calibration and data processing of older survey data was inadequate by modern standards. Poor background estimation, in particular, has resulted in poor accuracy of the estimated radioelement concentrations. Much of the older data are recorded in units of counts/sec (rather than radioelement concentrations), and the data values are therefore dependent on the instrument detector volumes, the survey height and the window energy limits used to measure the gamma radiation. Thus, data values from different surveys are not directly comparable. These problems, unless successfully addressed, limit the usefulness of radioelement data derived from airborne and ground gamma-ray surveys.

A radioelement baseline is a set of radioelement measurements that conform to some standard, and depict the concentration of the radioelements at the earth's surface at some point in time. A global radioelement baseline for gamma-ray spectrometric data requires that all gamma-ray data be acquired and processed in a consistent way. This will ensure that all radioelement estimates are tied to (or are consistent with) agreed reference standards. The primary reference standards are the geological reference materials for laboratory gamma-ray spectrometry issued by the IAEA Seibersdorf Laboratory, Austria, in 1987 [1]. Two essential ingredients underpin a global radioelement baseline for gamma-ray spectrometric data:

- a global network of radioelement standards that can be used for the calibration of gamma-ray instruments; and
- a set of standard procedures for the acquisition and processing of radioelement data.

If approved instrument calibration facilities are used and the standard procedures are followed, then gamma-ray spectrometric survey data will be both internally consistent and comparable between

surveys. This will greatly enhance the usefulness of these data in areas such as environmental management, regulatory requirements and the sustainable development of the earth's resources.

2. Benefits of a global radioelement baseline

There are many benefits of registering gamma-ray spectrometric data to a globally consistent baseline. Examples include:

Identification of uranium provinces. The assembly of baselines on a regional and global scale, where the concentrations of the radioelements are well standardized, plays a critical role in regional comparison and recognizing new uranium provinces.

Detection of uranium deposits. The search for buried deposits, or those with subtle, indirect signatures, often rely on the use of calibrated data, particularly when numerical interpretation techniques are applied, radioelement ratios are employed, or comparison with similar deposits is required.

The physical properties of uranium make it a difficult geophysical exploration target. Uranium ore bodies do not normally exhibit electrical, magnetic or gravity anomalies. Uranium radioactivity is usually the only detectable physical property. Field prospecting for uranium using gamma ray methods are limited by the low penetration depth (0.5 m) of gamma rays in rocks, and the statistical nature of radioactive decay which results in large errors in the estimates of radioelement abundances [2]. Due to attenuation of gamma-rays in the ground and air with distance, the detection of small, high-grade uranium sources is more difficult than the detection of extensive low-radioactivity areas. Thus, gamma-ray methods can often be used to identify broad alteration zones, which can be used to focus the exploration effort.

Subsurface uranium mineralization may also be detected by the presence of mechanical, salt and gaseous halos in their vicinity. A typical feature of these halos at the earth surface is subtle, elliptical uranium anomalies in the range 4-20 ppm eU. Their detection requires good quality data that has been effectively processed. The proper calibration of radiometric instruments on well established and verified calibration facilities is a precondition for the application of the gamma-ray method to uranium exploration.

Uranium resource evaluation. Calibrated gamma-ray spectrometry is used to estimate in-situ ore grades in boreholes, or uranium content of ores at various stages of crushing, sorting and milling.

The uranium reserves of subsurface deposits are based on estimates of the volume and grade of the mineralized body. While borehole gamma logs provide information on the thickness and extension of uranium mineralized zones, ore grade estimates require a rigorous interpretation of the data. This interpretation must consider the geological setting, the measurement technique and a series of corrections that must be applied to the data [2, 3]. Proper calibration of borehole logging equipment is essential. The processing of gamma-ray logs for ore grade evaluation is based on a comparison of measured count rates with similar signals registered in a borehole calibration facility of known uranium concentration. Borehole calibration facilities have been constructed in several countries [3-5]. A comparison of these facilities – a crucial first step in the establishment of a baseline, was carried out by Killeen [3].

Both total count and gamma-ray spectrometry measurements are indirect measures of uranium concentration [2]. The accuracy of ore reserve estimates using these methods is based on the assumption of radioactive equilibrium in the U decay series. Several borehole methods of directly estimating U concentration, such as X-ray fluorescence techniques and uranium fission by neutrons, were developed in the 1970´s [2].

Estimation of natural background and contamination of uranium mine and mill waste sites. Radioelement baseline studies play a critical role throughout the uranium production cycle to

determine the background levels of radiation, monitor changes in radiation over time, and to verify site remediation.

Uranium mining and milling involves disruption of the land surface, removal and transportation of large volumes of rock material, extraction of uranium from the ore and deposition of waste material. Waste rock dumps and tailings impoundments, which amount to millions of cubic metres by volume, may pollute soil, surface and underground water, and the atmosphere. A joint NEA/IAEA publication [6] gives a comprehensive review of the environmental aspects of the uranium production cycle. A few selected examples from the literature are given here.

Mapping the extent of uranium waste rock dumps and tailings is described by Thoste [7]. Uranium mining and ore processing in Saxony and Thuringia, Germany, resulted in 26 million tonnes of waste rocks, 175 million tonnes of tailings, and affected an area of 37 km^2. Radiation levels over the Jaduguda mine, eastern India, are typical for many uranium cycle facilities [8]. Tailing ponds, with a total area of 80 ha, and a ^{226}Ra specific activity of 5 000 – 8 500 Bq/kg, exhibit gamma dose rates of 2 500 – 4 000 nGy/h at the surface. Enhanced atmospheric radon concentrations of 30 Bq/m^3 over tailings and 10 – 15 Bq/m^3 close to the tailings pond boundary were measured. Facilities at Priargunsky U mining and processing centre, Russia [9], include 49 millions m^3 of mill tailings over a 377 ha area, with a specific activity of 1 100 – 27 700 Bq/kg. Gamma dose rate of 500 – 2 100 nGy/h, monitored in the area of contamination, decreases to 200 nGy/h at a distance of 200 – 250 m.

A comprehensive baseline study of uranium production facilities in the Czech Republic, and the effectiveness of remediation efforts, illustrates the use of gamma-ray spectrometric data for environmental purposes [10, 11]. Uranium mining in the Czech Republic over the past 50 years has resulted in 1 700 waste rock dumps, 800 mining shafts, 16 open pits and 16 large tailings impoundments. Waste rock dumps exhibit a dose rate mostly in the range 80 – 1 000 nGy/h, and U concentration generally in the range of 20 – 50 ppm eU. The highest radiation detected (up to 4 200 nGy/h and specific activity 1 000 Bg/kg ^{226}Ra) was measured over a uranium processing tailings impoundment at the Stráž deposit. Covering the highly radioactive wastes with a 0.8 m thick low radioactivity rock layer reduced the surface radiation to 260 – 350 nGy/h. Long-term uranium mining activities have also led to the contamination of some river sediments (the river Ploučnice). The radioactivity of the natural background, cosmic radiation and man-made sources in the environment were measured for comparison (Fig. 1). Conversion of observed high radiation values to effective dose, which determines the effect on populations, requires reliable radiation data based on baselines.

Assessment of environmental radiation. Standardized radiometric data, expressed in radioelement concentrations and gamma dose rate units, can be used for assessment of environmental radiation doses and the appraisal of local building materials. Calibrated radiometric instruments provide data on environmental gamma dose rates (nGy/h). Conversion constants for gamma dose rates 1 m above a plane and infinite homogeneous rock medium per unit K, U and Th concentrations are given in [2].

Radiation levels differ significantly in the natural environment and in areas of uranium production. The sum of terrestrial and cosmic radiation is typically in the range of 50 – 150 (250) nGy/h. This corresponds to annual effective doses of 0.3 – 0.9 (1.5) mSv. Highly radioactive uranium products and wastes yield dose rates of thousands of nGy/h [12]. Control of exposure time in uranium producing areas reduces absorbed doses to acceptable levels in a range up to 6 mSv per year [12]. This is comparable to globally accepted limits for absorbed doses of professional workers in radiation facilities [6].

The radioactivity of building materials is assessed by measuring the specific activity of K, U (source of radon ^{222}Rn) and Th by laboratory gamma-ray spectrometry. Calibrated portable gamma-ray spectrometers can be used for the in-situ measurement of the radioactivity of building material deposits, such as in quarries.

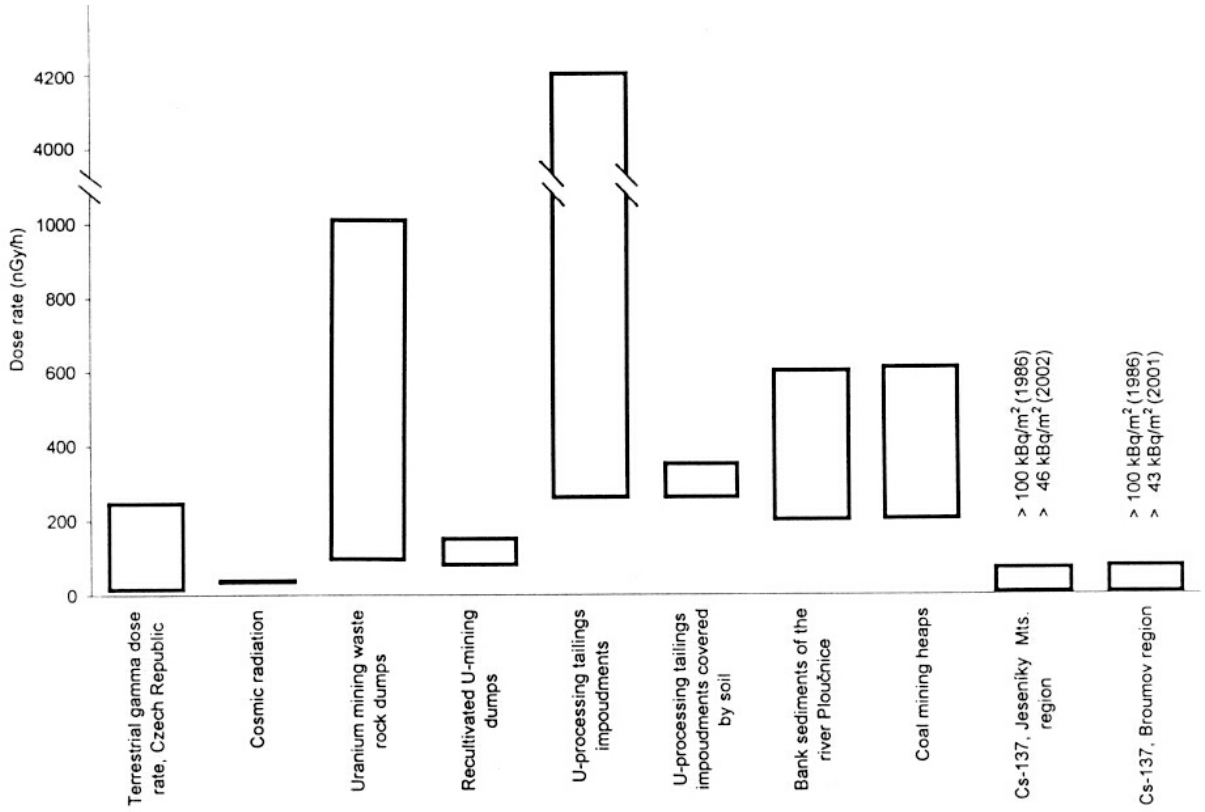

FIG. 1. Gamma dose rate of natural and man-made sources in the Czech Republic.

Geochemical baselines. The global radioelement baseline forms a component of the global geochemical baseline. Calibrated gamma-ray spectrometry is a useful tool for levelling between disparate geochemical surveys. Airborne gamma-ray spectrometry can provide a continuous, quantitative measurement of the K, U and Th contents across regions and countries. This can be used for comparisons and geochemical data levelling. Thorium, which is contained in resistant minerals, provides the most reliable reference level [13].

3. Registering new surveys to a global radioelement baseline

Comprehensive descriptions of the standards and procedures for the calibration of both airborne and portable spectrometers, and the processing of these data, can be found in IAEA publications [2, 14]. If these standards and procedures are followed, then surveys conducted with these instruments will be registered to a global radioelement baseline. Some of the more important considerations are discussed here.

Stripping ratios and sensitivity constants for portable instruments should be determined on well-maintained calibration pads whose radioelement concentrations are rigorously tied to primary reference standards.

Because airborne instrument sensitivities are a function of the height of the detector, they cannot be determined from measurements on calibration pads. Instead, they are estimated indirectly through the use of a calibration range. At the same time as the calibration range is flown, a calibrated portable spectrometer is used to measure the concentrations of the radioelements along the calibration range. This allows changing radiation output from the ground due to soil moisture and other environmental factors to be accommodated.

Inadequate atmospheric radon background removal can introduce systematic biases into airborne gamma-ray data. Inaccurate estimation of the K, U and Th sensitivity coefficients during calibration also introduces a bias. Again, the presence of atmospheric radon is often the source of the problem. A

methodology for testing and overcoming this problem using K and Th values to derive expected values for U can be found in [15].

Instrument sensitivity and height attenuation coefficients are derived using a source geometry approximating a radioactive half-space. Rugged terrain can lead to significant errors in both portable and airborne gamma-ray surveys. Trees, vegetation and other absorbers such as leaf litter on forest floors can significantly attenuate radiation. Soil moisture has a similar effect. Test lines flown at the start and end of each day's flying do not always reflect conditions over the entire area flown. Systematic flying of all tie-lines in as short period as possible offers a dataset for levelling of any residual inconsistencies.

4. Registering old surveys to a global radioelement baseline

Gamma-ray data from many older surveys were reported in units of counts/sec. They are thus functions of detection equipment and the acquisition parameters – detector type, detector volume, window energy limits and survey height all affect the observed count rates.

However, these older, non-standardized data can be back-calibrated. The principle of back-calibration is based on the comparison of the original K, U and Th window count rates with ground radioelement concentrations measured with a well calibrated portable spectrometer. Comparison is repeated for several sites – each homogeneously radioactive but with different radioactivity levels between sites. Instrument sensitivity coefficients are then derived as the ratios of the average fully-corrected energy window count rates to the average radioelement concentrations measured with a portable spectrometer over selected site. These sensitivities are then used to convert the original window count rates to radioelement concentrations [2].

5. Calibration facilities

Some 40 or more sets of specifically constructed pads located in 22 different countries are available for the calibration of ground and airborne gamma-ray spectrometers [16]. A calibration facility consists of four pads, three of which are, separately, enriched in K, U and Th. Ideally, all calibration pads should be tied to the global IAEA standards [1]. Three powder reference materials RGK-1, RGU-1 and RGTh-1 form a set distributed by the IAEA Seibersdorf Laboratory in 500 g masses (Fig. 2). The chosen matrix materials and the concentration of radioelements, which were analyzed in 29 renowned laboratories, comply with the need of precise calibration and laboratory gamma-ray spectrometry assays of rock samples. If calibration pad samples are measured using laboratory spectrometers calibrated by means of the Seibersdorf laboratory standards, then irrespective of which set of pads was used to calibrate a particular gamma-ray spectrometer, the results should be consistent. Some pads were constructed prior to the availability of the IAEA standards and temporal variations in radiation output have been documented for several sets of pads, particularly large stationary pads that had not been protected from moisture absorption and radon exhalation. Løvborg, under a research contract to the IAEA, compared twelve calibration facilities across ten countries. He showed that a well-calibrated portable gamma-ray spectrometer could be used to re-assign the reference K, eU and eTh grades to calibration pads to make them internationally consistent. A repeat of this exercise, incorporating all calibration facilities is now overdue.

6. Global gamma-ray spectrometric coverage

Tauchid et al., [16] present a map showing the estimated worldwide extent of airborne gamma-ray surveys, as percentage coverage in each country. In order to more realistically assess the possibility of generating a global radioelement baseline dataset, Figure 3 depicts the actual area of coverage in each country, together with an indication of the status of data calibration. The information is, as yet, incomplete but it is clear that we are approaching the position where a coordinated effort could be made to establish, verify and maintain the global radioelement baseline. Several national initiatives are already in place but further efforts are required to standardize existing surveys and improve coverage in many countries. As a first step towards assessing the existing needs, the map depicted in Fig. 3 is

accompanied by a countrywide summary of gamma-ray spectrometric data, including available details on survey specifications and calibration.

FIG. 2. IAEA standards RGK-1, RGU-1 and RGTh-1 for laboratory gamma-ray spectrometry.

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TOPIC 4 - URANIUM PRODUCTION

Cameco Corporation - the Key Lake Uranium Mill
Current status and vision for the future

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Abstract. The Key Lake mill located approximately 570 km north of Saskatoon, Saskatchewan, Canada and is currently the world's largest primary producer of uranium producing 8.5×10^6 kg U_3O_8 annually. The feed to the Key Lake mill currently originates from the McArthur River mine, an underground mine located approximately 80 kilometers north of the Key Lake mill. The McArthur River mine, located wthin the Athabasca Basin, is the world's largest high-grade uranium deposit with proven and probable reserve, as of December 31, 2003 of 190 million kg U_3O_8. Approximately 700 people are employed at Key Lake and McArthur River of which 57% of the workdforce are residents of Saskatchewan's north. The mine site and mill are remote and employees commute via air travel to and from the sites from Saskatoon, Saskatchewan as well as communities throughout northern Saskatchewan. Employees work a 7-day in/7-day out work rotation and reside in permanent camps during the work week at the mine and mill.

1. Historical operation

The Key Lake mine site is located approximately 570 kilometres north of Saskatoon, Saskatchewan, Canada on the southern boundary of the Athabasca Basin geological formation. It was originally constructed and licensed to operate as a mining and milling operation. Between 1982 and 1999, the site derived its ore from mining activities at the Gaertner and Deilmann open pit mines, located in close proximity to the mill. The grade of the ore extracted from these open pit mines ranged from 0.8-3.2% U_3O_8. Annual production at the Key Lake mill during this period ranged from 3.6 million to 6.4 million kg U_3O_8/y. During this time, tailings generated from the milling of these orebodies were placed into an above ground tailings management facility. Following completion of mining in the Deilmann pit in 1995, it was converted in to an in-pit tailings management facility with emplacement of tailings beginning in 1996. The remaining tailings from milling of Key Lake ore was emplaced in this in-pit tailings management facility.

2. Current operation

In 1999, the Key Lake mill began processing ore originating from the Cameco McArthur River mine located approximately 80 kilometres north of the Key Lake mill. The average grade of the ore in the McArthur river mine is 25% U_3O_8. The McArthur River operation is an underground uranium mine located approximately 620 kilometres north of Saskatoon, Saskatchewan in north-central Saskatchewan, Canada. The site is accessible via a publicly owened provincial highway to Key Lake and an all season haul road from Key Lake to McArthur River. The site is also accessible via an all season airstrip that is used to shuttle employees to the mine site generally on a 7 day in – 7 day out shift.

The McArthur River mine, located within the Athabasca Basin, is the world's largest, high-grade uranium deposit with proven and probable reserve, as of December 31, 2003 of 190 million kg U_3O_8. Following the initial discovery of the orebody in 1988, an underground exploration programme was initiated in 1992. The exploration was followed by the preparation of an Environmental Impact Statement and Joint Panel hearings. With the approval of the project by the federal and provincial government, the facility requested and received approval for construction in 1997. In 1999, with the

completion of construction, the McArthur River operation received federal approval to operate and necessary provincial operating permits.

The ore that is mined from the McArthur River operation is placed, in slurry form, into specially designed containers and hauled 80 km on the restricted access all season haul road to the Key Lake operation for milling. Uranium bearing waste rock (mineralized waste rock) is also shipped to the Key Lake operation for use in blending down the McArthur River ore to acceptable grades for milling. This ore is blended with McArthur River mineralized waste and Key Lake special waste and contaminated sand in order to reduce the feed grade to 4% U_3O_8 for milling. All tailings generated as a result of milling the ore and mineralized materials are deposited in the DTMF.

The mill facilities at the Key Lake operation are located in two distinct areas. The grinding and ore receiving facilities are located in close proximity to the Gaertner and Deilmann pits while the main mill facilities are approximately 1.5 km to the northwest. These two areas are connected by two covered and insulated service utilidors that contain the ore slurry, tailings slurry, water and steam pipes as well as the instrumentation system data transmission cables. The individual processing circuits within the Key Lake mill are discussed below.

2.1. Crushing

The crushing circuit is operated to crush the material that is too large to be fed directly to the semi autogenous grinding (SAG) mill. The crushing circuit consists of a gyratory crusher with a dump pocket on top and a surge bin immediately below the crusher. The broken rock is conveyed into a haul truck and transported back to the stockpile area for eventual processing through the grinding circuit. Presently the crusher is not used as the size of material to be fed to the SAG mill is sufficiently small to be directly fed into the mill.

2.2. Grinding/ore receiving/blending

The purpose of the grinding circuit is to grind low-grade material with water to produce slurry that is suitable for blending with the McArthur River ore. The grinding circuit consists of a SAG mill, ball mill, classification screens and a thickener. The final product is ground to a point where 50% of the material passes through a 75 micron screen. The ground ore slurry is then thickened to 45 to 55 percent solids and directed to the thickener underflow tank, also commonly referred to as the "blend tank".

The ore receiving facility is designed to receive high-grade ore slurry from the McArthur River operation. The slurry is removed from individual slurry shipping containers by a vacuum pump system, sampled for chemical analysis and then pumped into one of four air agitated storage pachucas. High-grade ore slurry from the pachucas is pumped to the blend tank and blended with low-grade grinding circuit slurry to produce a targeted 4% U_3O_8 leach feed grade. The resultant blended slurry is then pumped through the feed utilidor to the ore storage pachucas contained in the leaching circuit.

2.3. Leaching/counter current decantation

The purpose of the leaching/counter current decantation (CCD) circuit is to dissolve the uranium in the ore and to separate the uranium-bearing solution from the waste solids or residue. This is achieved by treating the ore with sulphuric acid and steam under oxidizing conditions through a series of atmospheric pressure and autoclave style leach vessels. Oxygen is produced on site in a 35 tonnes per day cryogenic oxygen plant for addition to the leaching circuit to produce the required oxidizing conditions.

The slurry is leached using 93% sulfuric acid and 99% oxygen as the oxidant (Eh maintained at +610 mV at the end of the leaching process). The temperature of the leach slurry is maintained at 60ºC through the addition of steam. The leaching process presently involves a combination of atmospheric

(100 kPa) and autoclave pressure leaching (640 kPa) that results in >99.5% extraction efficiency of uranium from the host rock (along with impurities such as As, Ni, Fe, Mo, Se and Ra-226).

An eight-thickener counter current decantation circuit separates the acidic uranium-bearing leach solution from the waste solids or leach residue. Water originating from a contaminated water reservoir is added to the CCD circuit as wash water for this process. The leaching/CCD circuit produces a pregnant solution that contains dissolved uranium and metal contaminants. The concentration of uranium in this pregnant aqueous solution ranges from 12-14 g U_3O_8/l. This solution is then sent to solvent extraction while the leached waste solids are pumped to the tailings area for treatment and pumping to the Deilmann Tailings Management Facility.

In recent years Cameco has been assessing the potential to change from atmospheric and pressure leach to a full atmospheric leach circuit. Full atomospheric leaching would result in a less aggressive leach with less impurities being leached. Additional benefits include reduced maintenance and radiation exposure associated with the current autoclave leaching circuit.

2.4. Solvent extraction

The purpose of the solvent extraction (SX) circuit is to purify and concentrate the uranium contained in the pregnant aqueous solution. The solvent extraction plant consists of two independent circuits, one for uranium recovery and one for molybdenum removal from the product stream. The molybdenum removal circuit operates as required when high molybdenum levels are present in the ore. Currently the molybdenum plant is not being used due to the lower observed concentrations of molybdenum in the ore.

The pregnant aqueous solution from the counter current decantation circuit is fed to the extraction circuit. An organic phase composed of kerosene, isodecanol and amine, is used to selectively extract uranium from the pregnant solution is a series of three mixer-settlers. The uranium depleted aqueous solution, now referred to as raffinate, is pumped to bulk neutralization for treament. The organic phase is now referred to as loaded organic. The concentration of uranium in the loaded organic solution ranges from 10-12 g U_3O_8/l.

The loaded organic solution from the extraction cells is scrubbed in a series of three mixer-settlers with dilute acid to remove any arsenic that may have been extracted with the uranium. The spent acid scrub solution is returned to extraction cells while the scrubbed loaded organic solution flows to the stripping cells.

The uranium is stripped from the scrubbed loaded organic in a series of four mixer-settler stages using an ammonium sulphate solution and ammonia gas to control the circuit pH. The resulting loaded strip solution containing the stripped uranium (130-140 g U_3O_8/l) is then pumped to a storage tank ahead of the molybdenum circuit while the barren organic solution (free of uranium) flows to the ammonia scrub cells.

Water is used in the ammonia scrub cells to remove any physically entrained strip solution that may have carried over in the barren organic solution from the stripping circuit. The spent scrub solution is pumped to the yellowcake circuit to be used as wash water for the yellowcake centrifuge circuit while the barren organic is reused in extraction cells at the front end of the solvent extraction circuit. A regeneration mixer-settler between the ammonia scrub stage and the barren-organic tank is used to scrub the organic solution for the removal of residual molybdenum.

When required, the loaded strip solution is treated for molybdenum removal in the molybdenum circuit prior to being pumped to yellowcake precipitation. The organic in this process is made up of kerosene and a molybdenum extractant. This process consists of two kerosene scrub mixer-settlers, two molybdenum extraction mixer-settlers, a molybdenium wash unit, and a single molybdenum strip unit. The purified loaded strip solution is then pumped to the yellowcake precipitation circuit while the molybdenum-bearing waste solution is pumped to the tailings management circuit.

2.5. Yellowcake precipitation

The purpose of the yellowcake precipitation circuit is to recover dissolved uranium from the purified loaded strip solution. The resultant barren-strip solution (the solution remaining after the uranium is removed) is re-used as strip solution is solvent extraction, with excess volumes serving as feed for the ammonium sulphate crystallization circuit. The yellowcake precipitation circuit consists of an agitated precipitation tank, a thickener, a sand filter and a storage tank for the barren-strip solution.

The loaded strip solution from the solvent extraction circuit is fed into the precipitation tank. Ammonia gas is added to the solution to maintain a pH of 7.2 and to precipitate uranium as ammonium diuranate. The resultant precipitate slurry is fed to the yellowcake thickener where it settles to 50 percent solids slurry. This thickened slurry is pumped to the yellowcake centrifuge for dewatering before entering the calciner.

The thickener overflow passes through a sand filter to remove any residual fine yellowcake particles. The solids are then returned to the precipitation circuit by backwashing the filter while the filtrate is pumped to the barren strip surge tank for re-use in solvent extraction or sent to the ammonium sulphate crystallization circuit for ammonia recovery.

2.6. Calcining/packaging

The purpose of the calcining/packaging circuit is to convert the ammonium diuranate to uranium oxide (U_3O_8) and package the product into drums for shipment to a refinery. The calcining circuit consists of a centrifuge, a six hearth calciner (or furnace), a trommel disintegrator, a Luxme conveyer, a product storage bin, a drum packing station, and associated gas collection and scrubbing equipment.

The yellowcake slurry from the thickener is fed to the centrifuge for dewatering. The centrate (water) is returned to the yellowcake thickener. The centrifuge cake is forwarded to the calciner where it is converted to uranium oxide (U_3O_8) in a calciner, operating at 840 degrees Celsius. The calciner discharge is passed through a rotating trommel screen to break any lumps and is conveyed to a product storage bin and later packed in 200 litre steel drums. In the past the packaged yellowcake drums were stored outside, however in 2004 a yellowcake drum storage building was installed for sheltered product storage and loading into vans for transport.

In 1999, Key Lake installed an upgraded gas scrubbing system for cleaning the calciner off-gas and reducing emissions. This scrubber consists of a quench tower venturi scrubber, adsorption scrubber, variable speed fan, and a candle mist eliminator. Subsequent testing of the air discharge showed a significant decrease in soluble particulate content compared to the previous scrubber. In early 2005, a major upgrade to the yellowcake packaging system also took place. This consisted of the complete containment of the packing system, improved filling stations, improved lid station and an automated washing sytem. Later in 2005, the existing baghouse air filtering system will be replaced with a venturi scrubber system.

2.7. Ammonium sulphate crystallization

The purpose of the crystallization circuit is to recover the ammonia from the Key Lake milling processes through the conversion of excess barren-strip solution to crystallized ammonium sulphate fertilizer.

The ammonium sulphate crystallization circuit consists of two evaporators, a crystallizer, a pusher centrifuge, a fluid bed dryer and a dust scrubber. The product from the plant is conveyed to storage bins located outside the building where it which must meet Agriculture Canada quality specifications, prior to being loaded into trucks and shipped to a distributor in southern Saskatchewan.

The barren-strip solution feed passes through the evaporators where water is removed to produce a saturated ammonium sulphate solution. The solution is then fed to the crystallizer where further

evaporation takes place and a supersaturated solution is produced. This process results in crystal formation and growth with the crystals being withdrwan from the crystallizer as slurry and fed to a centrigue for dewatering. The dewatered crystals are then fed to the fluid bed dryer. The vapour from the crystallizer and evaporators is condensed and used as wash water in the acid and ammonia scrub mixers in solvent extraction and as wash water in the yellowcake centrifuge feed tank.

2.8. Waste management

2.8.1. Waste rock management

Waste rock generated from underground mining activities is managed according to each site's waste management programme. The waste rock is classified as clean, mineralized, or potentially acid generating and the storage location for each type. Clean waste rock is placed on an unlined storage, due to the benign nature of the waste rock. Potenitally acid generating waste rock is stored on lined storage pads to ensure containment of potentially acid drainage.

Mineralized waste rock is also placed on a lined storage pad for environmental containment. This waste rock is not permanently stored at the McArthur River operation but is shipped to the Key Lake operation and used as blend material for the dilution of the high grade McArthur River ore. The need to comply with surface storage volume constraints will dictate the rate of transport of the mineralized waste rock from McArthur River to Key Lake during any given period. At the Key Lake operation the waste rock is placed on a lined pad where it is later used to assist in blending down the McArthur River ore slurry.

2.8.2. Tailings management

Prior to 1996, tailings were discharged into the Above Ground Tailings Management Facility (AGTMF). In 1996, the tailings deposition was changed over to the Deilmann Tailings Management Facility (DTMF). Following this change, the AGTMF has only been used to dispose of contaminated debris on the tailings surface, under a sand layer.

Currently the solid leach residues and water treatment plant precipitates are combined (referred to simply as tailings), neutralized to pH 11 with lime and pumped to the DTMF thickener where the percent solids is increased to a density of 35%. The thickened tailings are pumped to the tailings distribution system and discharged into the DTMF through one of several discharge pipes or through the floating tailings deposition barge.

The DTMF is located 2.5 km east of the Key Lake mill in the mined-our Deilmann open pit which is approximately 1 300 m long, 600 m wide and 170 m deep. The lower portion of the Deilmann pit walls is comprised of basement rocks of very low permeability, overlain by sandsotone with somewhat higher permeability. The upper pit walls consist predominantly of outwash sand with a very high permeability. Due to this permeability distribution in the geologic units, more than 99% of the natural groundwater flow at the Deilmann pit occurs at relatively low hydraulic gradients in the highly permeable outwash sands. These site-specific conditions make the Deilmann pit well suited to the tailings "plug" concept, whereby a high-density/low-permeability tailings deposit is developed. The "plug" concept, combined with the natural benefits of a low hydraulic gradient and high groundwater bypass flow, results in very low flows through the tailings, without the need for a surrounding man-made gravel/sand envelope.

An underdrain/partial side drain system, including a seepage recovery tunnel/pumping station, was installed in the basement portion of the pit to optimize porewater recovery from the tailings for treatment in the Key Lake mill. This approach also results in a further improvement of the tailings "plug" characteristics, through enhanced tailings consolidation and reduced tailings permeability.

In recent years the DTMF has been in a controlled flood to allow the water level to reach the operating level of 510 masl. As of February 2005 the water level in the DTMF was at approximately 496.9 masl.

The controlled rate of pit flooding has been slower than originally planned due to the flooding related pit wall sloughing along the northwest corner of the DTMF. As a result of the sloughing, the flooding rate had to be reduced and portions of the tailings piping and utilidor system required relocation away from the pit crest.

Once the flooding of the DTMF to the operating level of 510 masl is complete (estimated in 2006 or 2007) pumping from the DTMF underdrain system together with pumping from a barge and/or selected peripheral wells will continue to maintain a positive hydraulic gradient or "cone of groundwater depression" towards the DTMF. This will in turn assure hydraulic containment of the tailings porewater within the code of depression.

2.9. Water management

2.9.1. Bulk neutralization – mill effluent

The purpose of the bulk neutralization circuit is to treat contaminated waters collected or generated throughout the site to produce an effluent acceptable for discharge and to produce tailings suitable for deposition in the DTMF. The primary sources of contaminated water are: (i) raffinate from the solvent extraction circuit, (ii) dewatering activities, seepage/runoff from surfaces sources (including stockpiles), and the reject steam from the Reverse Osmosis (RO) plant which is stored in Reservoir #1 prior to treatment and (iii) tailings management facilities, runoff, and recylced off-specification effluent, which are stored in Reservoir #2 prior to treatment.

Raffinate from solvent extraction and contaminated water from the reservoirs in excess of mill requirements are combined and treated in the bulk neutralization circuit. The circuit configuration consists of three main sections: raffinate neutralization/radium-226 removal, pH adjustment and tailings neutralization and pumping. The raffinate neutralization/Ra-226 removal circuit consists of four neutralization pachucas and a bulk neutralization thickener. Lime is added to raise the pH to 9.2. Barium chloride is also added to facilitate the precipitation of Ra-226 as a Ra/Ba-SO_4 co-precipitate. The resulting chemical precipitates are settled in a lamella type thickener. The clear overflow solution from the thickener flows through three pH adjustment tanks where the pH of the effluent is incrementally reduced to pH 6.5 using dilute sulphuric acid. The effluent flows through a final clarifier to settle out the residual chemical precipitates. This configuration results in efficient removal to unwanted metals and radionuclides.

The effluent from the plant is placed into one of four monitoring ponds. Prior to releasing effluent to the environment the quality of the water in the monitoring pond is confirmed through sampling and analysis. Only after the results indicate the pond water is acceptable for release will the pond contents be discharged. Approximately 5 000 m^3 of effluent is treated and released to the environment on a daily basis.

The tailings neutralization section consists of two holding tanks connected to the tailings pumps. Waste solids from CCD circuit (leach residues) and the bulk neutralization thickeners discussed above are neutralized with lime to pH 11 and pumped via the DTMF thickener to the DTMF.

2.9.2. Reverse Osmosis – dewatering water

The reverse osmosis plant is fed from dewatering water collected in the area of the Gaertner pit. The dewatering water is pumped to raw water storage tank located ourside the plant prior to being fed to the RO process. The current feed rate of contaminated water to the RO plant is 10 000 m^3/day. Inside the plant, a potassium permanganate solution is injected into the raw water influent line to oxidize iron and manganese. The removal of iron and manganese is required to prevent plugging of the RO membranes.

A 50% sodium hydroxide solution is also injected into the raw water influent line to increase the pH of the raw water. The oxidized pH adjusted raw water is fed to the pre-treatment system (manganese

greensand pressure filters). Following the greensand filters there are ten cartridge polishing filters operating in parallel, which remove any colloidal material that has not been removed by the greensand filters. These polishing filters are in place to protect the reverse osmosis membranes from unnecessary fouling.

There are four individual reverse osmosis system modules. The modules are connected in parallel to a header system that has water supplied to it from the polishing filters. Each module has its own 150 HP submersible feed pump to supply the required volume to the reserve osmosis membranes.

Reject water from the reverse osmosis modules is used for greensand filter backwashing. Excess reject water plus greensand backwash water streams flow via the contaiminated sump at crushing and grinding to reservoir#1 for treatment and are released through the bulk neutralization circuit.

The RO treated water is then pH adjusted to above 6.0, but less than 9.5, using a sodium carbonate solution and is then discharged to the environment at Horsefly Lake and/or partially pumped to the mill for industrial water use.

3. Future outlook for the Key Lake mill

During the past 20 years global uranium consumption for nuclear energy has exceeded the primary production of uranium mines. Secondary supply sources such as various types of inventory and recycled nuclear products provided the difference in the world supply. While these inventories still exist they are considerably reduced and may be classified as strategic rather than excess. Existing uranium supply is expected to fall short of demand over the next decade demonstrating a need for new primary mine production and an increase in production at existing uranium mining/milling facilities. From 2005 to 2014 it is predicted that world consumption will be 2 000 million pounds U_3O_8. During that period, the estimated production from primary producers is 1 600 million pounds U_3O_8 thereby resulting in a 400 million pound shortfall. Cameco Corporation is planning to increase the capacity of the McArthur River mine and Key Lake mill to 22 million pounds U_3O_8 per year, pending regulatory agency approval.

Commercial development of the Inkai ISL uranium project

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Abstract. Commercial development of the Inkai In-Situ (ISL) Project is underway. Located near Taikonur, Kazakhstan, in the south-central portion of the country, the project is operated by JV Inkai and owned 60% by Cameco Corporation and 40% by National Atomic Company KazAtomProm. At full capacity, annual production of dried yellowcake, natural uranium oxide, will be 2 000 tonnes as U. The nature of this project and the ongoing commercial development activities are described in the following report.

1. Introduction

The Republic of Kazakhstan (RK), located in central Asia, has a population of 15 million people and covers a landmass of 2.7 million square kilometers. The country borders Russia, Uzbekistan, China, Kyrgyzstan and Turkmenistan. It is mountainous near its southern border and consists of vast Steppes in the central regions. The Inkai deposit is near the small town of Taikonur, located approximately 370 kilometers north of the city of Shymkent and approximately 125 kilometers east of the city of Kyzl-Orda at a latitude of 44 N (Fig. 1). Taikonur has a current population of about 450 people who are mainly employed in uranium development and exploration. The elevation of the Inkai deposit ranges from 140 to 300 meters above sea level. The climate in south central Kazakhstan is semi-arid with temperatures ranging from -35^{o} C in the winter to +40^{o} C in the summer.

The Inkai uranium deposit is being developed by JV Inkai, LLP, which is jointly owned by Cameco Corporation (Cameco), 60%, and National Atomic Company Kazatomprom (Kazatomprom), 40%. The deposit is divided into three (3) areas: Blocks 1, 2 and 3. JV Inkai holds a mining concession for Block 1 and geological concessions for Blocks 2 and 3. A successful pilot test of Block 1 was completed in 1989 and commercial development is now underway. In 2002, a larger pilot test of Block 2 was initiated and a major expansion of this extraordinary operation is also underway.

Inkai Block 1 commercial development activities include the construction of well fields, as well as uranium processing plants and ancillary facilities at the mining locations. In addition, an administrative office, camp, and vehicle storage garage are being constructed in the town of Taikonur.

Uranium ore reserves at Block 1 have been estimated at approximately 35 192 t U (91.5 M lbs U_3O_8). A majority of the reserves are in the Mynkuduk horizon which is at a depth of about 500 meters below the surface. Some of the reserves are located in the Inkuduk horizon, 150 meters above the Mykuduk zone. Commercial uranium production is scheduled to commence in 2007. Production for the initial years of operations is given on Table I.

Table I. Nominal production schedule (tonnes U)

2005	2006	2007	2008	2009	2010
150	300	750	1 500	1 850	2 000

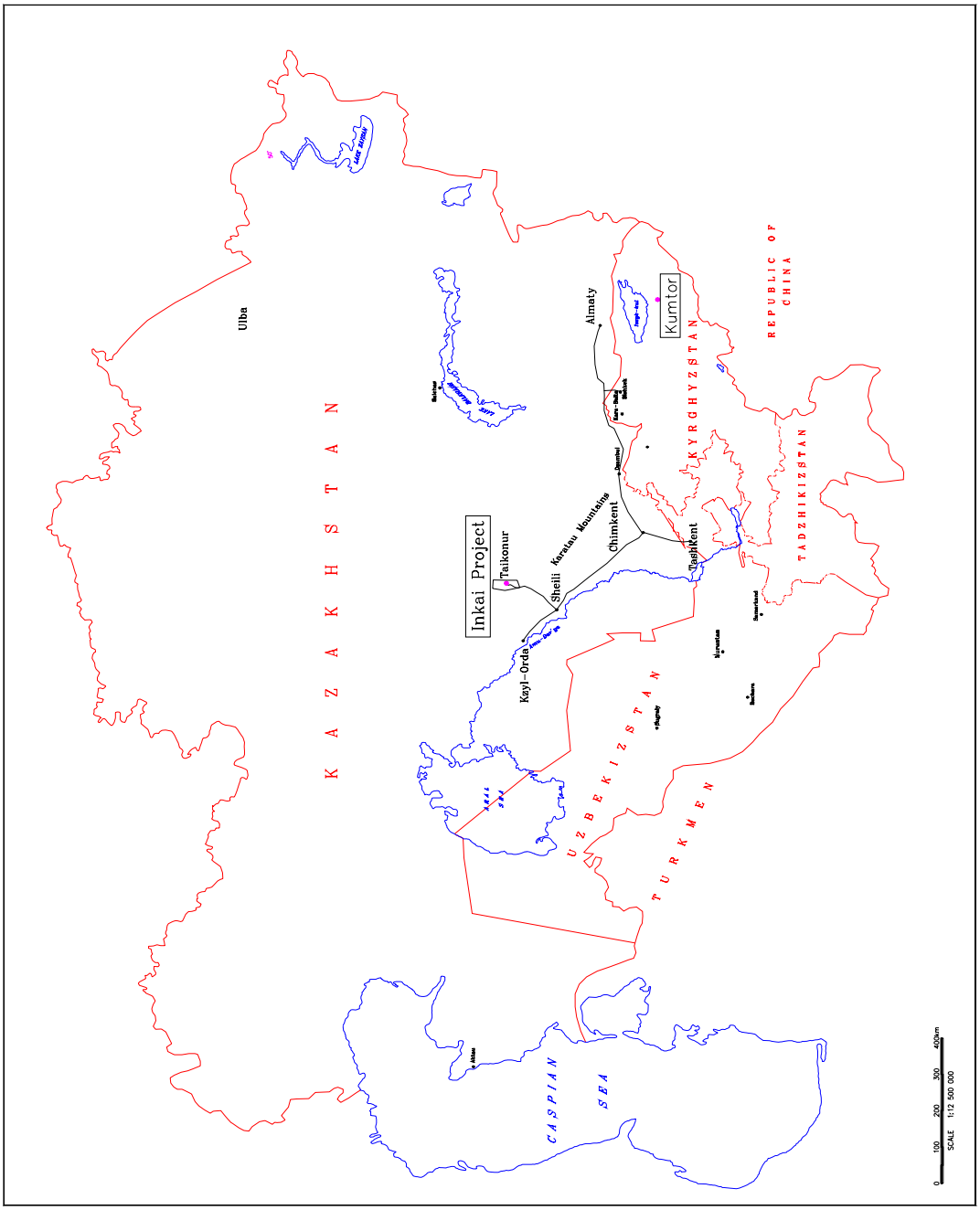

FIG. 1. Kazakhstan map.

2. Geology and reserves

The Cretaceous-Cenozoic Chu-Saryssu artesian basin extends for more than 1 000 kilometers from the foothills of the Tien Shan Mountains to the south and southeast, merging into the flats of the Aral Sea depression to the northwest, and is up to 250 kilometers wide. The basin is underlain by various Paleozoic and older rocks. The general structure of the Chu-Saryssu Basin is that of an asymmetric syncline (or monocline) with a broad, gently sloping, northeastern limb, which plunges to over 700 meters in depth, and a short up faulted limb marking the rise of the Karatau Mountains (an active NW-SE horst structure). The axis of the basin closely parallels its southwestern margin.

The source of the sediments, and also the uranium, is the Tien Shan Mountains, which abut the basins to the south and southeast. This segment of the Tien Shan includes a large number of Ordovician and

Silurian granites and granodiorites, as well as crystalline schists and slates. Additional minor sources of sedimentation are the Karatau Mountains and the Paleozoic uplands to the north. The mineralized horizons of the Chu-Sarysu Basin are shown in Fig. 2. The stratigraphic sequence at the Inkai and Mynkuduk deposits is shown in Fig. 3.

The Inkai deposit has developed along a regional system of superimposed mineralization fronts. Its overall strike length is 60 kilometers. To the northeast, the mineralization is semi-continuous with the Mynkuduk deposit, with both being located at the distal edge of a large northwesterly facing oxidation cell. The mineralization is hosted by four horizons, the Zhalpak, Inkuduk I and II and Mynkuduk horizons. The Inkuduk III horizon does not contain significant mineralization. The Mynkuduk deposit is developed in two levels of the Upper Cretaceous, the Mynkuduk horizon and the Inkuduk II horizon. The main portion of the deposit is contained in the Mynkuduk horizon (86% of the C1 reserves). The remaining 14% are hosted by the Inkuduk II horizon. The Inkuduk I horizon is not present in the Mynkuduk deposit.

The mineralized fronts at Inkai trend northwest and have prominent, long, east-west limbs with highly sutured, short, north-south limbs. It is the long-limb segments of the deposit (e.g., Centralny and Zapadny) that contain by far the most reserves. The Inkuduk mineralization at Mynkuduk shows broadly similar uranium distribution features.

As is typical for roll front uranium deposits, the hydrodynamic regime and permeabilities largely control the size and geometry of the ore zones. From observations of core, the redox boundary can be readily recognized by a distinct color change from gray on the reduced side to yellowish stains on the oxidized side, stemming from the oxidation of pyrite to limonite. The main uranium minerals are sooty pitchblende (85%) and coffinite (15%). Both uranium minerals occur in pores on interstitial materials such as clay minerals, as films around and in cracks within sand grains, and as pseudo-morphic replacements of rare organic matter, and are commonly associated with pyrite. The latter seems to have formed after the growth of pitchblende as it often coats or rims the uraniferous films and aggregates. No other elevated trace element, as potential deleterious material, has been detected. The uranium mineralization was reported to be essentially clean and monometallic. Only where occasional organic debris has accumulated do elements such as V and Mo show elevated values.

The groundwater movement in the Chu-Saryssu Basin is directed towards the northwesterly discharge areas. The annual natural flow rate averages 1 to 4 meters, depending on the various permeabilities of the different sand horizons. The Upper Cretaceous groundwater regime exhibits a layered sequence of aquifers due to gravity separation by different salt contents. At Inkai, from bottom to top these are: the salt water Mynkuduk aquifer (2.7-4.5 g/l TDS), the salt water Inkuduk aquifer (2.3-3.6 g/l TDS), the brackish water Zhalpak aquifer (1.1-1.5 g/l TDS), and the Paleogene fresh water (0.6-0.8 g/l TDS) aquifer. The confined Upper Cretaceous aquifers produce artesian conditions where the topography is depressed below the piezometric surface of about 135–140 meters above sea level. The general water table is at a depth of 8 to 10 meters at Inkai.

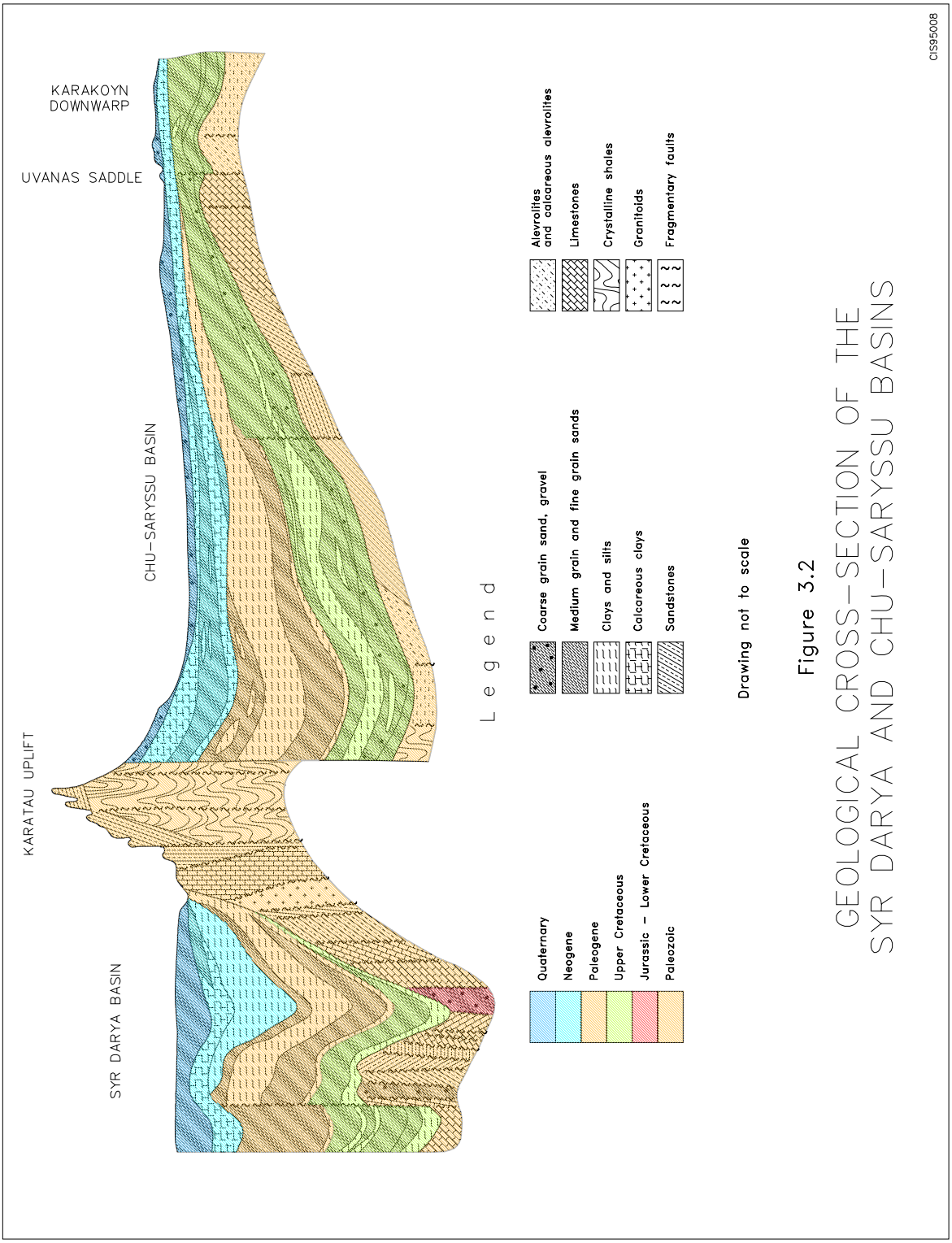

FIG. 2. Geological cross-section of the Syr-Darya and Chu-Sarysu Basins.

3. ISL mining

3.1. Test Block 1 (TB1)

A pilot test was performed by Kazatomprom in the northeast area of Block 1 starting in December 1988. The test lasted for 495 days and approximately 84% of the 36 mt U (92 900 lbs U_3O_8) of ore

reserves in the well field were extracted. The average head grade during the test was 87mg U/l (117 mg/l U_3O_8) and the average flow rate was 25m^3/hr (115 gpm or 38 gpm per production well).

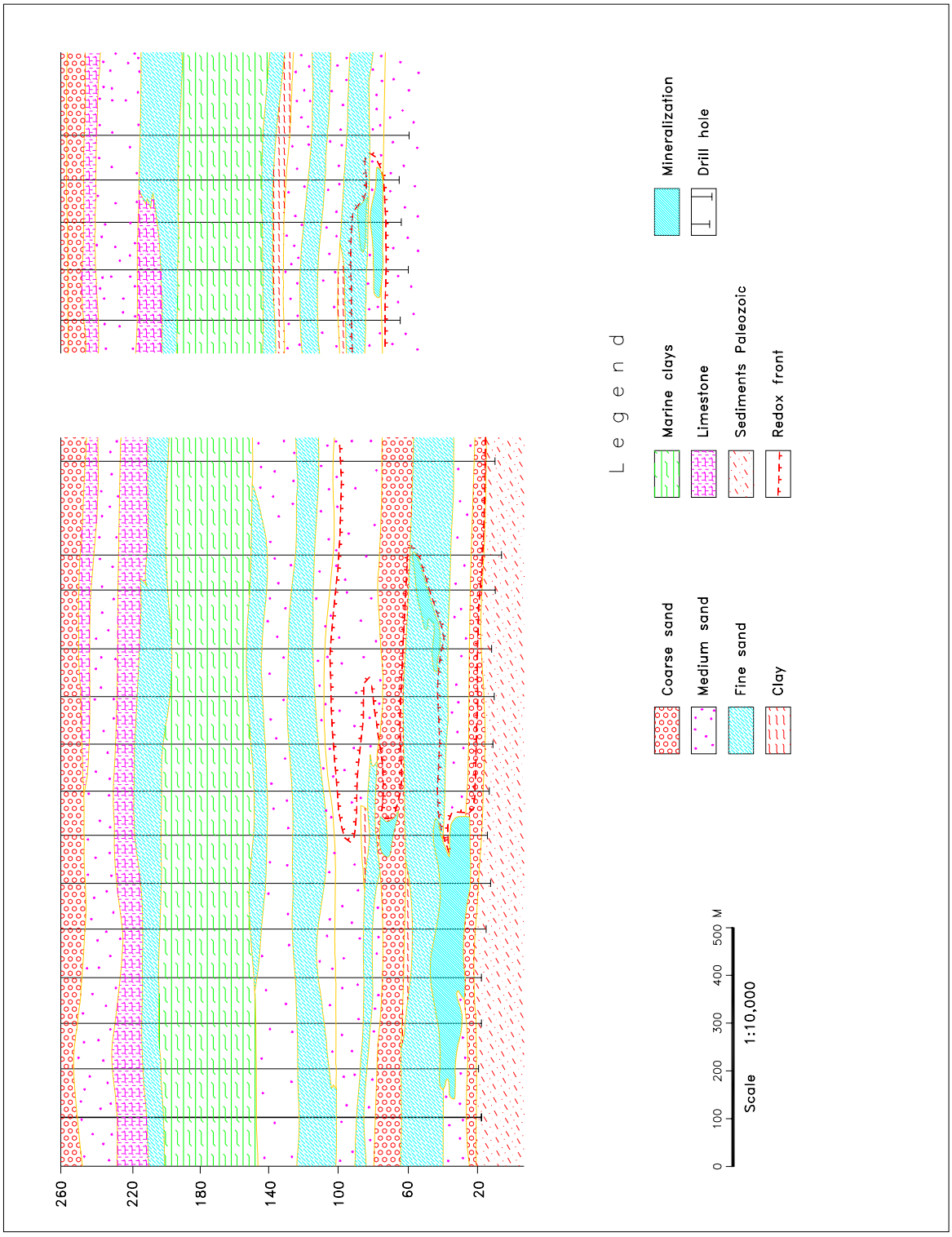

FIG. 3. Inkai deposit typical stratigraphy.

The well field for the test consisted of three production wells and six injection wells in a square pattern arrangement of 30 meters between rows of producers and injectors, 15 meters between producers and 15 meters between injectors. The total well field area was 1 800 square meters with an average pattern

size of 600 square meters. Total reserves of the well field were 35 810 kg U (92 900 lbs U_3O_8) or 11 937 kg U (30 967 lbs U_3O_8) per pattern. The wells were completed in the Mynkuduk formation approximately 500 m below the surface.

The test plant had an up-flow ion exchange system with no equipment for elutions or further processing. Ion exchange resin, once loaded, was trucked to the Centralia Mine, south of Block 1 for processing into a slurry product. The test successfully demonstrated the leachability of the ore. However, the close spaced well field design used would not be economic for commercial operations. A larger pattern size is necessary for commercially viable operations. The technical results of the Test Block 1 are shown in Table II.

Table II. Test Block 1 technical parameters

Total Uranium Recovered	8 991 kg U
Percent Uranium Recovered	84.7 %
Average head grade	86.7 mg U/l
Production well flow rate	8.4 m^3/hr
Acid Consumption/kg Uranium	47.4 kg/kg
Acid Consumption /tonne ore-bearing rock	24.4kg/tonne
Liquid/Solid Quotient	5.71

3.2. Test Block (TB2)

Test Block 2 is located in the northeast section of Block 2, approximately 15 km north of the town of Taikonur. As with the Block 1 test, the Kazakhstan government required a pilot test be conducted on a block of ore prior to commercial mining to demonstrate a sufficient reserve (typically 80%) recovery. The well field at TB2 consists of three mining units. Area 1 has been in operation since early 2002 while production in Area 2 began in late 2003. Area 3 is scheduled to begin operations in 2006.

The initial well field (Area 1) wells at Test Block 2 were installed in 1995 by Volkageology, the Kazakhstan national drilling contractor. Wells are completed (screened) in the Inkuduk aquifer at a depth of approximately 350 m. from the surface. The well spacing is 60 to 70 m. between rows, 30 m. between producers and 30 m. between injectors with some variations on that spacing as shown on Fig. 4. The overall area of the well field is 19 500 m^2 (209 917 ft^2) with an average pattern area of 2 786 m^2 (30 000 ft^2) per pattern. The reserves are estimated to be 195 990 kg U (508 440 lbs U_3O_8) or 28 000 kg U (72 634 lbs U_3O_8) per pattern. In 2003, Test Block 2 well field was expanded to test a hexagonal pattern, and to determine the installation cost for this configuration.

Starting in 2000, the TB2 processing plant building was constructed under the supervision of JV Inkai, Crow Butte Resources and Power Resources personnel using in-country contractors for all phases of construction. The building is 30 m. long by 20 m. wide and located on a spread-footer type foundation with a perimeter curb. Figure 5 shows the location of the plant in relation to the administrative building and other ancillary facilities. The building contains ion exchange and elution circuits capable of producing a liquid eluate product (approximately 25g/l). The eluate is shipped in 10 m^3 tanker trucks to Kazatomprom's Mine No. 6 in Shieli, approximately 175 km to the southwest of TB2. At Mine No. 6, the eluate is precipitated and dewatered to form a slurry product. The slurry product is then shipped to the Ulba Metallurgical Plant and Stepnagorsk in northeast Kazakhstan where the slurry is re-dissolved, processed through a solvent extraction circuit, and then precipitated and dried into a powdered natural uranium product.

Test Block 2 mining began on March 22, 2002 with the injection of acid into the Area 1 well field. Groundwater was circulated with the addition of acid for about two months before uranium was detected in the production fluid. The average head grade from Area 1 during the first two years of operations was more than 150 mg U/l.

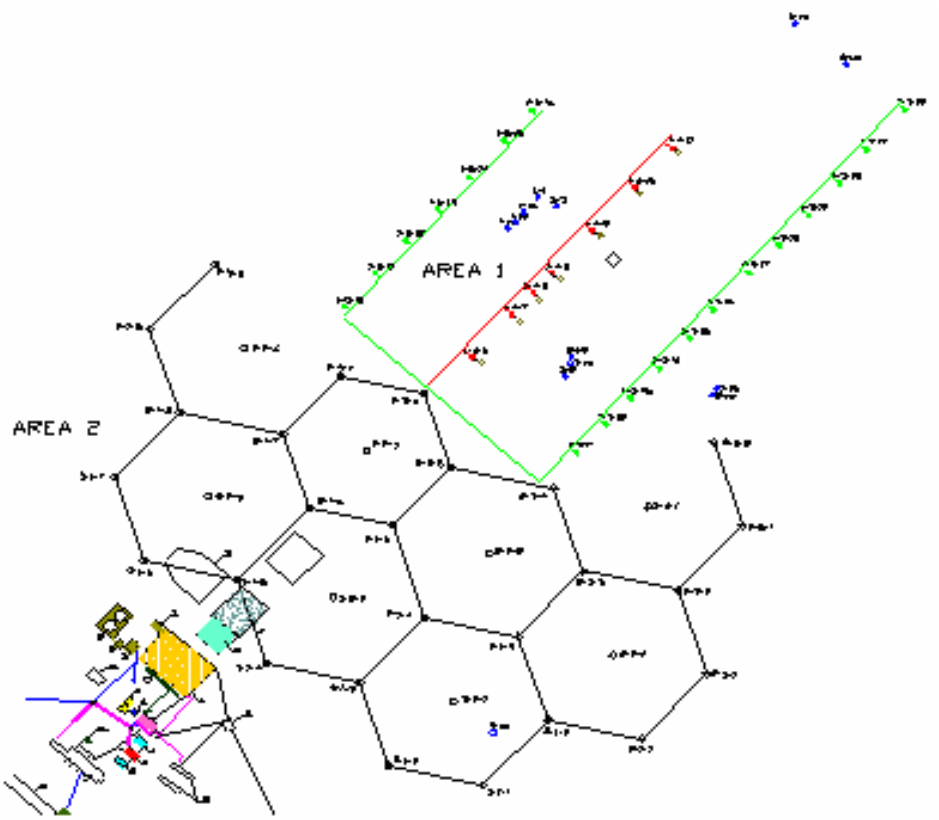

FIG. 4. Test Block 2 well field - areas 1 and 2.

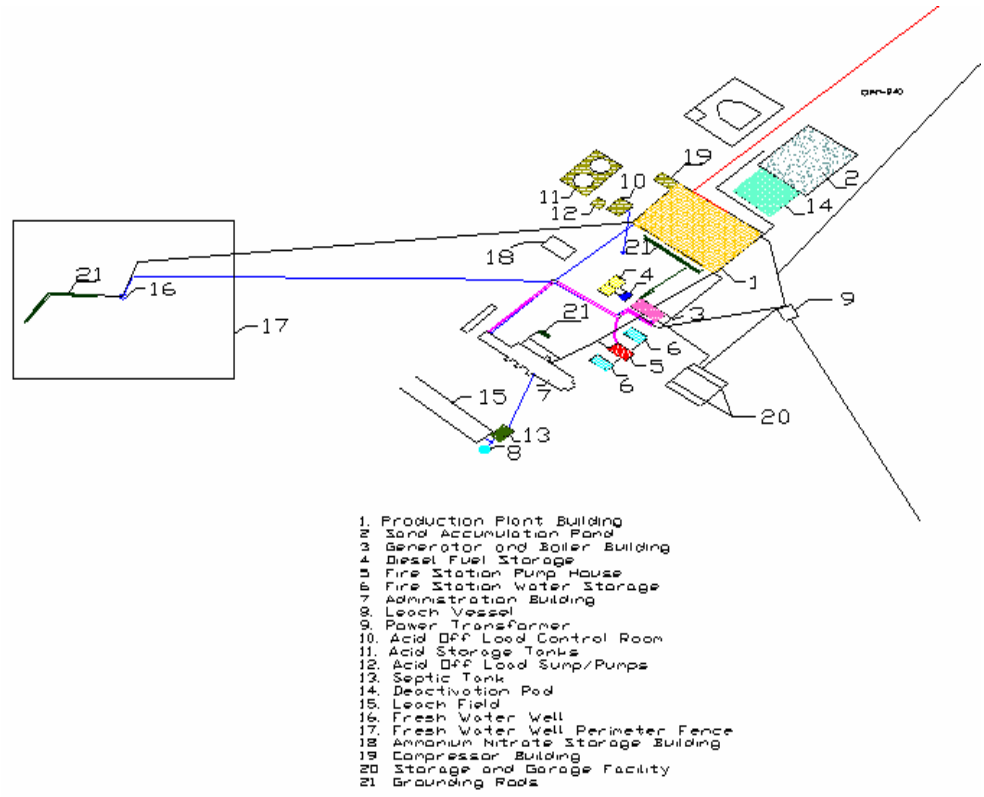

FIG. 5. Test Block 2 processing, administrative and ancillary facilities.

3.3. Commercial well field construction

Commercial well field construction activities will include installation of injection, production and monitoring wells and construction of the surface facilities necessary to connect the wells to the

processing plant. Drilling rigs used for exploration holes and well installation are trailer mounted and rated for a drilling depth of up to 1 500 meters. The rigs are powered by a diesel generator or AC power that feeds an electric motor which provides the rotary drilling force. Drilling mud is used to flush cuttings out of the hole using similar techniques as those at U.S. ISL operations.

To date, Volkageology has installed all of the wells for ISL uranium mining in Kazakhstan. It owns and operates its drilling rigs and has performed drilling services for JV Inkai at the Test Block 2 well fields. The commercial well field design for a typical one million lbs U_3O_8 mine unit, based on TB2 sizing, will have a total of 40 mining wells. Thirteen monitor wells will also be installed within this mine unit for a total of 53 wells per 385 t U (1 M lbs U_3O_8) recoverable.

3.4. Well field operations

At Inkai, the production solution from the well field production wells will be pumped to the processing plants using down-hole submersible pumps. The solution will flow through the ion exchange circuit and then will be pumped into the injection wells using centrifugal type pumps. The lixiviant flow is balanced on a pattern by pattern basis to keep the solutions within the well field perimeter. During the startup of a new well field area, the production solution bypasses the ion exchange circuit until the pH is low enough to preclude blocking of the IX circuit with aluminum or other elements.

3.5. Mining schedule

Mining is scheduled to start in Block 1 in 2007 near the main processing plant (MPP). The annualized ion exchange capacity for the MPP is a nominal 1 000 t U/yr while the yellowcake processing capacity is 2 000 t U/yr.

4. Uranium recovery and processing

The Inkai project will produce a dry uranium product that meets quality specifications of uranium hexafluoride conversion facilities. Because the plant feed is in the form of solution, the processing has no crushing or grinding circuits. The processing plants will consist of Ion Exchange Recovery (IX) Plants and a Main Processing Plant (MPP). The IX Plants will be located within the MPP and at the satellite units.

Uranium recovery using ion exchange resin involves the following processing circuits:

1) Ion Exchange resin loading
2) Resin elution
3) Precipitation
4) Product thickening
5) Product dewatering
6) Vacuum drying
7) Packaging

The IX Facilities will be equipped with resin loading and transfer circuits. Each facility is designed to process 216 liters/second (3 425 gpm) of lixiviate. Based on pilot test data, uranium concentrations from 20 to 1 000 mg U/l are expected to be typical of the produced lixiviate solution. The pilot plant has demonstrated that standard, commercially available ion exchange resins function well under these conditions. Ion exchange resin will be transferred by pipeline within the MPP for elution. Truck trailers will be used for resin transfer to and from the satellite plant.

The MPP will be equipped to elute resin from all IX Facilities. The elution, precipitation, product filtering, drying, and packaging circuits will be capable of processing 5.8 t U per day (2 000 t U per year).

4.1. Ion exchange (IX)

Groundwater containing soluble uranium in concentrations ranging from 20 mg U/l to 1 000 mg U/l or more (pregnant solution) is pumped from the well field via pipelines to the IX circuits in the MPP or satellite plant in a continuous process. Each IX circuit consists of three parallel modules of three IX columns, containing nominally 28.6 m^3 of polystyrene resin per column (Table III). This amount of resin can adsorb approximately 1 000 kg U per uranium loading cycle. A loading cycle for each column is about 1.6 days at an average head grade of 100mg U/l and a flow rate of 72 liters per second (1150 gpm).

Table III. Typical ion exchange resin specifications

Resin type	Type I, SBA
Mean size	525 –625 microns
Density	1.08 g/ml
Total capacity	1.3 meq/l
Bulk weight	640-700 g/

The pregnant uranium solution will flow through a sand separator prior to entering an IX circuit. Entrained sand and other soils are captured and collected in a lined settling pond. As an option, the pregnant solution will flow directly to the IX circuit. A pipe manifold system delivers the pregnant solution to the three IX modules. The solution flows into the top of the first IX column in the module, through the bed of resin and out of the bottom of the column. The solution then flows in the same down flow fashion through the second and third column in the module before exiting the plant. The concentration of uranium in the solution continues to decrease as it passes through each column and the uranium adsorbs onto the IX resin. The concentration of uranium in the barren solution that is pumped back to the well field is near 3 mg U/l. The pH of the fluid is maintained near two and sulfuric acid is added to the lixiviant prior to returning to the well field.

Once the resin in an IX column is fully loaded with uranium, the column is isolated from the continuous IX circuit and the resin is pumped with water across a screening device into an empty elution vessel (EV). A batch of eluted resin from one of the EVs is then transferred to the isolated column and the column is put back into service to restart the uranium loading cycle.

Sulfuric acid in the mining solution creates a corrosive environment for the IX equipment. The IX vessels will be constructed of stainless steel or carbon steel with internal and external coatings. Valves and pipe that comes in contact with the pregnant and barren solutions also will be acid resistant.

4.2. Elution

The elution vessels, located in the MPP are adjacent to the IX circuit. Loaded resin is transferred from the IX circuit to one of the four elution vessels. In the MPP, the resin is pumped with water to the elution vessel. The satellite plants utilize bulk trailers to haul the resin to the MPP for elution. Elution vessels are pressure vessels of the same construction as the IX columns.

Uranium that is adsorbed onto the IX resin during the loading cycle is removed from the resin using ammonium nitrate and sulfuric acid solutions during the elution process. Elutions are a five step batch process with the final eluate having a concentration in the range from 20 to 25 g U/l. First, eluant from the strong eluant tank is pumped to the elution vessel which contains the loaded IX resin. The pregnant eluate (final eluant product) from this step is stored in the pregnant tank and fed to the precipitation circuit. Three more batches of eluant are passed through the elution vessel making an ever richer eluant in each step. Following the elution, the resin is converted from the nitrate form to the sulfate form in the denitrification stage.

4.3. Precipitation

The pregnant eluate for the elution circuit is fed directly to the precipitation circuit. The pH of this stream is adjusted to a value near 2.0 by addition of anhydrous ammonia. Dilute hydrogen peroxide is then added to form solid uranyl peroxide particles.

4.4. Product thickening and dewatering

Following precipitation, the slurry is pumped to a two stage set of thickeners for an initial washing and removal of undesired dissolved salts. The thickener underflows at 30% solids are fed to two plate and frame filter presses for secondary washing and dewatering.

4.5. Drying and packaging

Dewatered solids are transferred into a progressive cavity pump using a shaft-less screw conveyor in a batch process. The pumps then deliver the solids to one of three rotary vacuum dryers, which operate in a batch mode.

The yellowcake will be dried in low temperature vacuum dryers that are totally enclosed during the drying cycle. The off-gases generated during the drying cycle will be filtered and scrubbed to remove entrained particulates. The water sealed vacuum pump also will provide ventilation while the dryer is being loaded and unloaded into drums. The vacuum dryers operate at low temperatures (< 140° C) and no measurable quantities of insoluble uranium solids are produced, further reducing environmental and occupational risks. This drying technology requires a high purity feed stock because operating temperatures are not sufficient to volatilize contaminates.

The dried, yellowcake product will be packaged in approved steel drums for storage and shipment by truck to another facility for further processing. The vacuum pump system is employed during packaging to minimize the potential for airborne particulate emissions within the packaging area.

4.6. Personnel

Personnel for the Inkai Project will consist mainly of Kazakhstan citizens from the region. Some of the available employees have experience at Kazatomprom mines, but the majority of the staff for commercial operations will be newly trained. Expatriate employees are anticipated for involvement for the development stage and the start up of the plant and well field. An estimated work force of employees and expatriates is shown below.

Workforce at Full Production (2 000 tonnes U/yr):

- Head office in Almaty
- One main processing plant and two satellite plant (2 000 t U/year)
- Full time operating schedule (24/7)
- 14 day employee rotational schedule for operations
- Employee commuter pick-up extending to Shymkent
- Residence facilities at Taikonur (complete lodging/dining/laundry)
- Approximate Total 450-460

4.7. Process control

For control and monitoring purposes, two separate PLC control systems are provided. Each system is designed and instrumented to accommodate the steady state or batch flow characteristic of particular process flow streams or unit operations.

In particular, this distinction is highlighted as follows:

1. Steady State
    - Well field/Resin Loading Circuit

2. Batch
    - Elution
    - Precipitation
    - Product Filtering, Drying and Packaging

Since the well field/resin loading circuit operates at a steady state, modest deviations from the normal operating flow rates and pressure profiles (± 10% or greater) are indicative of major operating upsets. An automatic Emergency Shut Down (ESD) system consisting of pressure and flow rate switches is provided for this circuit. Once the upset is identified and corrective action taken, only then can the circuit be manually restarted. This type of control system provides the best protection against fluid spills to the environment and product losses. Back-up for the automatic ESD system is provided by local displays of the same flow rates and pressures that the ESD system monitors.

The elution, precipitation, and product filtering, drying and packaging circuits operate in a batch nature. These circuits are controlled by programmable logic controllers (PLC) which sequences the opening and closing of appropriate valves once the processes are manually initiated. In addition, the PLC provides closed loop feedback control for the elution and precipitation circuits. All automatic valves are equipped with manual control override. Local indication of pressures, levels, flow rates, pH and temperature are provided for complete manual control of these circuits if required.

The control systems will employ state-of-the-art hardware with proven as well as demonstrated process logic. Like all elements of the designs, instrumentation and control designs are based on modern practices with proven techniques.

4.8. Plant operations

The MPP and satellite plants will operate 24 hours a day, 365 days a year without shutdowns except for unscheduled maintenance or electricity outages. Plant availability is estimated to be near 95%.

5. Infrastructure and administration

The town of Taikonur has approximately 60 homes that were constructed in the late 1970s for workers performing uranium exploration in the area. The town has a school, medical clinic and small store. The medical clinic has a Kazakhstani doctor capable of performing rudimentary medical treatment. Most of the food is purchased in Shymkent or Shieli. JV Inkai currently has a small camp, garage and administrative facilities in Taikonur as part of the Test Block 2 pilot operations. An administrative office is also located in Almaty. Processing plant and well field facilities are located at the Test Block 2 site, 18 km north of Taikonur.

During commercial operations administrative offices, man camp and garage facilities will be located in Taikonur and an administrative office will be located in Almaty. JV Inkai currently owns or leases buildings in town for these facilities, each will be expanded to serve commercial operations. The main process plant, satellite plants and well fields will be within a 30 km radius of Taikonur in the areas designated as Blocks 1, 2 and 3.

6. Environmental and permitting

6.1. General

The environmental management system at the Block 1 commercial mine is designed to ensure compliance with Kazakh regulatory requirements and appropriate standards and good practices employed at U.S. operations (Crow Butte and Highland/Smith Ranch projects will also be

incorporated. An environmental management system based on the ISO 14001 standard will be implemented.

6.2. List of permits

Table IV identifies the various regulatory permits and licenses relating to environment, health and safety at the commercial mine. The *Subsoil Use Agreement* was established in 1999. All others are currently being obtained.

Table IV. List of permits

	Regulatory Document	Issuing or Approving Agency
1	**Subsoil Use Agreement**	**Republic of Kazakhstan Agency on Investments**
2	State license for construction and operation of commercial mining facilities	Committee on Atomic Energy – Ministry of Energy, Industry and Trade of the Republic of Kazakhstan
3	State license for uranium export	Committee on Atomic Energy – Ministry of Energy, Industry and Trade of the Republic of Kazakhstan
4	Environmental Assessment (OVOS)	Ministry of Natural Resources and Environmental Protection
5	Water Use Permit	South Kazakhstan Territorial Ecology Committee
6	Land Use Permit	
7	Sanitary Passport – Well Field	South Kazakhstan – Sanitation and Epidemiology
8	Sanitary Passport – Processing Plant	South Kazakhstan – Sanitation and Epidemiology
9	Sanitary Passport – Low Level Radioactive Waste Storage Facilities (Block 1 and Block 2)	South Kazakhstan – Sanitation and Epidemiology
10	Technological Passport	Regional Mine Technical Inspection (RGTI)
11	**Medical Clinic License**	**Suzak Rayon – Sanitation and Epidemiology**
12	Pollution Permit	South Kazakhstan Territorial Ecology Committee
13	Radiation Protection and Uranium Safety Quality Assurance Program	Committee on Atomic Energy – Ministry of Energy, Industry and Trade of the Republic of Kazakhstan
14	Sanitary Passport - Yellowcake and eluate transport	South Kazakhstan – Sanitation and Epidemiology
15	License for fuel storage facilities	
16	Domestic waste disposal permit	South Kazakhstan – Sanitation and Epidemiology, Regional Fire Marshal, South Kazakhstan Territorial Ecology Committee
17	License for performing survey work	
18	License for Emergency Response Team	Ministry of Emergency Situations
19	Annual Water Use Limit Permit	Aral-Syrdaria Water Basin Administration
20	Permit for Radioactive Waste Disposal	South Kazakhstan Territorial Ecology Committee
21	License for transport of hazardous materials	Transport Control Committee
22	Special water use permit	Aral-Syrdaria Water Basin Administration
23	Industrial Object/Facility Safety Declaration	Ministry of Emergency Situations
24	Inventory of Pollution Sources	South Kazakhstan Territorial Ecology Committee

6.3. Environmental impacts

The baseline conditions and potential environmental impacts of the commercial mining facility based on RK and western (U.S.) standards were assessed. The anticipated environmental impacts are common to any uranium acid in situ leach project and are described in detail in the OVOS (Republic

of Kazakhstan equivalent of environmental assessment) and western environmental assessment reports.

6.4. Environmental baseline assessment

The Environmental Baseline Assessment of the JV Inkai *In-Situ* Uranium Leaching Project was conducted as a joint effort between AATA International, Inc, based in Fort Collins, Colorado, USA, and the Kazakhstani Agency Institute for Applied Ecology (KAPE) based in Almaty, Kazakhstan.

In 2001-2002, both American and Kazakhstani environmental scientists completed field investigations and research to characterize baseline environmental conditions at the JV Inkai site. This environmental baseline assessment is designed to be the first stage in development of the detailed Western-style Environmental Impact Assessment (EIA) and Kazakhstani OVOS for the project, which is required as part of commercial development of the project. It will address the project engineering, impacts, remediation, environmental monitoring and mitigation.

In 2002, Proektno-Konstruktorskaya Organizatsiya LLP, submitted a basic OVOS addressing environmental impact issues in Block No. 2 to Kazakhstani state authorities. With amendments from the *Expertiza* Committee, this OVOS was approved in 2002 as part of the overall design plan for Block No. 2 test-mining phase of the project. A similar assessment for commercial operations in Block No. 1 is now being reviewed by the regulatory authorities.

7. Project summary

The Inkai in-situ leach (ISL) uranium project is located near Taikonur, Kazakhstan, in the south-central portion of the country. The project is operated by JV Inkai LLP owned 60% by Cameco and 40% Kazatomprom. JV Inkai holds a mining concession for Block 1 of the Inkai deposit and also holds geological concessions for two adjacent areas, Blocks 2 and 3.

Test mining at Blocks 1 and 2 successfully demonstrated the leachability of the ore using sulfuric acid and the economics of the project. Average head grades at Block 2 have exceeded 150 mg U/l for the first 27 months of operation.

The investment for construction of the commercial facilities exceeds $80M US. This includes construction of the main processing plant (MPP), two satellite facilities, the initial well field, camp, and miscellaneous ancillary facilities. Construction began in 2004 with installation of a 100 man camp at Taikonur. In 2005, construction of the main processing plant and initial well field begins. Construction of two satellite plants is scheduled for the years 2006 through 2009, bringing the total production capacity to 2 000 t U/year (5.2M lbs U_3O_8). The uranium product at Inkai will be dry and contaminant-free, meeting the quality specifications of uranium hexafluoride conversion plants throughout the world. Production operations will begin at the MPP in late 2007 and the design capacity (2 000 t U/year) will be reached in the year 2010.

Block 1 has recoverable uranium reserves estimated to be 35 192 t U (91.5M lbs U_3O_8) yielding a life-of-mine of 35 years (until the year 2041). Block 2 has an estimated resource total of 108 081 t U (268M lbs U_3O_8). Block 2 resources are listed in the C_2 category, the lowest resource category in the Kazakhstan reserve estimate system. No reserves or resources are listed for Block 3 at this time.

An environmental assessment of the commercial plan has revealed no unusual nor excessive risks. The planned environmental management system is designed to meet ISO 14001 certification requirements. Similarly, health physics practices will meet all international standards.

With a projected in-country staff of about 450, Inkai will provide a significant benefit to the Kazakh economy. To further enhance these benefits, a strong sustainable development program will be an integral component of the new commercial mining venture.

AREVA in Niger, a long term uranium producer

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Abstract. Niger through Areva ranks number four amongst uranium producing countries and holds the fourth world resources. Niger Uranium story started fifty years ago and AREVA is its first partner since. AREVA/COGEMA inherited the exploration programs conducted by former "Bureau Minier de la France d'Outre-mer" and "Commissariat à l'Energie Atomique" in the early sixties. Arlit's deposits came out of that. In association with other partners (Niger government through ONAREM, Japan and Spain), uranium production started in 1967 with joint venture company SOMAÏR followed by COMINAK. That partnership stands sound through the 1980 – 2003 market depression and production rate never slows since. Near by prospects allow extension and keeping activities ahead as it is the case now where the two companies have more than ten years production assured reserves. New major project is also on hand with more than 150 000 tonnes of uranium. AREVA/COGEMA foresaw the current market upraise when it launched a large exploration program three years ago in its previous allotted area. Regulatory agreement is underway for more prospecting areas allocation. More decades of uranium production resources are expected. This long partnership is supported by a sustainable development commitment in a hard to live desert area: health care, school, training, water supply, energy and employment.

1. Introduction

Areva is the 2nd world uranium producer. Much of its production comes from Niger (Fig. 1) where it is established for more than forty years contributing to the geological appraisal of the northern part of the country, and for local economy development as well. In association with foreign partners and Niger government, it created subsidiaries producing uranium for more than thirty years. Reserves are in place for more decades to come.

Research program is engaged to find more resources and make the story continue.

The fact is that Areva makes Niger currently ranking as number four amongst uranium producing countries and therefore is a major contributor to world uranium supply. Its share in European Union uranium supplies (about 15% of uranium purchases and 13% of total supplies in 2003) is particularly prominent and deserves a special focus This must be made sufficiently known as it is important for the overall appraisal of world uranium supplies.

2. Geological background

Main Niger's uranium resources are all contained in the proterozoïc sediments of the Tim Mersoi sub-Basin which is mainly the continental part of the sedimentary layers of the Iullemmeden sedimentary basin. The large deposits currently mined by Cominak and Somaïr are respectively located in the Guezouman conglomeratic formation, supposedly of a Visean age, and to the Tarat sandstones formation which is younger and supposedly of a Namurian age. (Cf. Geological Map).

Upward in the sedimentary pile, other mineralizations and deposits have been identified. The most important one being the Imouraren deposit located in the Tchirezrine sandstones of a Jurassic age. To describe the deposits in a very simple way, one can characterize them as belonging to the "Sandstone type" uranium deposits (Fig 2).

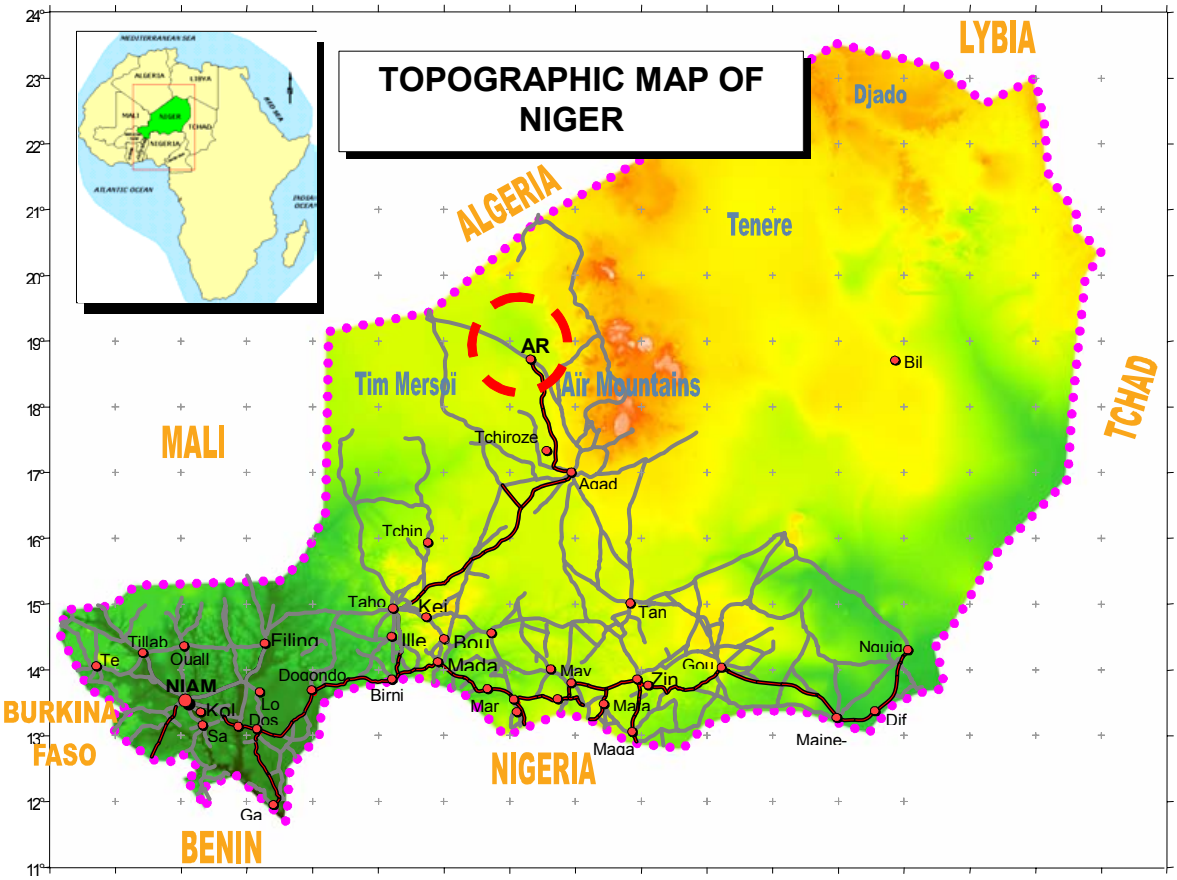

FIG. 1. Topographic map of Niger and its situation in Africa.

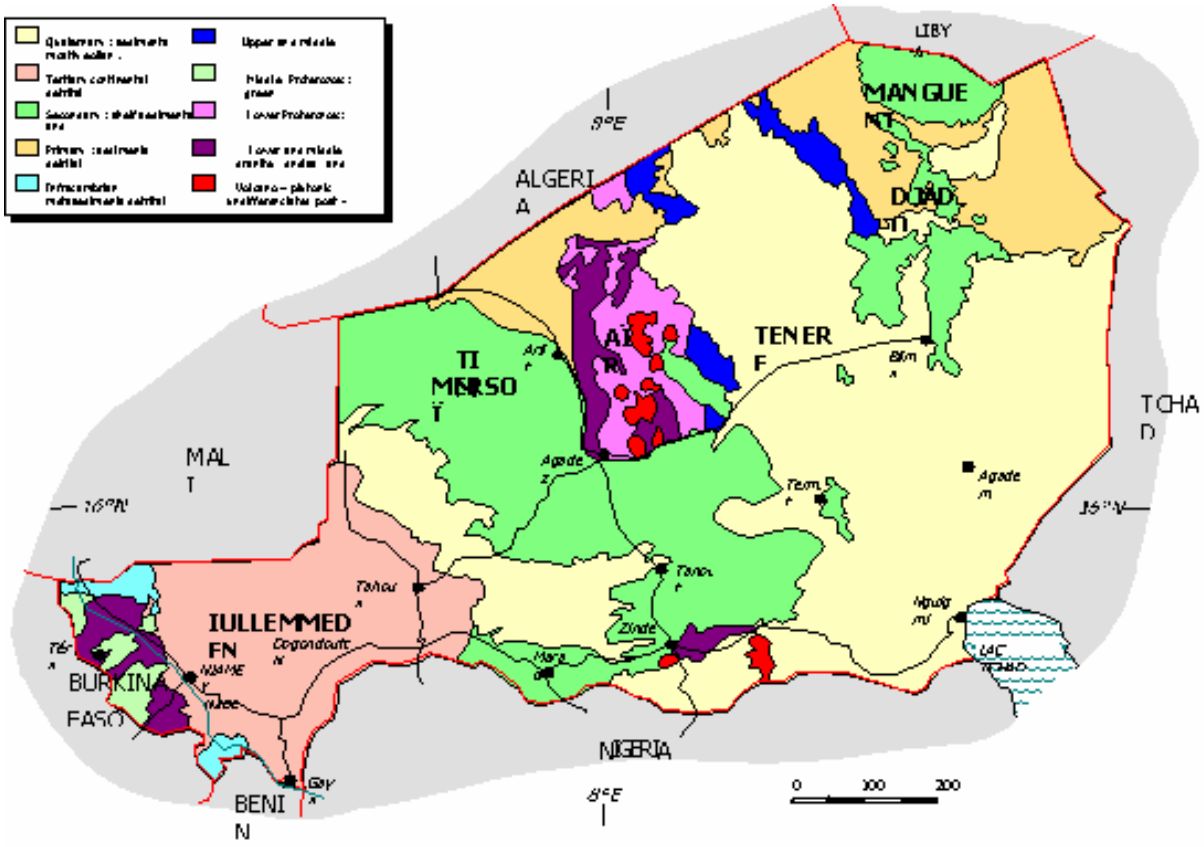

FIG. 2. Niger simplified geological map.

3. A brief history of uranium in Niger

The starting point of uranium history in Niger can be set in year 1958, with the discovery of uranium showings at Azelik by the "Bureau Minier de la France d'Outre-mer".

Made aware of the discovery at a moment when uranium was actively search, the French "Commissariat à l'Energie Atomique CEA" almost immediately started a detailed study of the showings and launched an airborne & field survey.

From 1958 to 1967 the research perimeters covered the area starting 100 km southern-east of Agadez city to 100 km northern-west of Arlit (Fig. 2).

The research methods used were:

- geological survey and mapping,
- airborne survey,
- structural geology,
- deposit modeling,
- rotary drilling,
- geological control and estimation,
- comparison with other similar geological context.

These actions were completed with hydrological studies and deposits valuation.

The whole program was supported by CEA strategy to endow France with civil and military nuclear facilities. At the same time, similar programs were conducted in France, central Africa, Madagascar and Canada.

Hundred of geologists and big amount of money were engaged.

By the time, Niger became an independent state and CEA dealt with local legal, licensing, and partnership building procedures.

As a consequence, in 1959, the discovery of Azelik and Abakorum deposits took place.

A succession of discoveries followed : Madaouela in 1963; Arlette, Ariège, Artois, Taza, Tamou and Takriza in 1965; Imouraren in1966; Akouta in 1967.

4. From deposits discovery to uranium production corporations.

Discussion started in 1967 with the Niger government to set up production units with a large partnership. Orebodies valuation focused on Arlit deposits for mining projects. Project teams were set up both on field and in France while political discussions are underway with Niger government and foreign partners to settle the corporations agreements.

4.1. Somaïr

Based upon orebodies discovered in 1965 (Ariège, Artois, Arlette) and subsequently developed, the Société des Mines de l'Aïr (SOMAIR) was the first one to be incorporated on February 1st 1968. Its headquarters is in Niamey, the capital of Niger.

Stripping started in 1969, ore production in 1970. Somaïr has its own mill, the Arlit mill, started in December 1970. Since 1980 it includes two production lines totaling a capacity of 2 300 t U/year. Due to depressed market conditions, the first line was shutdown in 1982. It remains partially operable. The Arlit mill has its own sulphuric acid production plant, using imported sulphur.

Production is coming from several open pits of about 70 m deep.

- Arlette open-pit opened in 1968
- Ariège in 1976 (now exhausted)
- Taza in 1986 (southern part already exhausted)
- Takriza
- Tamou

Other open pits are projected to mine the deposits Artois and Tamgak.

4.2. Cominak

Cominak was setup as a company on 12 June 1974. This was decided quite shortly after the discovery of the Akouta orebody in 1967 and Akola. As it is for Somaïr, its headquarters is in Niamey.

The mine entrance (a 20% twinned decline, one for engine circulation, one for a belt-conveyor for the ore) is situated at Akouta. It provides access to the producing stopes about 250 meters deep underground. The mill is also next to the mine (the Akouta mill). It was started in late 1978. Its current production capacity is about 2 500 t U/year.

The Akouta mill has its own sulphuric acid production plant, using imported sulphur.

Besides ONAREM and COGEMA, Cominak gathers two others important shareholders, OURD Japan and ENUSA of Spain.

4.3. Production records and corporations' potential

SOMAÏR and COMINAK are in production for more than thirty years and their production level has been constant for the last 20 years. They came across the depressed market with different adjustment, adapting their production costs to the situation, without cutting their output (Fig. 4).

Their contribution to the already produced uranium has already been mentioned as one of the few showing a cumulated production in the range of 100 000 t U and more. But more importantly, its remaining reserves and resources are quite large.

Reserves figures are corresponding to the part of the known resources that is fully evaluated according to a well defined mining project and are ready for production. They are expressed in Table I as recoverable concentrates (taking into account all mining and milling losses).

Regarding the two producing companies, these figures indicates that about ten years of forward production are already delineated. Further development work, and related expenses will be required to keep ongoing this horizon of visibility.

Table I. Reserves figure for SOMAÏR and COMINAK as for Jan 05

Mine/Project	Total Reserves (t U)	average grade (kg U/t)
COMINAK	23 626	4.54
SOMAIR	13 489	2.99

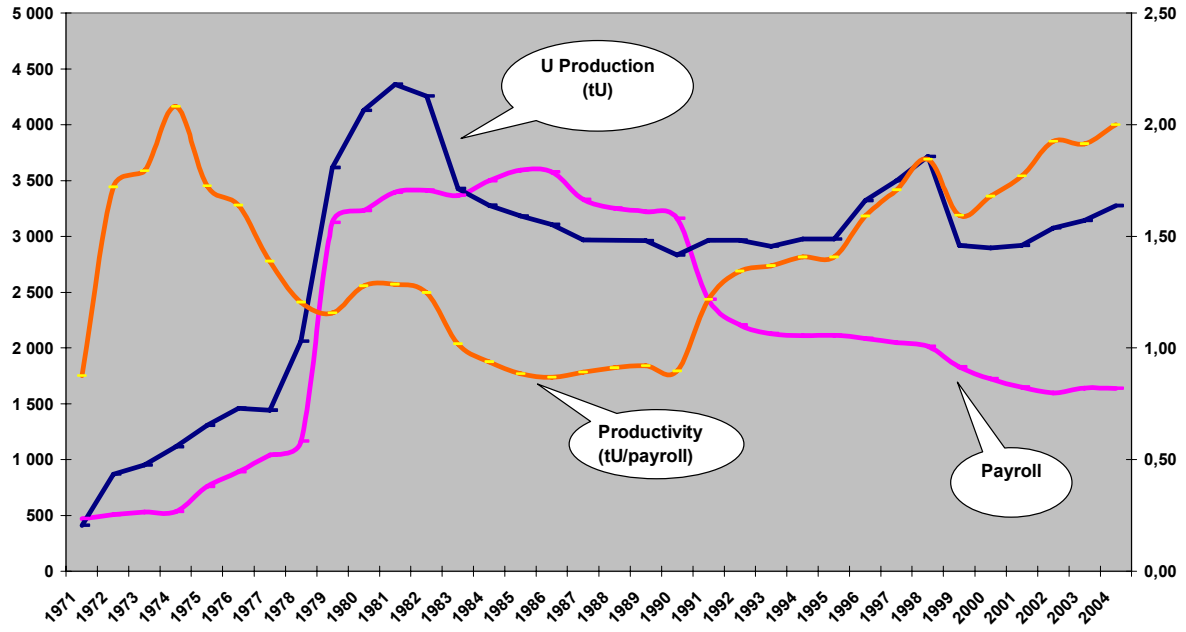

FIG. 4. Production, payroll and productivity of the mining corporations.

5. New mining projects and exploration program

5.1. Mining project

Lot of research has been done in the sixties. Afasto and Artois deposits, discovered at that time, are studied as part of COMINAK and SOMAÏR respectively. The reserves figure above includes them as extensions.

The Imouraren deposit is under licensing process with the Niger Government. This deposit is located 80 km south of Arlit (Fig.3). It is the same sedimentary type. More drilling is necessary to reassess the global reserves. The recognition grid is 50 m to 200 m depending on the 48 km2 areas. The uranium resources estimate based on that grid is 150 ktU with an average grade of 0.11%. The depth is 130 – 180m.

Imouraren deposit was discovered in 1966 during the wide range CEA research program.

In 1974 CEA went into partnership with CONOCO and ONAREM to develop it. Two feasibility studies were carried on in 1977 and 1980, just when uranium market collapsed. The project stopped then.

Imouraren is now planned to be in production within the next three years.

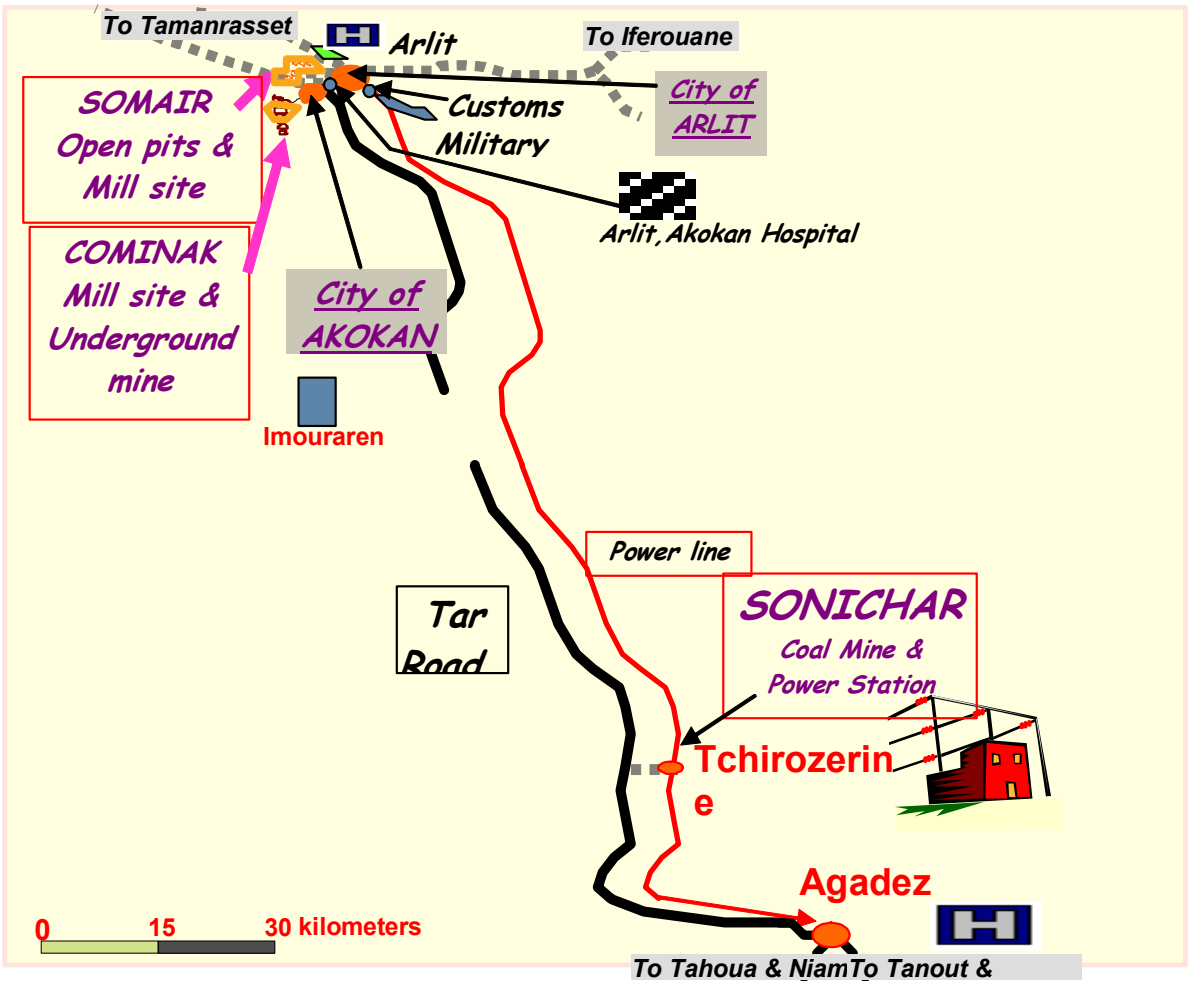

FIG. 3. Mining sites and Project localizations.

5.2. New exploration program

Areva didn't wait for the 2004 market trend to think about extending its uranium reserves in Niger. Through its partnership, it pushed since 1999 COMINAK and SOMAÏR to look fore more uranium within their close neighborhood. Drilling was engaged with budget and technical support. The Afasto (15 000 t U) and Artois (11 000 t U) extensions for COMINAK and SOMAÏR are part of this effort.

Meanwhile, Areva consider conducting research operations by itself. Program is set since 2001 to get research teams back, budget and conduct research operations within its older licensed areas, and introduce claim request for knew perimeters. A geophysical airborne was carried on in 2003 with up to date technical method. The results of that operation are used as guidelines for exploration activities for many years to come (Figs 5, 6 and 7).

COGEMA NIGER, an old COGEMA office in Niger is reopened to supervise these operations.

The research program plans to drill 100 000 m/year for the next five years.

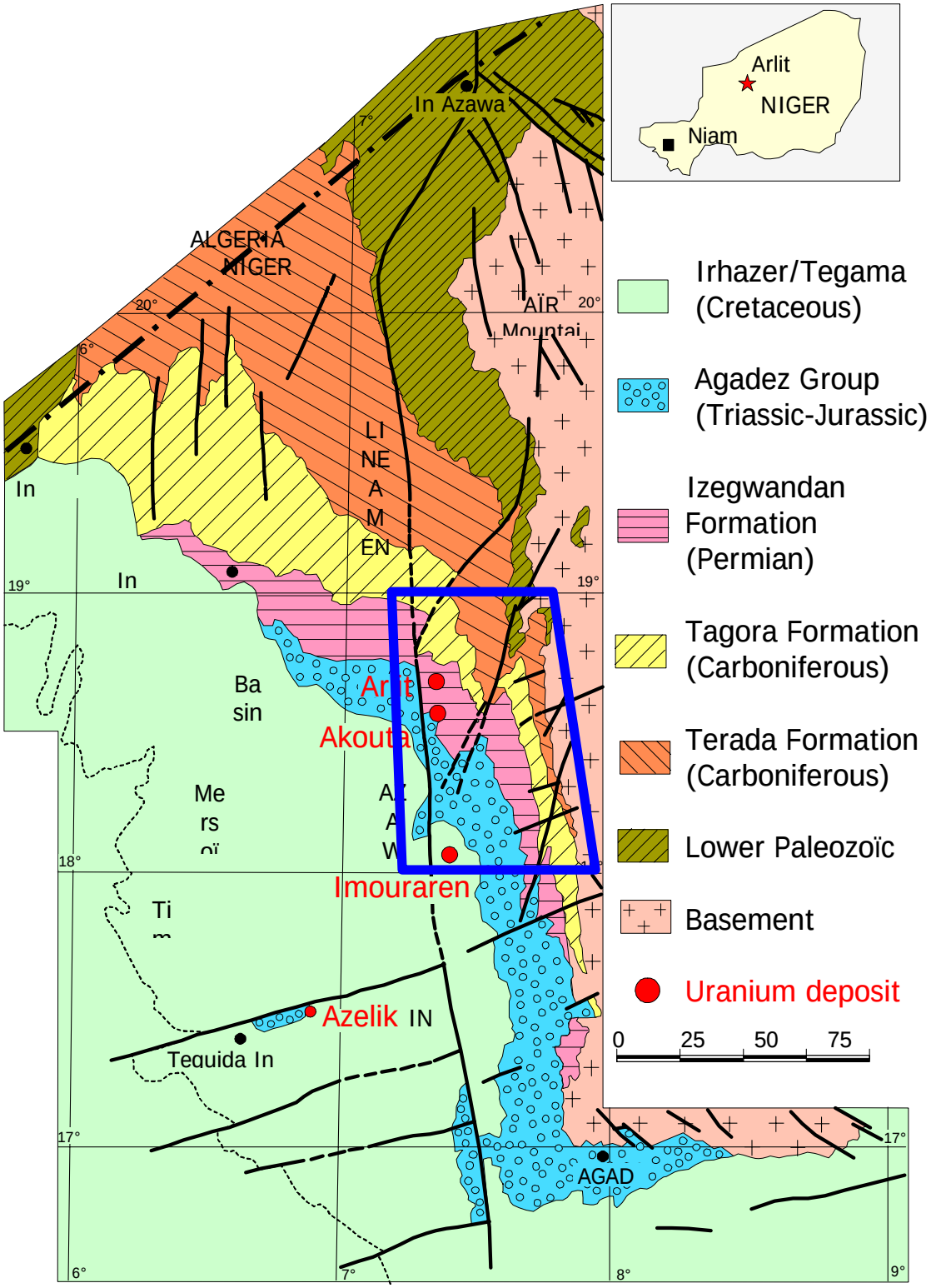

FIG. 5. Geological map of the eastern Tim Mersoï basin (after Julia 1960) and 2003. airborne perimeter

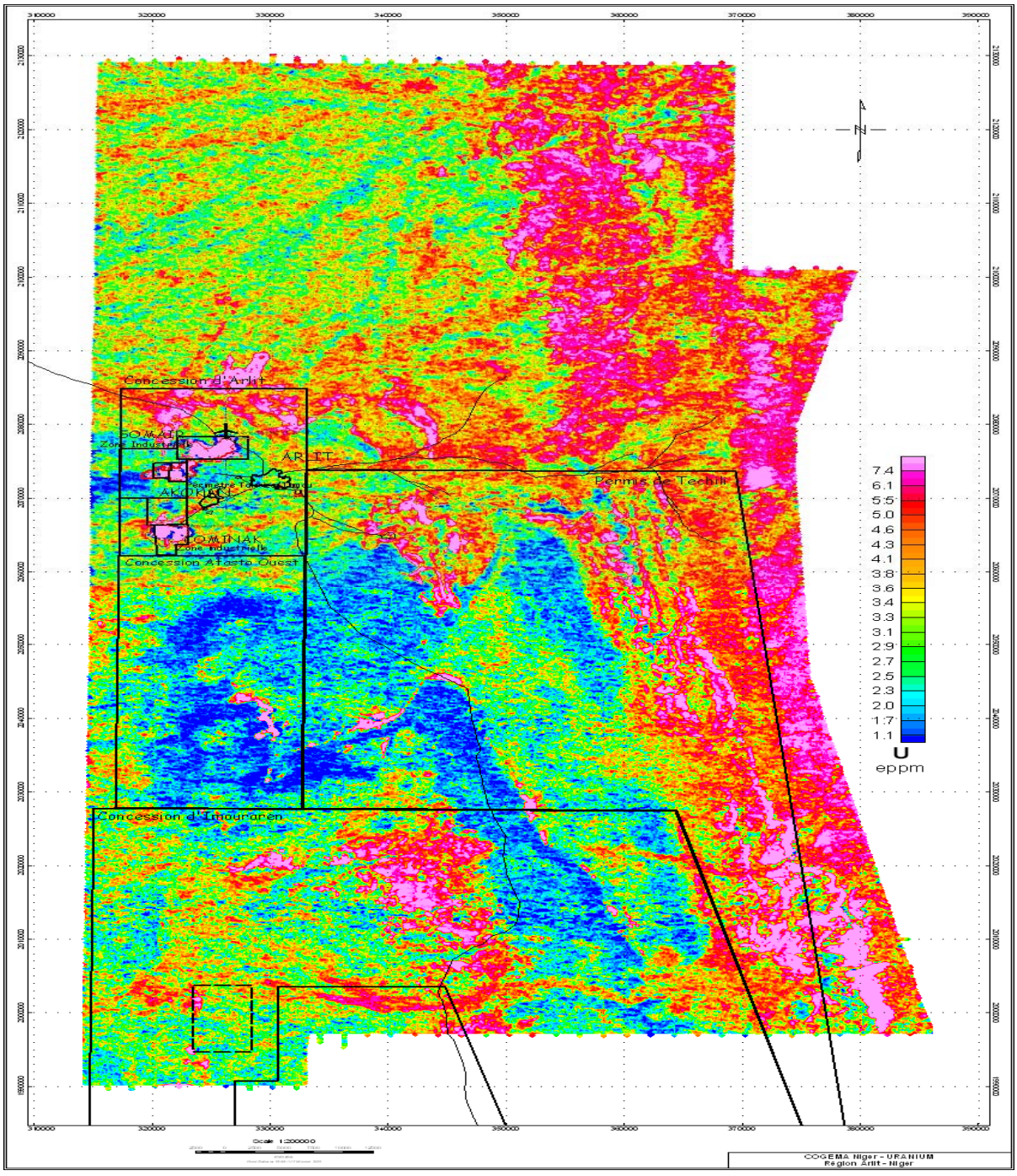

FIG. 6. Airborne results showing uranium occurrence.

FIG. 7. Drilling campaign over Afasto deposit.

6. Sustainable development aspects

Over the past 40 years Areva carries out its activity with real support to its surroundings and Niger institutions, but also its employees.

This effort can be summarized below.

Table II. Sustainable development figure

Local employment	• 1 637 workers (20 000 people including family members) at end of 2004, 600 indirect payroll; 99% of workers and management are from Niger.
Education and training	• Training centers inside companies, Emaîr (Agadez) for supervisers training, abroad centers for specialized needs (Italy, Senegal, France).
Infrastructure and Energy	• 600 km of road Tahoua-Arlit, Coal power plant at Tchirozerine 99%of output mining dependant.
Radiation protection and Environment	• No worker over 18 mSv since end of 2003, added dose value < 1 mSv for environment. Somaïr and Cominak ISO 14 000 certified.
Safety	• Accident rate slowing steadily since ten years, < 7
Social	• 70 000 people in Arlit and Akokan, with free access to companies hospitals and water supply. Much help to schools.

Moreover, starting from 2003, Areva went through a global SD initiative to support its activities all over the world.

A global Policy is built for Niger related to the mining area. It aims to consolidate what has been done so far, and wide open the scope with:

- a local economic development program,
- dialog and consensus building with different level stakeholders,
- reassessment and budgeting future rehabilitation program.

7. Conclusion

Enjoying more than thirty years of safe, efficient and smooth operations, Areva production in Niger appears as an essential component for a suitable stability of World uranium supply, and particularly for the European Union.

The uranium reserves indicates that mining operations can continue to operate at current output for more than a decade.

The resources base already identified means that several more decades of production are very likely, and the geological appraisal of the overall potential provides an even more optimistic view.

Combined with safe, environmentally benign operations such a potential will ensure Niger a long term income from its uranium exports, and the delivered countries a secure and long term supply.

1958: Discovery of uranium showings at Azelik by the "Bureau Minier de la France d'Outre-mer"
1958: Detailed study of the showings and airborne & field surveys by the French "Commissariat à l'Energie Atomique"

1958: December: Creation of the Republic of Niger
1959: Discovery of Azelik and Abakorum deposits
1960: August 3: Niger Independance
1963: Discovery of the Madaouela deposit
1965: Discovery of Arlette, then Ariège, Artois, Taza, Tamou and Takriza
1966: Discovery of Imouraren
1967: Discovery of Akouta
1968: Setup of the Société des Mines de l'Aïr (SOMAIR)
1971: First commercial production in Arlit (SOMAIR)
1972: Discovery of Ebala
1974: Incorporation of the "Compagnie Minière d'Akouta" (COMINAK)
1974: Imouraren Joint Venture Agreement
1978: First commercial production in Akouta (COMINAK)
1979: Incorporation of the "Société Minière de Tassa N'Taghalgue" (SMTT)
1996: SOMAIR purchases SMTT assets
2002: Re-activation of exploration and development programs (TAGORA project)
2006: Expected milestone: 100 000 tU of cumulated commercial uranium production in Niger

TOPIC 5 - WASTE MANAGEMENT

ICRP path forward to the next recommendations
WNA preliminary views on the ICRP proposed profound changes to the current RP system and on continuing to build an international consensus towards an improved proposal

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[b] RPWG - The Radiological Protection Working Group of the WNA

Abstract. For several years, international policy on radiological protection has been under discussion with a view to a significant revision (recently delayed until 2006-2007). The focal point of this discussion has been an evolving draft proposal of the International Commission on Radiological Protection (ICRP). The ICRP's seminal role in its field is well-known. Generally, ICRP recommendations are translated into the international and national standards that govern industry operations worldwide.

The current ICRP draft proposal, which is entitled: "2005 Recommendations of the International Commission on Radiological Protection", was presented in May 2004 at a key international conference called IRPA-11. This proposal emerged from two earlier forums jointly organized by ICRP and the Nuclear Energy Agency (NEA) of the Organization for Economic Co-operation and Development (OECD). Moreover, following IRPA-11, ICRP launched an open consultation on its draft proposal that ended in December 2004.

This openness in the development of the next ICRP recommendations has been widely appreciated by the international RP community and no doubt helped many parties further reflect on the current RP system and on its potential evolution. Further to this open consultation process, ICRP acknowledged the overall negative reaction its draft proposal provoked. The key reasons that seem to explain this negative reaction are that:

1. The ICRP proposal includes a number of 'Profound Changes' to the current RP system
2. The general context does not warrant such changes
3. The overall rationale of the ICRP proposal is insufficient in view of such changes

The most fundamental of these 'Profound Changes' (detailed herein in Annex A) are:

1. The introduction of new dose constraints (per single source) that are given a primary, broader and stricter role than the current dose constraints (defined as part of the current optimization procedure) and even than the current dose limits. Figures 1 and 2 herein illustrate the potential magnitude of this issue.

2. An RP system to be based on natural background radiation rather than on the well-developed health risk-based approach of the current RP system.

[†] The Radiological Protection Working Group (RPWG) of the WNA consists of well versed radiological protection professionals from various sectors of the nuclear industry and from various countries (Canada, France, Japan, Sweden, United Kingdom, United States) The list of RPWG members is shown in Appendix 1.

3. A broad policy on the RP of non-human species and subsequent steps are prematurely introduced as an integral part of the RP system – while the current common position is to first develop an international consensus on the need for such a system, and then, if necessary its form and content. This is to be developed through an IAEA international action plan (yet to be approved by the Member States) that will coordinate, over the next few years, the input from many parties, including those from IAEA, UNSCEAR, ICRP and many others.

Key factors that show that the general RP context does not warrant such 'Profound Changes' include:

- There is widespread recognition of the need for stability in regulatory systems - many international and national regulations have only fairly recently been brought into line with the current RP system.

- The current RP system is working well for 'Practices'.

- ICRP's new scientific evidence that indicates that the overall risk from ionizing radiation is slightly lower than originally thought (ICRP60), is further confirmation of the adequacy of the current RP system.

Our views are that the current RP system can and should be improved through consolidation and simplification with substantive changes being focused to correct specifically identified shortcomings or weaknesses. For a careful and smooth evolution of the current RP system, it is essential that any proposed changes do not unnecessarily disturb the current RP system for "Practices" (e.g. see Figs 1, 2). The ICRP draft proposal should clearly identify shortcomings or weaknesses and explain how it specifically helps to address them. It is precisely this overall rationale that is insufficient.

In March 2005, ICRP asserted that many comments on its draft proposal "arise because the Foundation Documents (FDs) have not yet been put out for consultation". The resulting expectation is that the ICRP five draft FDs[1] will complement its draft proposal (including the overall rationale of the proposal).

ICRP's openness with regard to the on-going consultation on these draft FDs is appreciated. The consultation deadlines are July 10 for FDs #1 and #2 and July 24 for FDs #3 to #5. In view of the expected close relationship between the current ICRP draft proposal and draft FDs, the WNA plans to provide comments to ICRP in two steps: 1) broad level comments by June 2005, and 2) more specific comments on each FD by the above-mentioned deadlines.

In the interim, WNA felt it important to draw the attention of the international RP community to the WNA preliminary views about the ICRP draft proposal (and FDs) in the context of continuing to build an international consensus towards an improved draft proposal. In the next pages, these views are presented in the following categories:

1. Areas that seem to be in line with the current international consensus
2. Areas that seem to have evolved but need to progress further
3. Areas that seem to depart from the current international consensus

In view of the upcoming ICRP deliberations, we hope that this information could be useful to a wide range of interested parties for the preparation of their own submissions to ICRP.

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[1] The ICRP five draft FDs are:
1. "The Optimisation of Radiological Protection – Broadening the Process"
2. "Assessing Dose of the Representative Individual for the Purpose of Radiation Protection of the Public"
3. "Biological and Epidemiological Information on Health Risks Attributable to Ionising Radiation: A Summary of Judgements for the Purpose of Radiological Protection of Humans"
4. "Basis for Dosimetry Quantities Used in Radiological Protection"
5. "The Concept and Use of Reference Animals and Plants for the Purposes of Environmental Protection"

WNA Preliminary Views on the ICRP Draft Proposal (and FDs) in the Context of Continuing to Build an International Consensus towards an Improved Draft Proposal

I - Areas that seem to be in line with the current international consensus

1. "There is no hurry" – in terms of significant work that lies ahead for the development and completion of a suitable proposal for the next recommendations.

2. The overall intent to consolidate and simplify the current RP system with a view to making it easier to understand and comprehend.

3. The indications that the proposal "will consolidate and replace all the numerical advice included in and developed" since ICRP60 "(stand-alone document)".

4. The indications that the Principle of 'Justification' will be re-integrated.

II - Areas that seem to have evolved but need to progress further

1. The draft proposal shows progress in terms of the consolidation of information into a main stand-alone document. ICRP should consider further consolidating this information. Key suggestions for the main stand-alone document are:

    - Significantly expand (preferably at the beginning) the rationale that identifies the specific shortcomings or weaknesses of the current RP system and explain how the proposal specifically helps to address them, without unnecessarily disturbing the rest of the current RP system.

    - Significantly expand (preferably at the beginning) the core information about the ICRP itself (its mission, role, aim, scope, etc., including its relationships with other key international organizations) so that a non-familiar reader can have a broader view and understanding of ICRP and of its recommendations. This would be of great value to a broad range of stakeholders.

    - Group all policies together along with the key numerical values of protection (i.e. dose limits). Simply stating that some or all post-ICRP60 policies continue to be valid does not really address the current concern about clarity.

    - Simplify the number of key numerical values of protection. At the international level, numerical dose limits should be kept whereas numerical new dose constraints (per single source) should not as the latter cannot be possibly integrated without raising important issues about the current RP system. (Though, the current concept of dose constraints should be kept.) *Annex B* herein further elaborates on this issue.

    - The supporting scientific information (such as the dose conversion factors) could be integrated into separate more detailed documentation. This would facilitate updating this data without triggering a review of the main document.

2. It is well recognized that the RP system for 'Intervention' is causing some difficulties. Further ICRP guidance in this respect would be most welcome provided that it does not perturb the RP system for "Practices". Some progress has been made but further guidance is needed. For example, guidance on the specific context for using higher values than the current dose limits for the public is needed.

3. Extremely low doses – ICRP should consider recommending more clearly, for sound policy making, a practical dose level (which would theoretically bear some tiny risks) from which protection should be systematically ensured – and in turn prevent applying the RP system where

it is unlikely to produce any substantive RP benefit. ICRP should consider incorporating this practical dose level in its guidance on estimating risk from ionizing radiation and on the scope of application for "Collective Dose". Similarly, the concepts of "Exclusion" and "exemption" are welcome but ICRP should consider further alignment with the international consensus reached by the IAEA (2004) on this key topic (*Annex C*).

III - Areas that seem to depart from the current international consensus

The 'Profound Changes' addressed earlier herein depart from the current international consensus:

1. The introduction of new dose constraints (per single source): see Fig 1, 2

We suggest keeping the current concept of dose constraints intact without introducing the concept of new dose constraints (per single source).

2. The RP system is based on natural background radiation rather than on the well developed health risk-based approach of the current RP system

We suggest keeping the current health-risk approach for the basis of the RP system while allowing natural background radiation to be used as a useful comparator and for practical context.

3. A broad policy on the RP of non-human species and subsequent provisions are prematurely introduced as an integral part of the RP system

We suggest keeping this on-going development outside of the scope of the draft proposal and FDs and ensuring that it is an integral part of the IAEA joint international effort. Once it is internationally road-tested and understood, the ICRP model on Reference Animals and Plants (definition and dosimetry) may eventually prove to be a key component in the development of an RP system for non-human species. The ICRP subsequent steps (e.g., a common approach, assessment of effects, derived consideration levels, etc.) on the potential use of this model are premature at this time.

4. Other "Profound Changes"

- Justification, Practices and Intervention

We suggest that the "Justification" Principle and the concepts of "Practices" and "Intervention" should be re-integrated as per the current RP system. Further developing the guidance on the concept of "Intervention" would be an improvement.

- Optimization

We suggest that the "Optimization" Principle should be kept as per the current RP system. Removing the new concept of dose constraints (per single source) should help to achieve this. Best Available Technology (BAT), not entailing excessive costs, should be part of Optimization with considerations for health-driven standards. This would be more consistent with the "Optimization" Principle and with the fundamental aim of the draft proposal which includes "the balancing of risks and benefits".

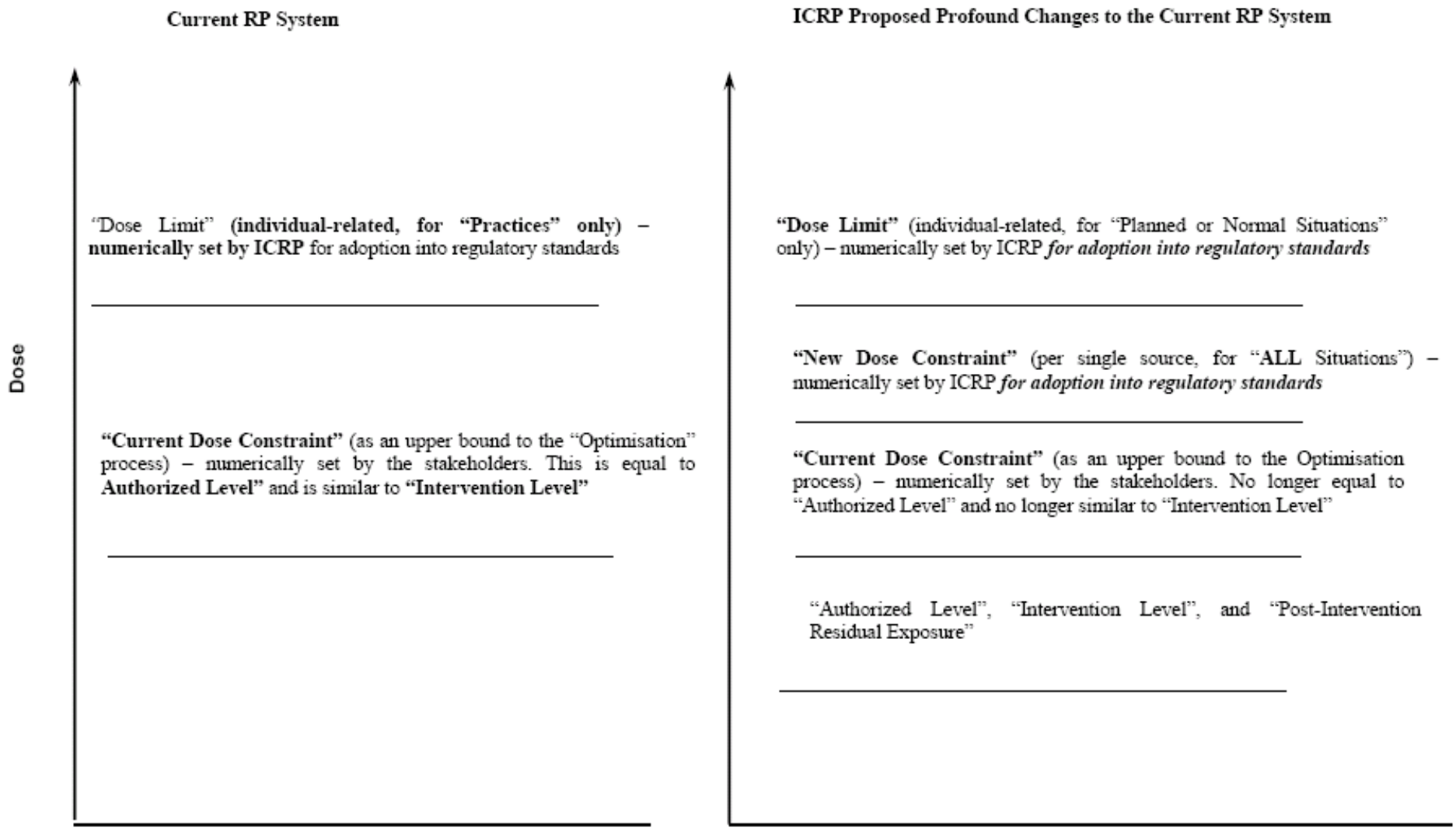

FIG. 1. Comparison between current and proposed systems.

Key Features of the Current RP System:

"Justification", "Optimisation" and "Limitation"

- Well implemented into the regulatory context

"Dose Constraint" as the upper bound of the "Optimisation" process

- Well implemented into the regulatory context
- "Dose Constraint" for "Practices" equals "Authorized Level"
- "Dose Constraint" for "Intervention" is similar to "Intervention Level"

Context of Application for "Practices" and "Intervention"

- Well implemented into the regulatory context

Key Features of the Proposed RP System:

"Dose Limit", "New Dose Constraint (per single source)" and "Expanded Optimisation"

- "New Dose Constraint" can interfere with "Dose Limit" and "Optimisation", thus it can in turn interfere with compliance matters and the "Current Dose Constraint" set by stakeholders
- How "Dose Limit" and "New Dose Constraint" can co-exist?
- As the current "Dose Limit" does not apply to "Intervention", New Dose Constraint" for "Accident/Emergency Situations "or for "Existing Controllable Exposure Situations" would represent a regulatory change
- Would "Justification" be re-integrated?

"Current Dose Constraint", "Authorized Level", "Intervention Level", "Post-Intervention Residual Exposure"

- Does the "Current Dose Constraint" remain unchanged – e.g. as the upper bound of the optimisation process? What is meant by "Authorized level", "Intervention Level" and "Post-Intervention Residual Exposure"?

Context of Application for "Planned or Normal Situations", "Accident or Emergency Situations", and "Controllable Existing Exposure Situations"

- Do the fundamental concepts of "Practices" and "Intervention" (and their differences) remain unchanged?
- Can a single "New Dose Constraint" apply to "ALL Situations"?

Note: "Optimisation" inherently accounts for social and economic factors.

FIG. 2. Key features of current and proposed RP systems.

ANNEX A

ICRP Proposed 'Profound Changes' to the Current RP System

1. The introduction of new dose constraints (per single source) – See Figs 1, 2

By 'Profound Changes', we mean moving from the ***current RP system*** consisting of:

- "Justification",

- "Optimization" - with "Dose Constraints" (equals to "Authorizel Levels" for "Practices", and is similar to "Intervention Levels" for "Intervention") as upper bound of this process,

- "Limitation" ("Dose Limits" for "Practices" only), and the separate domains of "Practices" and "Intervention";

to the ***proposed RP system*** consisting of:

- *Dose limits (for "Planned or Normal Situations" only)*,
- *New Dose Constraints, per single source, that are given a primary, broader and stricter role than the Current Dose Constraints (defined as part of the current optimization procedure) and even than the Current Dose Limits,*
- *Expanded* "Optimization" - with the "Current Dose Constraints as upper bound of this process,
- *"Authorized Levels", "Intervention Levels", "Post-Intervention Residual Exposure", and the new domains of "Planned or Normal Situations", "Accident and Emergency Situations" and "Controllable Existing Exposure Situations"*.

How could an RP system that includes dose limits, new dose constraints, the current dose constraints (the latter defined as upper bound to the optimization procedure), authorized levels, intervention levels, and post-intervention residual exposures work better in practice? What are the differences between dose limits, new dose constraints, current dose constraints and authorized levels (intervention levels and residual exposures)? How would this be simpler and easier to understand and comprehend? How could an RP system that makes dose limits secondary to more stringent new dose constraints be consistent with one of the main outcomes of the ICRP/NEA forum in April 2003 (Lanzarote, Spain) namely to "keep dose limits"? This implied that dose limits should remain the most stringent level of protection and that the concept of current dose constraints should stay intact as part of the optimization.

It is also important to emphasize that it is not clear that the new dose constraints, per single source, would be a better concept than dose limits. For example, new dose constraints, per single source, may not always be relevant for occupational exposure. In practice, the dosimetry of workers at the management level and at the national dose registry level are excellent means to ensure that all exposures are accounted for. (It should be borne in mind that a dosimeter can cover all occupational exposures even from sources that may have been overlooked.)

2. The RP system is based on natural background radiation rather than on the well developed health risk-based approach of the current RP system

We recognize that a reference to natural background (including radon!) and to its inherent variability is a useful comparator and gives practical context for appreciating the appropriateness of protection actions. We believe that it is important to retain this. However, assessment of dose limits must continue to be guided by the question of whether a significant health risk is posed. For example, linking the public dose limit to health risk evidence is extremely important even if this may involve accounting for some kind of a safety factor.

Current ICRP discussions seem to indicate that some connection is to be drawn between the world average natural background, which becomes 1 mSv/y if the contribution from radon is excluded, and the allowable public dose limit. The fact that this "without radon" level is roughly the same as the current public dose limit of 1 mSv/y is purely coincidental and has no scientific significance regarding the question of the adequacy of the public dose limit.

Moreover, it is important to keep the system flexible in view of potential future health risk evidence that may trigger changes to the key values of protection (e.g.. dose limits). Irrespective of background, lower values may become appropriate should the risk from radiation be higher and vice-versa. The health risk assessment approach is fit for both human and non-human species. The case for moving away from a risk-based RP system to a RP system based on natural background radiation is not compelling.

3. A broad policy on the RP of non-human species and subsequent steps are prematurely introduced as an integral part of the RP system

It is important to recall here that the current common position is precisely to develop an international consensus on the need for an RP system of non-human species, and if necessary, the form and content of such a system (IAEA draft international action plan, June 2004). The common understanding is that an IAEA international action plan (that is yet to be approved by the Member States) will coordinate, over the next few years, the input from many parties, including those from IAEA, UNSCEAR, ICRP and many others.

Logically, ICRP's ground work on non-human species that is being developed by its new committee on the environment should be part of this joint international effort and the necessary time should be taken to have these emerging concepts internationally understood and "road-tested" prior to considering any subsequent steps. It is essential that ICRP maintains a clear distinction between its ground work on non-human species and the well-matured material (RP system for humans) that is expected to form the basis (as Foundation Documents) of its next recommendations. Clearly, the case for introducing a broad policy on non-human species and any subsequent steps is premature at this time.

4. Other 'Profound Changes'

"Justification", "Practices" and "Intervention"

- The Principle of "Justification" is eliminated

- The key concepts of "Practices" and "Intervention" are replaced by the new concepts (not yet defined) of "normal operations" or "planned activities", "accident or emergency situations", and "controllable existing situations"; thus eliminating the important distinction between "Practices" and "Intervention". It should be borne in mind that the well advanced international consensus on the "Principles of Nuclear, Radiation, Radioactive Waste and Transport Safety – DS298 – Safety Fundamentals" at the IAEA level, embraces the key concepts of "Practices" and "Intervention".

Optimization

- By definition, new dose constraints (per single source) are substantially different from the current dose constraints. This would imply corresponding changes to "Optimization".

- Indicating that Best Available Technology (BAT) and "Optimization" complement each other, can possibly substantially modify the essence of the "Optimization" Principle. BAT not entailing excessive costs, should be part of Optimization with considerations for health-driven

standards. This would be more consistent with the "Optimization" and with the fundamental aim of the proposal which includes: "the balancing of risks and benefits".

ANNEX B

The Key Issue of Simplifying the Number of Numerical Values of Protection

Whereas there is a strong international consensus for integrating the current dose limits in a consolidated main document, numerical new dose constraints (per single source) which would be more stringent than the current dose limits cannot be possibly integrated without disturbing the current RP system. Other key fundamental scientific values (such as the dose conversion factors) can be integrated in separate ICRP documentation.

We recognize that industry and many others may not have reacted when such more stringent numerical dose constraints were published, but it should also be recognized that the ICRP process for dealing with these values has not been subject to the same level of openness and international discussions/debates that ICRP60 and the current ICRP draft proposal were subject to. Anyhow, the fact remains that the proposed basis for these values appears weak and that these values have still not benefited from a real debate. Should this be relevant, applying the new ICRP MUM (Meet Understand and Modify) approach would be most welcome here.

With this in mind, prudence and concern with regard to continuing to build a solid international consensus suggest that the case for having numerical new dose constraints (per single source) in parallel to the current dose limits, thus interfering with the optimization process (accounting for social and economic factors), stakeholder involvement, and ultimately compliance matters, is not compelling. One cannot preclude that it may not be possible to define such values at the international level.

ANNEX C

Practical Dose Level for Making Sound Policy Making at Low Doses, Collective Doses, and Exclusion, Exemption and Clearance Levels

Practical dose level for sound policy making at low doses – Defining a dose level from which protection should be systematically ensured – and in turn preventing the application of the RP system where it is unlikely to produce any substantive benefit - is a necessity for sound policy making. Based on Optimization and its essential aim of achieving a reasonable balance of risks and benefits, it is clear that down to very low and extremely low doses, such a practical dose level has an important role to play even if it would bear some tiny theoretical risks. ICRP should consider incorporating this practical dose level in its guidance on estimating risk from ionizing radiation and on the scope of application for "Collective Dose".

We recognize that the context of the ICRP CI Task Group draft report may not be the suitable place to address this. However, the matter of adopting such a dose level on the basis of a reasonable balance between scientific and non-scientific issues should be seriously considered by the ICRP (at the upper level – e.g. Committee 4 or the Main Commission itself).

Collective doses – We welcome the ICRP effort in limiting the scope of collective dose. As such, we recognize the value of disaggregating the collective dose results, provided that this procedure also includes a dose level as mentioned above.

Exclusion and exemption levels – Similarly, we would welcome the concept of concentration levels from which protection should be systematically ensured. As part of optimization, provisions for higher concentration levels in the context of exemption and clearance levels would represent an improvement. This is another practical area where balancing beneficial actions giving rise to radiation exposure and the detriments of radiation exposure are particularly important. Further guidance would

be welcome here. We would also welcome further alignment with the international consensus reached by the IAEA in 2004 on the key topic of exclusion, exemption and clearance levels.

APPENDIX 1

WNA RADIOLOGICAL PROTECTION WORKING GROUP – RPWG
(Official List – May 31, 2005)

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BARC (India)	Ambika Shai Pradhan
Barsebackkraft (Sweden)	Carl Göran Lindvall
BNFL-BNG (UK)	Roger Coates
Cameco (Canada)	Al Shpyth, *Vice-Chair*
Cameco (Canada)	John Takala
CEZ (Czech Republic)	Josef Koc
CNNC (China)	Huiling Cong
EDF (France)	Yves Garcier
Enusa (Spain)	Guillermo Sánchez
ERA (Australia)	Ian Marshman
KANSAI (Japan)	Shinichiro Miyazaki, *Chair*
NEI (USA)	Ralph Andersen
OPG (Canada)	Robin Manley
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WM Mining Inc (USA)	Wallace Mays
WNA (International)	Sylvain Saint-Pierre, *Secretariat*
WNA (International)	Tetsuji Kishida, *Mentor, WNA Board*

Corresponding Members

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Conceptual model for water management in Brazilian semi-arid regions
From intervention to sustainability, case of Lagoa Real Uranium Plant

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Abstract. The world water lack problem has been already diagnosed and is acknowledged as one of the greatest challenges for this century. The scientific literature, documents and either nationals or internationals official reports like the Brazilian Water Agency (ANA) and UNESCO point out the main shortages and general management practices. Also in Brazil, it's a multi-facet problem that envelops several social agents for many decades and has tragic consequences in some regions of the country, like is the case of the northeastern semi-arid region. This work presents the strategies for expertise integration to attend demands for the establishment of partnerships that include several institutions, with different experiences in the region, to improve the acquaintance with dry climate in Brazilian semi-arid. The general objective was developing a conceptual model of technical multi-institutional arrangements as tools for aquifer management, promoting sustainable use of groundwater in the semi-arid region. Here, we present a conceptual model based in technical, political and socio-economical dimensions of sustainability that exchange information among them and with management requirements. This process must be turned in more productive agricultural systems with the introduction of new technology that respect the family arrangement of the production units. It is also expected that validation of this conceptual model allows an applicable alternative to other areas in the future, respected of course all the geo-socio-economical constraints of each site.

1. Introduction

In order to cope with uranium demand from the internal market, and with the possibility of the beginning of operations of a third nuclear power plant (Angra III) there was a need to reactivate the Brazilian uranium production. It was achieved by the start of production at the Lagoa Real uranium province production center in 1999. The deposit was discovered in 1977 and its known resources were estimated to total 85 000 t U at the below US $80/kgU cost category [1]. The ore is mined by open pit methods and uranium is extracted by acid heap leaching. A capital investment of US $23 million is reported. The newest uranium plant being operated in Brazil is located at a semi-arid region, in the municipalities of Lagoa Real and Caetité, State of Bahia, northeast region of Brazil, which shows rainfall rates of 800 mm/a.

The conceptual operation plan did not include liquid effluent releases into the environment. However, the evolution of mining process showed that several climatic and geo-environmental features (e.g. strong rainfall during short periods and increase of radionuclide concentrations in groundwater) were not take into account and must be addressed by the establishment of one Water Management System (WMS). This is a control system that allows operator to manage water volumes from run-off, even during very high events of precipitation. On the other hand, the knowledge of the hydrogeological patterns is one main issue to understand recharge process and water-rock interaction that determine the groundwater quality. These informations processed in data banks coupled with georeferred images in an integrated system will be one essential tool for the water management of the region.

Data from the monitoring program carried out by the mining operator revealed that increases in uranium concentration in groundwaters at the influence area of the open pit are already being observed. In addition, elevated uranium concentrations in wells out of the influence of the mining

activities are also observed. Because of that, water from these wells cannot be released to the local population and there is a need to prove the inhabitants that the mining and milling operations are not affecting these waters. Besides the influence of mining activities in the groundwater other pollutant sources have to be assessed like the waste-rock/leached ore piles as well as the leaching tanks.

2. Description of the study area

2.1. Uranium production unit (URA)

The uranium province of Lagoa Real is located at the Center-South region of Bahia State, and has high-grade uranium deposits with average U_3O_8 concentrations of about 0.3%. The site has 34 radiometrical anomalies spread over an area of 1 200 km^2. The ore bodies are distributed along an arch structure 40 km long with its central part defined by the geographical coordinates 13o56'36" S and 42o15'32" W.

Mineralogical analysis of the ore bodies shows that 65 to 70% of the rock is composed by plagioclase-albitite; 10-20% by pyroxene; 2.5% by granade; 2.5% by epidote; 1.5% by biotite and 1-2% by carbonates. Uranium occurs as uraninite by means of discrete inclusions or interstitial grains in the mafic minerals, mainly aegirite-albitite or is present in the inner albitite crystals [2].

The Cachoeira ore body shows the highest uranium concentration, i.e., 2 320 ppm U_3O_8 and holds the major reserve amongst the 34 anomalies. Mining activities are developed at an open pit cast. The depth is supposed to reach 140 m. Mining operations are expected to continue over 16 years. The initial production is estimated to be about 400 t of DUA.

Uranium extraction is made by the Heap Leach method. Piles of 25 000 to 35 000 are constructed. The granulometry of the ore within the piles is in the range of 3/8" and 1". At these conditions the solubility is estimated to be about 70%. The exhausted ore is disposed off in piles along with the waste rocks from the mining activities. The leaching solution is captured in holding tanks that are covered with geo-synthetic membranes (PEAD). The liquor is the pumped to the milling unit where the uranium is isolated by means of organic solvent extraction and then precipitated as ammonium di-uranate (yellow-cake).

2.2. Geological background

Geological studies accomplished in the region show that the local geological framework of the area is constituted predominantly by rocks metasomatic metamorphic of the crystalline bedrock, with structure cataclastic, especially granitoid, orthogneiss and albitite. Those rocks are partially covered with sediments detrital, sandy-loam, little or nothing consolidated, with thickness that doesn't surpass to 50 meters. The regional metamorphism of the granitoids led to the formation of the orthogneisses. This rock type constitutes the host rock of the albitites bearers of uranium mineralisation. The uranium occurs under the uraninite form through tiny inclusions or interstitials granules of the mafic minerals, mainly aegirine-augite, or they are present inside the albite crystals [3].

The area in study suffered considerable tectonic activities. Previous studies show that the great general structural features of the area are related to glide away stress domains with great lineaments of general direction N-S. The occurrence of mineralized bodies reflects a strong structural control. The albitites are distributed, basically as two main alignments in form of arches, with trend varying of NE in the southern extremity to N-S in the center, changing for NW in the northern limits of the Uranium Province, characterizing a long sigmoid structures. The most important fault system in the area is represented by fault with movement (gravity and/or push) of E for W [4]. Those features are usually in agreement with the predominant foliation that is of cataclastic origin. The observed faulting is defined by two main systems, usually sub-vertical, being approximately a parallel the direction of the foliation and other perpendicular. The folds are incipient and subsequent to the ductile shear. The existent folds are intra-foliates of type sheath folds. Although, in Cachoeira deposit a great fold of the reclined type was evidenced with 200 meters of width. In the deposit area the gneisses occurs in a compact way,

with direction varying between N50-60W and with the dip of 60 NE or possesses level of variable lamination. Geophysical studies indicate that the zone of preferential fracturing in the rocky system happens up to 30 meters of depth [4].

2.3. Physiographical aspects

There are three main geomorphologic units; plane relief, hillsides and alluvial terrace limit the study area.

The unit plane relief occupies the higher topographical portion of the area, the altitudes vary from 750 to 1 100 meters, with surface almost glides. This unit presents slope smaller than 10% and is sustained by granites or alkali-gneisses. The covering is residual detrital with restricted zones of outcrops. The drainage is incipient due to the low topographical gradient and the processes of infiltration of pluvial waters are accentuated. The vegetation is a kind of brushwood (caatinga) or savannah (cerrado) and locally arboreal.

The unit hillside occupies the intermediate topographical portion between the plane tops and the lowlands, possessing variable slope between 10 to 20%. This unit develops accentuated downhill, when happens on granitics and gneisses rocks. The residual and/or transported soils of composition sandy-loam to silty-loam cover most of this unit. The downhills exhibit morphology as rectilineal soft, convex and rarely concave. In function of the concentration of the pluvial drainage they present, locally, erosion forms associated to gully and rill-erosion. The predominant vegetation is secondary, having an alternation between old pastures and cultures of subsistence.

The unit alluvial terrace occupy the valleys floor and flood plains of the main drainages of the area. This unit is filled out by sediments alluvial-colluvial, of sandy-loam composition with particle size varying of fine the average.

The area in study is drained by the Vaca stream, tributary of the high course of Fundo stream, including in the right margin the sub-basins of Gameleira, Cachoeira and Engenho streams and in the left the Varginha stream. The streams are ephemeral, dry in the winter and torrential in the rainy station. The drainage pattern is in way general dendritic and with variable density. The climate is tropical hot and humid, with a marked wet season from October to April being dry the rest of the year. The total rainfall averages 800 mm/y. The average annual temperature is 22^{o}C and more than 80% of precipitation falls between October and March

3. Water Management Issues

The conceptual framework

For mining operations it is vital to plan for minimization of impact at the earliest stages, as few changes in layout are possible once operations have commenced. Accordingly, it is important that the company manages the EIA (Environmental Impact Assessment) process professionally and impartially from the outset, and carry out regular auditing after operations starting operations. The main impacts of pollutants to water resources in the mining area are:

(a) Drainage from mining sites and pumped mine water;
(b) Sediment runoff from mining sites;
(c) Effluents from minerals processing operations (ideally the plant operates in a closed system);
(d) Soil contamination;
(e) Leaching of pollutants from tailings and disposal areas and contaminated soils.

The company should set itself measurable environmental targets. These targets have to accomplish all the aspects concerning to water management procedures, starting with the water budget of each step of the mining and milling process. It must take to account all forms of water input and output (e.g. water

used in the process, water reused, water wastes, water run-off, water storage) to achieve a trustworthy balance which permits to establish suitable procedures to water management.

Figure 1 shows the conceptual model based in technical, political and socio-economical dimensions of sustainability that exchange information among them and with management requirements.

Figure 2 shows the logical framework based in the following integrated aims:

(1) Assessment of social-economical dimension and establishment of environmental education program;Produce geological and geophysical regional mapings and detailed scale cartography for the pilot areas;
(3) Frame environmental diagnosis to produce useful information for water resources management (e.g. land-use, climate, recharge);
(4) Increase water supply for multiple uses (e.g drill and recover wells, water desalination);
(5) Assess environmental impacts and risks to human health;
(6) Research and implement social actions seeking for sustainable development in the selected areas;
(7) Design georeferred data banks with social-economics and environmental information to provide direct assistance to water management decision makers.

This framework seeks to show that the tools developed to water management in poor regions, in spite of several other possible ways, should necessarily be compromised with some basic assumptions. The first one is the technical support, through developing studies involving multiple basic and applied scientific fields (e.g. geology, hydrology, chemistry, ecology, engineering, economics and sociology). It is fundamental to force the use of this knowledge in the decision making process about water planning.

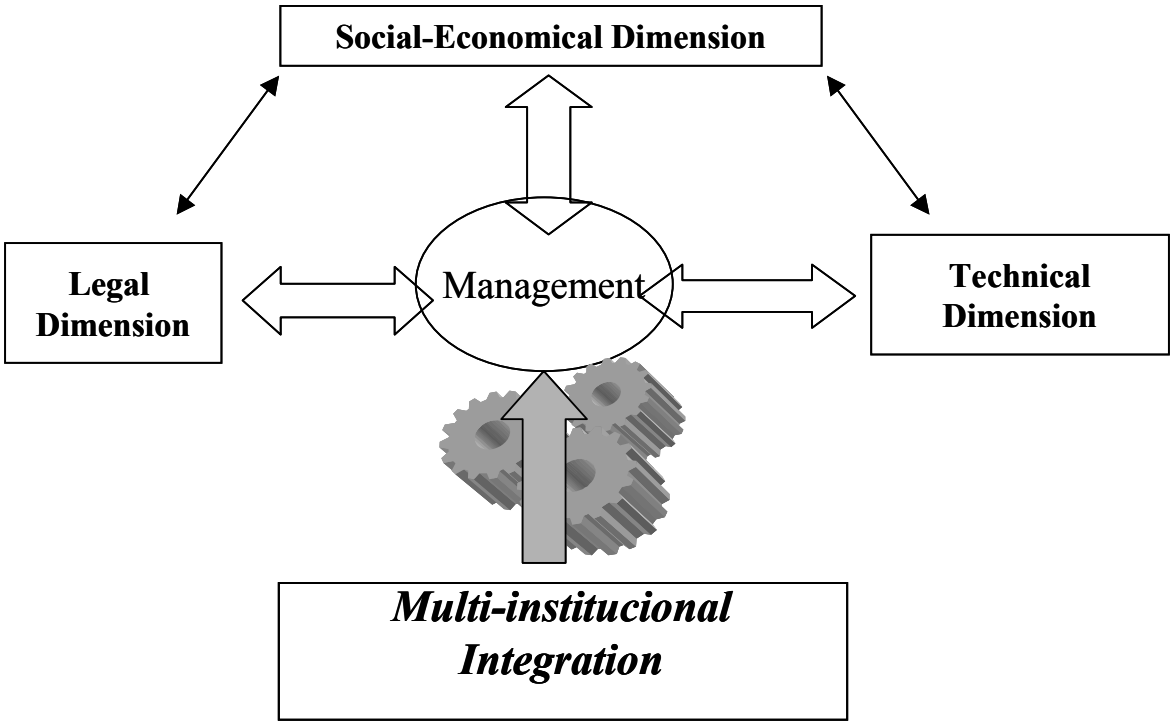

FIG. 1. Conceptual model of water management with the dimensions of sustainability.

A second assumption is the optimization of the activities through one thematic frame that avoid the actions overlay and seek for completeness. Finally, other aspect which can not be neglected is the fact of water offering is not enough; It means the offer need to be transformed into sustainable (measurable) economical improvement with respect to the social and cultural values of each community.

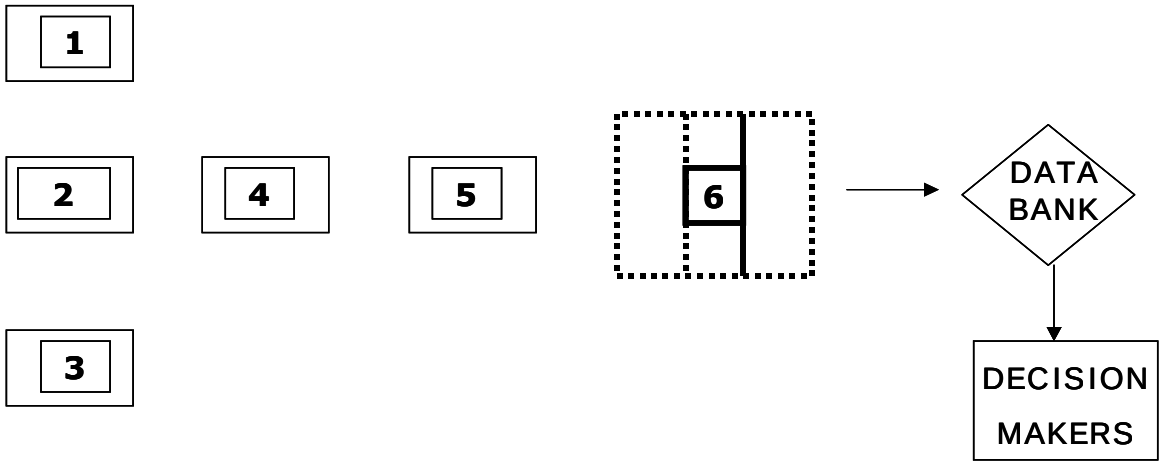

FIG. 2. Logical framework of the conceptual model.

The mining industries and regulators - in particular the case of Uranium production and nuclear regulation - represent a great opportunity and challenge to testify the performance of this framework as conceived by the proposed model.

3.1. Superficial water management issues

Heavy rainfalls observed during 2004 summer has caused, undesired liquid effluent emissions into the environment. Seepage waters from the waste rock/leached ore piles probably caused the observation of above background uranium concentrations in run-off samples.

Despite of these events characterized by very high precipitation during pretty short time periods were unusually seen in the region, it seems not to be the principal cause of overflow of the ponds receiving these pluvial waters. This could be confirmed by the fact that other overflow event happened this year, which was not characterized by such rainfall pattern. The main factor controlling the overflow of the ponds is the water volume remaining in the mine pit after rainfall as well as the waste-rock piles surface area available for the run-off infiltration. This is a natural consequence of the mining development that was not properly taken into account.

So, other crucial point is the characterization of all pollution sources to model contaminant migration in different scenarios, especially if there is possibility of liquid effluent releases in the near future, as seems to be the present case.

The operator, in his original mining project, provide through a waterways network the restraint only of pluvial drainages that fall directly over the mining pollution sources, that is waste-rock/leached-ore piles and open-pit mine pumped waters. The water pathway of pluvial drainage from the mining sources can be viewed in Fig. 3, which shows the simplified scheme of drainage water management during the 2004´s summer precipitation.

We estimated the radiological impact from the release of these waste-waters during the 2004th event. For this aim, it was considered the total activities (particulate + dissolved) of U, Th, Ra-228, Ra-226 and Pb-210 (Bq/L) in the pond waters and in the clear-waters dam outlet during the event (Table I) to evaluate the radionuclide balance and calculate the doses for water drinking and milk ingestion.

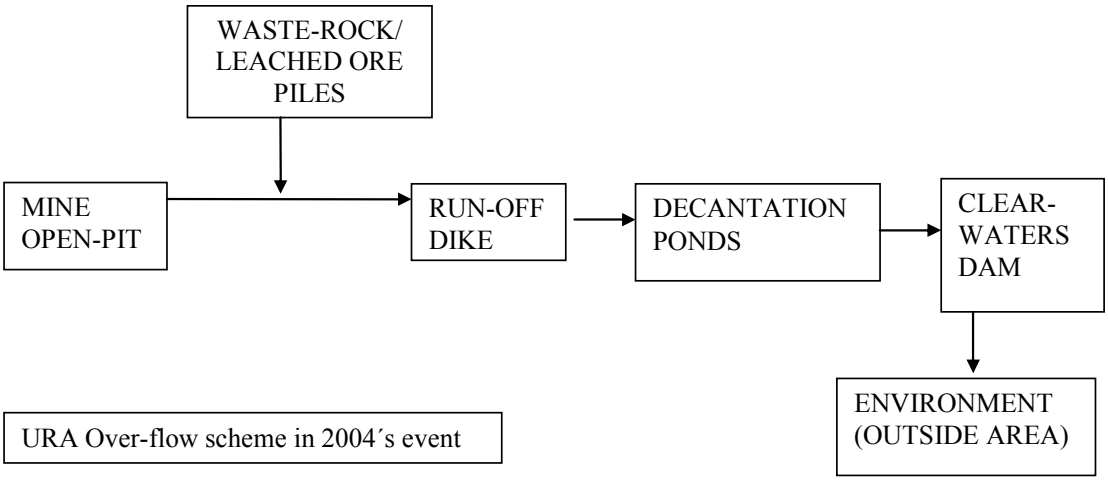

FIG. 3. Water pathway of pluvial drainage from the mining sources.

Table I. Radionuclide geometric mean[a] values of run-off samples in the ponds and dam outlet

Sampling site Bq/l	U	Th	Ra-228	Ra-226	Pb-210
Decantation pond 4	4.0	0.1	3.2	2.0	1.4
Dam outlet	0.2	0.0085	0.04	0.03	0.07

[a] number of observations (n = 09) for each value

To determine if these releases to the environment were potentially harmful to the environment and the public health, we must accomplish the dose assessment. To make this assessment is necessary to frame a hypothetical scenario in which all the principal exposure paths are taken into account. The chosen scenario must be the more conservative it is possible, but avoiding unrealistic assumptions. In the present case, we considered the direct ingestion by the neighboring communities of water in a rate of 2 L.day^{-}1 during all the year of 2004. Also, we consider the consumption of 1 L.day^{-}1 of milk during the period, since cattle are usually seen during water in this area. The water dam diluted the releases from the ponds, so to make this assessment realistic we calculated the dilution into this volume (200 000 m^3).

The equation below was used to calculate the equivalent of the committed effective dose due to water and milk ingestion:

$$H_E = \sum_n C_{w,n} \times I_{ig,w} \times FDC_{ig,n} \quad (1)$$

where :

$C_{w,n}$ is the concentration of radionuclide 'n' in water or milk (Bq/L),

$I_{ig,w}$ is the annual ingestion rate of water or milk (L/year),

$FDC_{ig,n}$ is the Dose Conversion Factor of radionuclide 'n' by ingestion (Sv/Bq).

The mean radionuclide concentrations were showed in Table I and the annual ingestion of water and milk were, respectively, 730 and 365 Litres. The milk concentration was evaluated through equation 2.

$$C_{m,i} = F_m C_{w,i} Q_F \exp(-\lambda_i t_i) \quad (2)$$

where:

$C_{m,i}$ is the Milk Concentration (Bq/L),

F_m is the fraction of animal ingestion that shows up in each milk litre in kinetic equilibrium conditions (d/L),

Q_F is the water amount ingested by the cattle (assumed to be 75 L/d),

t_f is the mean transport time of the water activity to milk and receptor (d),

λ_i is the decay rate of radionuclide i (d^{-1}).

The dose calculated in this manner, from all radionuclides measured, was 0.1 mSv/year, which corresponds to 10 % of the dose limit for public members. The contribution of milk ingestion reach the value of 1.5 μSv/year, representing only 1.4 % of the effective dose. It is reasonable to think that the water leakage will not supply the population located below the dam for more than 6 months. So, the resulting dose would be half of the previous value, i.e. 0.05 mSv/year in this more realistic approach. Whatever the case, the calculated dose permits to conclude that no significant impact occurred as a consequence of the event.

On the other hand, the proper management of these pluvial waters is an imperative question for the operator, since the waters accumulated in the mine pit and run-off dike reach values pretty much higher than in the decantation ponds and the dam. These waters must not be released to the environment because they could cause significant impacts, especially in events of low-concentrated summer rainfall, which produce little dilution of the effluents.

To solve these problems, the operator has to develop detailed studies about the water balance of the mining process as well as the numerical modeling the potential flows from the open-pit mine and waste-rock/leached-ore piles to the environment. The conceptual model frame-work presented here use three basic approaches to this matter: i) Perform multidisciplinary environmental diagnosis to know the process, ii) Assess the impact and health risks of the exposure and iii) Use data bank information to management.

3.2. Groundwater management issues

The semi-arid region of the Northeast of Brazil is characterized by a lack of perennial superficial waters due to the low precipitation and high evaporation rates. In addition to this, the precipitation events are irregular in time causing long periods of dryness with catastrophic consequences. Because of this situation, groundwater is of strategically importance in the Northeast and represents a vital factor to its socioeconomic development. Owing to adverse climatic conditions with recurrent droughts, intense pressure is being put on the use of groundwater resources. However, there is still insufficient knowledge of the basic aquifers characteristics leading to an over exploitation of the water resources. Groundwater occurrence on its turn depends on a series of geological and climatological characteristics that are very variable in the region.

Analyzing the geological and local geomorphological systems, for hydrogeological studies, it can be inferred with base in the geological and geophysical investigations (mixed surveys) accomplished, that the typical geological section of the catchment is constituted for:

a) Layer 1: Superficial coverings with thickness varying from 8 to 10 meters and varied geometries. This unit is constituted by alteration soils (colluvial and residual) sandy-loam presenting permeability is in the 10^{-4} to 10^{-5} cm/s range.

b) Layer 2: Crystalline rocks, basically constituted by granitoid and orthogneiss, with degree of varied fracturing. The permeability of this unit is very low (Loss specific <0.1l/min/m/kg/cm^2), and;

c) Layer 3: alluvial and colluvial deposits including sediments sandy-loam. The space distribution of this unit happens in a way disordered at the bases of the main drainages of the area.

The geological settings of the groundwater have to be considered in order to understand the water-rock interaction. This process controls the main hydrochemical characteristics of groundwater. There are several wells located far from the mining area, many of them used by local population (Table II), which present very poor quality water standards. The water quality also changes dramatically between the dry and wet season. We also estimated the radiological impact from water drinking for five wells, considering the same consumption established for superficial water (i.e. 730 L/year) and the geometric mean of values obtained for the environmental monitoring program since the beginning of mining (Table III). Only the well from the community of Maniaçu (LR001) presented dose value for ingestion above 1/3 of the dose limit for public individuals (optimization level).

Table II. Mean values of groundwater quality parameters in five wells used for population supply (units - pH - [H+], Conductivity - uS/cm, Alcalinity - ppm $CaCO_3$, elements - mg/L)

Well	pH	Cond	Alc	K	Na	Ba	Mn	Fe	Al	SiO_2	SO_4	F	Cl	NO_3	NH_4
001	7,5	1200	73	35	120	1,05	0,29	0,11	0,05	67	7	0,4	225	197	0,122
042	7,5	380	105	5	68	0,22	0,05	0,2	0,5	55	12	1	55	39	0,230
211	5,8	139	56	7	11	0,6	0,05	1,4	0,05	47	11	0,2	7	0,5	0,62
213	7,5	1270	167	15	156	0,07	0,17	0,54	0,05	62	40	1,5	305	0,8	0,06
265	8,2	900	31	8	99	0,05	0,05	0,05	0,05	42	139	3,8	106	0,3	0,018

Table III. Geometric mean values of radionuclides and ingestion dose of groundwater from five wells used for population supply (Radionuclides - Bq/L, Dose by ingestion - mSv/year)

Well	U	Th	Ra-228	Ra-226	Pb-210	Ingestion Dose
001	0,20	0,001	0,6	0,50	0,1	0,36
042	0,1	0,014	0,1	0,02	0,05	0,09
211	0,11	0,003	0,09	0,10	0,06	0,11
213	0,15	0,016	0,12	0,10	0,07	0,13
265	0,3	0,003	0,08	0,03	0,07	0,11

In aquifers where vegetation cover is scarce and the discharge is mainly controlled by evaporation process, soil salinization and low recharge rates often produce hyper saline waters not suitable for human consumption. Because of that, some sort of water treatment is needed, e.g., water desalination by reverse osmosis. However, this type of technology is not available in large scale due to its low yield and high production of salty wastes. As a consequence of this, the technological challenge for the semi arid is the development and implementation of environmental management strategies arising from consistent investigation works that include the relevant social-economical aspects. The multiple uses of water and the potential conflicts between local communities and industrial facilities are very relevant issues that were taken into account by this conceptual water management model.

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Assessment of the contribution of the Koshkar-Ata tailing dumps in contamination by radionuclides and heavy metals of ambient air in the area of Aktau city

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Abstract. The paper presents data on concentrations of toxic metals and radionuclides in air particulate samples collected at settlements nearby Koshkar-Ata tailing dumps. The data are from a larger study designed to provide a scientific basis for the development of a rehabilitation measures policy on tailing facilities of uranium industry bearing a potential hazard to local inhabitants. Aerosol samples were collected on filters in mobile monitoring posts at nearest settlements around the tailing dumps (12 samples). Deposited atmospheric pollutants (DAPs) were collected on special pads set on stationary posts in the vicinity of Koshkar-Ata (66 samples). The analytical techniques used were for radionuclide and toxic constituent determination were, inductively coupled plasma mass spectrometry (ICP-MS) as well as gamma spectrometry with high sensitivity and pure Ge detector, respectively.

1. Introduction

For a number of years the Institute of Nuclear Physics of the National Nuclear Centre of the Republic of Kazakhstan (INP NNC RK) actively participated in the realization of many research and nature protection measures in territory of Mangistau region.

The outcomes of activities indicate that in Mangistau region, a number of different sources of hazardous radiation objects contribute to the general radioecological conditions. These sources are the numerous enterprises on oil production and processing, the reactor BN-350 installations, mining and reprocessing enterprises of uranium industry and sites of conducting underground nuclear explosions, etc.

The most complicated ecological conditions have arisen around the Koshkar-Ata tailing dumps, 8 km East of the Caspian Sea coast near the city of Aktau, 5 km North of an industrial zone, in all areas of a natural valley "Koshkar-Ata". Since 1965 the drain-free valley Koshkar-Ata was used as a depository of waste from the uranium mining industry. The volume of accumulated solid waste is approximately 105 million tons, including 52 million tons with an enhanced level of concentration of natural radionuclides and a total activity of more than 370 TBq (10 000 Ci).

The decrease in the level of the aqueous phase caused by fall-off of volumes of manufacturing effluents has resulted in the considerable areas of exposed bottom sediments becoming a source of toxics dust. In the arid climate of the region, the wind erosion of radioactive sediments promotes raising this dust into the atmosphere and distributing it to large areas.

In 2003-04, INP specialists participated in the development and maintenance of a system of monitoring the pollution of ambient air caused by radionuclides and heavy metals.

2. Determination of the level of pollution impact on the near ground atmospheric layer in the settlements

2.1. Sampling methods

A method of atmospheric air pollution observation has been developed. For this purpose stationary and mobile posts for regular sampling of air particulate matter were established. In order to determine the level of pollution impact on the near ground atmospheric layer, a radioecological examination of the neighboring to Koshkar-Ata settlements was made.

The following procedures were performed:

- Sampling of aerosols in the settlements - (12 samples)
- Collection of DAPs on special pads - (66 samples)
- γ-spectrometry of collected samples
- Determination of elemental composition of DAPs

For the implementation, four mobile points for monitoring of aerosol sampling at nearby settlements Akshukur, Bayandy, Mangystau rail station, Aktau city around Koshkar-Ata, were selected (Fig. 1). The intensity of dusting in different weather conditions was controlled at the indicated points during two field seasons (from June till September). A 10-hour sampling was performed at 1m height with the high volume air sampler STAPLEX MODEL TFRC-4 and glass fibre filters TFAGF810 of 10.16 cm diameter and of 0.3 μm pore size were used for aerosol collection. Air was drawn at 7.5 CFM.

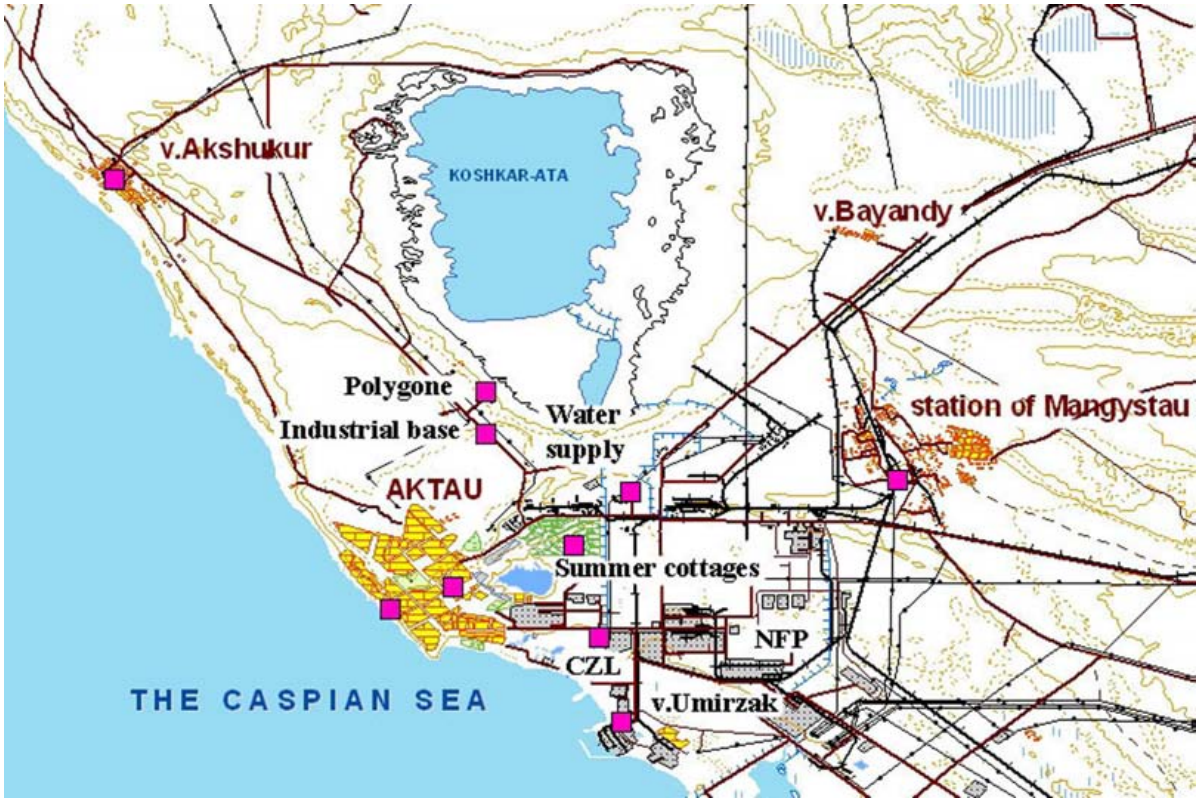

FIG. 1. Aerosols and deposited atmospheric pollutants sampling layout.

Additionally, collection and analysis of DAPs in the immediate vicinity of the tailing lake and adjacent settlements was conducted (Fig. 1). DAPs were accumulated for analysis at special pads in specified locations.

These special pads of 1 m^2 were made and placed at 1m height to collect atmospheric pollutants, and were arranged in the following places:

- Akshukur village
- Mangystau rail station
- Summer cottages in close vicinity to the tailing lake
- City's special Polygon for solid and food domestic waste utilization (North-Western shore of the tailing lake)
- Industrial base between Aktau city and the tailing lake,
- Central water supply station of Aktau City,
- City of Aktau.

Samples of DAPs were taken monthly during the entire period of monitoring.

2.2. Instrumentation used

Determination of concentrations for natural radionuclides and heavy metals in collected aerosol samples and DAPs was performed using complex methods such us γ-spectrometry, chemical methods and mass spectrometry with inductively coupled plasma.

Aerosol samples were analyzed for ^{210} Pb content. The activity concentration values were determined using γ-spectrometry with a planar ORTEC GLP-25325 germanium detector, the diameter being 25mm with a resolution of 325eV for the 5.9keV of ^{55}Fe.

Flatbed samples were analysed for ^{210}Pb using γ-spectrometry with a germanium hyperpure detector "EUROSYS MESUARES" with volume 139cm^3 and 1.8keV resolution for the 1 332keV of ^{60}Co.

Chemical analysis was made on aerosol and flatbed samples. Toxic constituents were determined using a mass spectrometer with inductively coupled plasma ELAN 9000 from PerkinElmer.

3. Results and discussion

3.1. Radionuclide analysis

From the results of radionuclide determination of dust conducted in 2003, a conclusion was made on the presence in ambient air of enhanced concentrations of the isotope 210 Pb. This isotope of lead has the most significant activity compared with the rest natural radionuclides of the uranium and thorium series.

The analysis of the obtained data demonstrates that there was no exceeding of measured values of interference levels (100 $mBq.m^{-3}$ for 210Pb) for all cases, i.e. the actual volumetric activity on the two orders lower normative.

It is necessary to note that during all monitoring seasons (2003-04) there was a high level of humidity and precipitation, and a low average wind speed during the spring – summer period. All these factors promoted a decrease in the level of intake of radionuclides and toxic matters in the near ground atmospheric layer, but it is possible that under more representative climatic conditions for the given area, the concentration of radionuclides in the atmosphere can be much higher. However, the probability of exceeding the levels of interference is negligible.

The survey demonstrates that the concentration of the isotope 210Pb (Table I) in samples of aerosols does not depend practically on the position of a settlement in relation to the tailing lake but corresponds to normal conditions.

Compared with the data of 2003, the level of volumetric activity in settlements has changed negligibly. The values of volumetric activity of 210Pb in samples of aerosols in settlements exceed value of volumetric activity on open air. This fact is most likely connected to an increase in concentration of radon due to construction and economic activities as well as other sources of intake of 210Pb (availability of worked out carriers [1] and presence of underground sources of mineralized radon waters). However, the level of excess is minute.

Table I. Volumetric activity of an isotope ^{210}Pb in aerosol samples collected in settlements

№	Filter	Location	Sampling date	^{210}Pb mBq/m^3
1	GF102-17	Bayandy	05.07.2004	1.2±0.4
2	GF102-19	Bayandy	08.07.2004	1.6±0.6
3	GF102-18	Bayandy	09.07.2004	<0.589
4	GF102-20	Mangystau rail station	13.07.2004	1.0±0.4
5	GF102-26	Mangystau rail station	27.07.2004	1.2±0.6
6	GF102-27	Mangystau rail station	28.07.2004	1.2±0.4
7	GF102-22	Aktau	15.07.2004	1.0±0.9
8	GF102-23	Aktau	16.07.2004	1.2±0.4
9	GF102-25	Aktau	17.07.2004	1.4±0.4
10	GF102-15	Akshukur	01.07.2004	1.0±0.4
11	GF102-16	Akshukur	04.07.2004	<0.6
12	GF102-21	Akshukur	14.07.2004	1.4±0.4

For an estimation of levels of radioactive atmospheric fallouts in different sites, 66 samples of DAPs were collected and analyzed (Table II).

Table II. Results of γ-spectrometric analysis of DAP samples, 2004 (Bq/m^{2}month)

Sample ID	Location	Accumulation period	^{210}Pb
1137	Akshukur village	August 2003	1.68±0.08
1545	Akshukur village	October 2003	2.45±0.05
1563	Akshukur village	November 2003	1.88±0.07
3	Akshukur village	December 2003	3.27±0.07
269	Akshukur village	February 2004	3.96±0.1
408	Akshukur village	March 2004	0.17±0.02
776	Akshukur village	April 2004	1.95±0.07
950	Akshukur village	June 2004	0.6±0.04
133	City	January 2004	17.21±0.2
339	City	February 2004	14.75±0.21
418	City	March 2004	9.61±0.14
571	City	April 2004	4.36±0.12
766	City	May 2004	2.02±0.06
1140	Summer cottages	August 2003	1.89±0.04
1544	Summer cottages	October 2003	2.28±0.11
1564	Summer cottages	November 2003	2.25±0.08
98	Summer cottages	January 2004	6.03±0.12
182	Summer cottages	February 2004	1.13±0.04
778	Summer cottages	April 2004	2.19±0.07
952	Summer cottages	June 2004	1.02±0.04

Sample ID	Location	Accumulation period	^{210}Pb
1138	Industrial base	August 2003	2.02±0.08
1547	Industrial base	October 2003	2.48±0.08
1561	Industrial base	November 2003	3.19±0.07
1	Industrial base	December 2003	4.82±0.11
270	Industrial base	February 2004	0.14±0.02
407	Industrial base	March 2004	1.14±0.03
777	Industrial base	May 2004	3.4±0.09
951	Industrial base	June 2004	0.92±0.04
1546	Polygon	October 2003	1.62±0.07
1664	Polygon	November 2003	3.49±0.08
2	Polygon	December 2003	3.7±0.08
1136	Mangystau rail station	August 2003	2.12±0.03
1342	Mangystau rail station	September 2003	1.68±0.09
1548	Mangystau rail station	October 2003	1.93±0.08
1663	Mangystau rail station	November 2003	2.71±0.08
12	Mangystau rail station	December 2003	2.79±0.08
341	Mangystau rail station	February 2004	3.07±0.1
363	Mangystau rail station	March 2004	0.68±0.04
528	Mangystau rail station	April 2004	0.51±0.04
775	Mangystau rail station	May2004	1.43±0.04
949	Mangystau rail station	June 2004	0.75±0.04
814	Umirzak village	June 2003	1.03±0.04
1081	Umirzak village	July 2003	4.33±0.08
1124	Umirzak village	August 2003	2.9±0.08
1340	Umirzak village	September 2003	1.39±0.04
1551	Umirzak village	October 2003	1.64±0.07
1662	Umirzak village	November 2003	4.12±0.08
13	Umirzak village	December 2003	2.7±0.07
91	Umirzak village	January 2004	1.58±0.07
340	Umirzak village	February 2004	0.94±0.04
419	Umirzak village	March 2004	0.33±0.03
572	Umirzak village	April 2004	0.4±0.01
773	Umirzak village	May 2004	0.32±0.03
947	Umirzak village	June 2004	0.26±0.03
826	CZL lab	June 2003	0.68±0.04
1091	CZL lab	July 2003	3.02±0.08
1135	CZL lab	August 2003	1.29±0.04
1333	CZL lab	September 2003	1.03±0.04
1539	CZL lab	October 2003	0.95±0.03
343	CZL lab	February 2004	2.72±0.09
424	CZL lab	March 2004	1.08±0.05
577	CZL lab	April 2004	2.93±0.09
770	CZL lab	May 2004	1.01±0.05

Sample ID	Location	Accumulation period	^{210}Pb
183	Water supply	February 2004	1.43±0.04
727	Water supply	May 2004	0.14±0.03
953	Water supply	June 2004	1.17±0.04

The minor increase of numerical values takes place for points of monitoring in “City”, “Summer cottages” and “Polygon”. This can be explained by the fact that “Polygon” and “Summer cottages” are in close proximity to the tailing lake, and the increase of value of activity in “City” is connected to the availability of other sources of radon. (Table III).

Table III. Average sedimentation rate of ^{210}Pb (Bq/m^{2}month) in DAP samples at the specified locations of monitoring

Installation point	Date of sampling	
	2003	**2004**
City	15	9.6
Summer cottages	1.4	2.4
Industrial base	1.5	2.3
Polygon	1.5	2.9
Mangystau rail station	1.8	1.8
Umirzak village	1.9	1.7
CZL lab	1.8	1.6
Water supply	0.9	0.9
Akshukur village	1.8	2.0

From the above data it is necessary to specially mark the point "City" in which the high values are permanently fixed. The indicated fact testifies the availability of other sources of intake ^{210}Pb in the environment besides the tailing lake Koshkar-Ata.

Thus, the impact of the tailing lake Koshkar-Ata on pollution of a near ground atmospheric layer of adjacent areas by radionuclide ^{210}Pb is fixed, but this is registered only for neighboring sites using highly sensitive methods of survey. We suspect it is connected to the availability in the region of other sources of intake of radon into the atmosphere.

3.2. Element analysis by ICP-MS

The data from microelemental analysis of DAP samples in the immediate proximity of the tailing lake and settlements were used to analyze dust structure. The elements, on which one was registered significant concentrations, are listed in Table IV. The remaining chemical elements are present at quantities conforming to the Clark contents, at a level of the detection limit of the method.

Table IV: Microelemental structure of DAPs

	The concentration of element in the sample (μg/m^{2}month)			
Element	**Akshukur village**	**Aktau city**	**Industrial base**	**CZL laboratory**
Ni	1560 ± 310	511 ± 10	280 ± 60	1830 ± 370
Cu	30 ± 6	17300 ± 3500	48 ± 10	350 ± 70
Zn	120 ± 20	4600 ± 900	200 ± 40	510 ± 100
Rb	30 ± 6	10 ± 3	260 ± 5	19 ± 4
Sr	300 ± 60	270 ± 50	300 ± 60	300 ± 70
Y	10 ± 2	5 ± 1	10 ± 2	11 ± 2
Zr	10 ± 3	20 ± 5	10 ± 2	16 ± 3
Cs	3.0 ± 0.6	1.0 ± 0.2	2.0 ± 0.4	2.0 ± 0.4
Ba	500 ± 100	300 ± 60	490 ± 100	580 ± 110
La	10 ± 3	5 ± 1	20 ± 3	17 ± 3

Element	The concentration of element in the sample (μg/m^{2}month)			
	Akshukur village	Aktau city	Industrial base	CZL laboratory
Ce	30 ± 5	10 ± 2	40 ± 7	35 ± 7
Nd	7000 ± 1400	2400 ± 500	7300 ± 1500	6800 ± 1300
W	0.10 ± 0.02	6 ± 1	0.07 ± 0.01	0.6 ± 0.1
Pb	80 ± 10	300 ± 60	340 ± 70	70 ± 10
Th	4.0 ± 1.0	1.0 ± 0.3	3.1 ± 0.6	2.6 ± 0.5
U	2.0 ± 0.3	1.0 ± 0.2	3 ± 0.5	3.3 ± 0.6

The data show an increase in dust contents of such elements as lead, nickel, copper, zinc, neodymium, lanthanum and cerium on the site of anthropogenic impact. A significant exceeding is not shown for the other analyzed elements.

One should pay an attention to a different ratio of microelements in the structure of the dust. In samples taken from the inhabited areas of Aktau, the concentration of rare earths as well as uranium and thorium correspond to background values. In addition, enhanced concentrations of heavy metals (copper, nickel, zinc, and lead) are also present. In Akshukur village area, the rare earths were surveyed and the uranium content was at a background level. In points located near to the tailing lake and Nitrogen Fertilizer Plant (NFP), along with rare earths there is uranium, its concentrations is double.

We recorded enhanced concentrations of toxic and radioactive elements in dust in the NFP area as having the same order as perimeter sites which testifies to the availability of a number of sources of pollutants. Industries handling uranium phosphorous ore exist around the city and are possibly one such source as they produce a mixture of pollution which negatively impacts upon the environment.

It should be noted that in the structure of DAPs there are heavy metals and rare earths conditioned by economic activities of industrial and transport agencies.

3.3. Priority chemical agents and radionuclides being subject to control

Pollutants in aerosols and DAPs are divided into two groups:

(1) Natural radionuclides of a uranium series
(2) Heavy metals, including rare earth

From the above results, isotope ^{210}Pb is present at quantities high enough to allow reliable measurements. In spite of the fact that the concentrations ^{210}Pb are much less than the level of interference, as the member of uranium series of radioactive decays, it is in equilibrium with the remaining members of this series, in particular with isotopes ^{210}Bi, ^{210}Po, having much higher toxicity. Therefore reference to priority agents is justified. As ^{210}Pb is a decay product of the inert gas radon, for increased effectiveness in assessing the radiological situation along with study of concentration ^{210}Pb by γ-spectrometry it is recommended to study an equivalent equilibrium volumetric activity of radon.

The presence of industrial and transport firms in the inspected terrain causes availability of heavy toxic elements in the 1-3 danger groups. The most significant quantities are of copper, nickel, zinc, lead, tungsten and chromium. Industrial wastes situated within the borders of the Koshkar-Ata tailing lake on unauthorized disposal sites and dumps of worked-out open pits contain (along with natural radionuclides) the rare earths La, Ce, Nd. Thus an estimation of ecological conditions in region of the city Aktau necessarily must consider the elements enclosed in the Table V.

Table V. Priority chemical agents

Element	Concentrations		
	In dust (in soils of Koshkar-Ata)	Background site	MPC
	Radionuclides		
^{210}Pb	0,33 - 1,311 mBqm^{-3}	0,273 mBqm^{-3}	110 (mBqm^{-3})
^{222}Rn	2 - 22 Bqm^{-3}	2 Bqm^{-3}	200 (Bqm^{-3})
	Heavy metals		
Ni	50-270	<30	N/A
Cu	30 - 200	10 - 40	N/A
Zn	40 -200	20 - 40	N/A
Pb	10-70	<10	N/A
Cr	200 - 2000	50 - 200	N/A
W	15 - 120	20 - 50	N/A
	Rare earth		
La	300 - 1000	<20	N/A
Ce	50 - 2000	50 - 200	N/A
Nd	50 - 300	<20	N/A

4. Conclusion

Results of measurements on both volumetric activities of isotope ^{210}Pb and concentrations of rare earth and heavy metals in studied samples, demonstrate the presence of enhanced concentrations of the indicated elements in territories adjacent to Koshkar-Ata. This is evidence of the negative environmental impact of the tailing dump. However, the level of concentration of radioactive and toxic elements detected by highly sensitive methods of analysis is much lower than maximum permissible values and cannot result in a considerable deterioration of the quality of the environment.

The negative impact is registered only in the immediate vicinity of the perimeter of the tailing lake in the first hundreds of metres. The volumetric activity of isotope ^{210}Pb in the near-surface atmospheric layer is two orders lower than that of interference.

ACKNOWLEDGEMENTS

We gratefully acknowledge the assistance of the INP specialists and funding from NATO's reintegration grant "Experimental investigation of radioactive contamination of air at the Koshkar-Ata tailing dump".

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Geochemical controls on the solubility of Ra-226 in uranium mine tailings

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Abstract. The mine tailings at the Key Lake uranium mill have been continuously emplaced in the Deilmann Tailings Management Facility (DTMF) since 1996. At the start of emplacement, the concentration of dissolved Ra-226 in the tailings supernatant in the DTMF was predicted to be less than 150 Bq/l. In 2001, the concentration of dissolved Ra-226 in the tailings supernatant was measured to be 280 Bq/l. Results of bench scale experiments showed that the addition of barium chloride to the tailings slurry would result in the precipitation of dissolved Ra-226 through the formation of a Ba/Ra-SO4 co-precipitate with a resulting concentration of 50 Bq/l. Implementation of a barium chloride addition system in the mine tailings processing circuit was completed in July 2002. Since its implementation, the concentration of dissolved Ra-226 in the tailings supernatant has decreased to about 18 Bq/l.

1. Introduction

Radium (Ra-226) is a highly toxic radioactive (t1/2 = 1599 years) contaminant associated with uranium ore (seven tons of uranium bearing pitchblende contains approximately 1g of radium). Ra-226 is considered to be one of the most radiotoxic elements because its metabolic behavior in the human body is similar to that of calcium [1]. The World Health Organization (WHO) publishes microbiological, chemical and radiological guideline values for drinking water. These guidelines are updated in accordance with current epidemiological studies. The WHO, in 1996, recommended that the gross activity of Ra-226 in drinking water should not exceed 0.1 Bq/l [2].

High grade (25% U_3O_8) uranium-bearing ore from the McArthur River mine is processed at the Key Lake mill which is located about 80 km south of the McArthur River mine site. Mine tailings from this ore are emplaced in the Deilmann Tailings Management Facility (DTMF) located at the Key Lake Mine site. Mine tailings, from ore originating at the Key Lake mine site, have been historically emplaced in the DTMF since 1996. All uranium-bearing ore originating from the Key Lake mine site has been processed (1999) and the Key Lake mill currently processes ore from the McArthur River mine exclusively. Processing of McArthur River Ore at the Key Lake mill began in 1999. Yellowcake (U_3O_8) production at the Key Lake mill increased from 4.35 million kg in 1999 to 8.16 million kg in 2001. During that same period the associated annual average dissolved radium (Ra-226) concentrations in the tailings supernatant increased from 90 to 279 Bq/L. Figure 1 illustrates the historical correlation between annual yellowcake production in the Key Lake mill and the concentration of dissolved radium in the tailings supernatant from 1996 to 2001. From 1996 to 1999 there was a decrease in the concentrations of dissolved Ra-226 in the tailings pore fluids with the concentrations decreasing from approximately 150 Bq/l in 1996 to approximately 80 Bq/l in 1999. However, since the start of milling of McArthur River ore in late 1999 the concentration of Ra-226 in the tailings supernatant increased to 280 Bq/l by 2001.

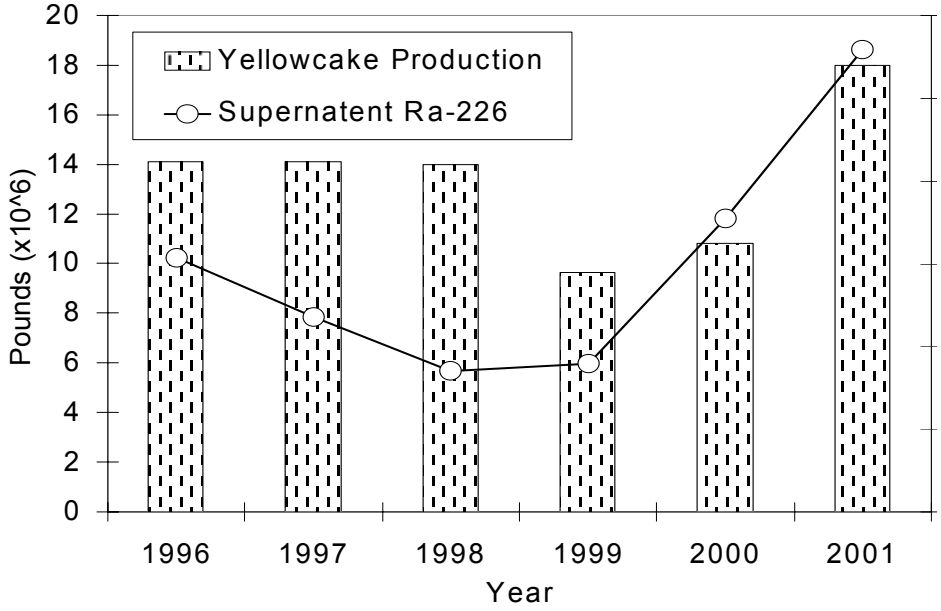

FIG. 1. Annual averages of dissolved radium concentrations in the tailings supernatant correlated to annual yellowcake production.

Based on the design criteria of the DTMF when it was constructed, it was estimated the dissolved Ra-226 concentrations in the tailings supernatant would not exceed 150 Bq/L (McArthur River/Key Lake EIS). As of 2001, no controls were in place in the mill to reduce the concentration of dissolved radium in the tailings pore fluids.

The objectives of this study were to: (i) evaluate the historical concentrations of Ra-226 in the tailings pore fluids and compare those concentrations to the concentrations that were predicted in the McArthur River Environmental Impact Statement and (ii) determine the most efficient and economical mechanism to reduce the concentration of Ra-226 in the DTMF tailings pore fluids. The objectives were met by compiling historical Ra-226 concentrations in the DTMF from 1996 to 2004. Next, bench-scale test work was conducted to determine the potential mechanisms to control the solubility of Ra-226 in the tailings pore fluids. This presented additional technical challenges due to the fact the tailings is in a slurry form as compared to the conventional procedure of treating dissolved radium in effluent water. The selected chemical process was then implemented in the mill process to test the process under normal operating conditions. Finally, an evaluation of the concentration of dissolved Ra-226 in the tailings pore fluids was conducted to determine the effectiveness of the established process.

2. Mill processing and radium chemistry

Tailings are produced at the Key Lake mill through the combination of leach residues (from the counter current decantation circuit underflows (U/F)) and precipitates from the effluent treatment circuit (bulk neutralization (BN) and radium removal (RR) thickener underflows). The ratio of the three feed solutions varies but is typically found in the ratio: CCD#8 U/F 70%, BN U/F 25%, and RR U/F 5% by volume. This admixture is at a pH of approximately 5. The mixture is pumped from the tailings feed box to the first tailings holding tank where lime is added - increasing the pH to approximately 11. Retention time of the tailings slurry is approximately one hour. The slurry then reports to the second tailings holding tank. In this tank the pH of the slurry is maintained at pH 11 with lime for an additional one hour. Mine tailings produced from the milling process are then pumped to the TMF thickener where the tailings are thickened to approximately 35% solids (wt/wt). The tailings are then discharged to the DTMF. During the milling process, Ra-226 is selectively separated from uranium in the solvent extraction process with Ra-226 ultimately introduced into the mill tailings before discharge.

Radium exists as the divalent cation (Ra^{2+}) and its chemical behavior is similar to barium (Ba) and somewhat related to calcium (Ca). The solubility of Ra-226 in aqueous solutions is 0.0021 g/L (7.77 x 10^7 Bq/L in terms of activity). The solubility of $RaSO_4$ in solutions containing SO_4 ions strictly follows the law of mass action, taking into account the activity coefficients of both ions. In groundwater, radium concentrations are usually too low to reach saturation with respect to any pure mineral phases, and are controlled by adsorption, by solid solution formation, or by both. Previous test work on the geochemical controls of Ra-226 in uranium mine tailings have resulted in a variety of conclusions including co-precipitation of radium with barium, lead, or calcium in sulfate media. Authors in [3] indicated that radium is preferentially associated with barium sulfate and sparingly associated with gypsum. In 1995, Somot et al. used KCl to dissolve the gypsum fraction of neutralized tailings, indicated that radium correlated to calcium and not to barium in a tailings leach experiment. In 1995, Landa and Gray performed series of sequential extractions on uranium mill tailings that suggested that alkaline earth sulfates and hydrous ferric oxides were important hosts of Ra-226.

Historical treatment practices for control of Ra-226 in hydrometallurgical solutions produced in the uranium milling process include co-precipitation with barium sulfate ($BaSO_4$) or the use of ion exchange resins. The favored current approach, which is used in the effluent treatment processes at the mill sites of Key Lake and its sister milling operation at Rabbit Lake (located 200 km away), is the formation of a Ra/Ba-SO_4 co-precipitate. The tendency for radium to form a coprecipitate (solid solution) with divalent sulphate salts is well documented [4]. Coprecipitates occur when a precipitating mineral incorporates minor constituents from solution into the solid phase as impurities [5]. Sulphate-based coprecipitates have been identified as potential geochemical controls for radium in uranium mill tailings. Barium, lead and calcium sulphates are probable geochemical controls on the solubility of Ra-226 in pore fluids contained in uranium mill tailings [6]. Constable and Snodgrass [3] indicated that radium is preferentially associated with barium sulphate and sparingly associated with gypsum. In this process, the barium cation (as $BaCl_2 \cdot 2H_2O$) combines with the sulphate anion (present in large concentrations in the milling process) to form an in-soluble barium sulphate (barite) precipitate. During the formation of the barite crystal, Ra-226 is incorporated into the barite crystal by replacing barium in the crystal lattice. Co-precipitates occur when a precipitating mineral carries minor constituents from solution into the solid phase as impurities. This occurs even when the solubility product of the impurity in solution is not exceeded. This practice has proven successful for the long-term stability of Ra-226 in chemical precipitates formed in the effluent treatment circuit. The treatment of effluent water for the precipitation of dissolved Ra-226 historically involved the addition Ba as barium chloride at low pH (typically <4).

3. Methods and materials

3.1. Effect of pH on dissolved radium concentrations

To assess the behavior of Ra-226 over the pH range 1-11 in tailings slurry and mill effluent, samples of CCD#8 thickener U/F (CCD#8 U/F) and a synthetic mixture of effluent water that simulates the feed to Key Lake's bulk neutralization circuit were tested. The CCD#8 U/F slurry was pH adjusted in both continuous and batch modes over the pH range 1-11 using lime. In the batch test, one litre of CCD#8 U/F slurry was pH adjusted to the desired pH and allowed to mix for a period of two hours. The pH was constantly monitored to maintain a constant pH throughout the experiment. Pore water was collected for analysis by sequentially filtering the slurry mixture through 3 μm and 0.45 μm filter paper. The resulting pore water was submitted to the Key Lake chemistry laboratory for the analysis of dissolved Ra-226 using alpha spectroscopy.

Test work in the continuous mode was completed on a ten-litre sample of CCD#8 U/F slurry. The pH of the slurry was adjusted by one pH unit from pH 1 to pH 11. The slurry was adjusted to the desired pH, mixed for two hours and an aliquot (~100 mL) of the slurry was obtained. The collected sample was filtered (as per the batch test) for the analysis of dissolved radium. The pH of the slurry was then increased to obtain the desired pH as per the pH profile until the terminal pH was obtained.

Ten litres of untreated effluent water (29% reservoir 1, 43% reservoir 2, and 28% raffinate) was pH adjusted in a continuous mode as per methodology described above. Raffinate is defined as the acidic hydrometallurgical solution after the uranium was removed during the solvent extractions process. In the solvent extraction process the uranium anion is selectively removed from the other dissolved metals and radionuclides, including Ra-226. Water contained within reservoir #1 at the Key Lake mill originates from waste waters produced from various circuits in the Key Lake mill. Water from reservoir #2 originates from tailings pore water pumped back from the DTMF and above ground tailings management facility. Preparation of samples for analysis of Ra-226 was completed in the same manner as described above.

3.2. Radium control with barium chloride addition

A stock barium chloride ($BaCl_2.2H_2O$) solution was prepared at a concentration of 25 mg/mL as Ba. An aliquot of this solution was added directly to the CCD#8 U/F slurry and prepared tailings to achieve a final concentration of 100-mg Ba/L slurry. Several tests to determine the optimum addition mechanism of barium for the control of dissolved radium were completed. This involved the addition of barium at varying slurry pH levels. As in the above test work pH control was completed through the addition of lime.

Long term stability test work on prepared tailings samples was completed over a period of six months to determine the rate of precipitation/dissolution of Ra-226 in the tailings pore fluids by adding 100 mg Ba/L of tailings slurry. Barium (as $BaCl_2.2H_2O$) was added at varying pH levels as well as various terminal pH levels. Ratios of the tailings blend for tailings production were followed as outlined in the introduction of this paper. Barium was added to one litre of tailings slurry at the desired pH and the slurry mixed for a period of one hour. Lime was added to obtain the terminal pH and the tailings slurry mixed for an additional hour. An aliquot of the tailings pore fluids was obtained, filtered, and submitted to the chemistry lab for dissolved Ra-226 analysis. The tailings slurry was stored in containers with zero headspace. The tailings pore fluid sampling process was repeated at 30 and 60-day intervals to monitor the long-term controls on dissolved radium. All aging tests were conducted at 200C.

3.3. Control of Ra-226 in the DTMF tailings supernatant

Following the bench scale test work, a barium chloride addition point was added in the Key Lake mill to add a 0.16 M barium chloride solution to the tailings slurry. Mill modifications were completed in July 2002 and the addition of barium chloride to the tailings slurry began immediately thereafter. The barium chloride and tailings slurry were mixed in a series of two tailings mix tanks with an overall retention time of 20 minutes in each tank. The addition rate of barium chloride to the tailings slurry was controlled at 0.075 kg Ba/t tailings slurry. Lime was also added to these tailings tanks to maintain the pH of tailings slurry at pH = 11. The tailings slurry was then pumped to the tailings management thickener prior to emplacement in the DTMF. Samples of the tailings supernatant were collected on a monthly basis to monitor the concentration of dissolved Ra-226 in the tailing supernatant following the addition of barium chloride to the tailings slurry in the milling process.

4. Results

4.1. Effects of pH on dissolved radium concentrations

Neutralization of the CCD#8 U/F slurry with lime was completed in batch and continuous mode. The resulting dissolved radium concentration profiles are illustrated in Fig. 2. The initial pH of the CCD#8 U/F slurry used in the batch scale test work was 1.69 and the initial dissolved Ra-226 concentration was 51.4 Bq/L. Results from the analysis of Ra-226 in the batch tests showed that from pH 2 to pH 6 the dissolved radium concentration increased sharply reaching a maximum concentration of 1 025 Bq/L (Fig. 2). From pH 6 to pH 9 the dissolved radium concentrations steadily decreased to a concentration of 418 Bq/L. Finally, from pH 9 to pH 11 the dissolved radium concentration once again increased from 418 Bq/L to an overall maximum concentration of 1 168 Bq/L.

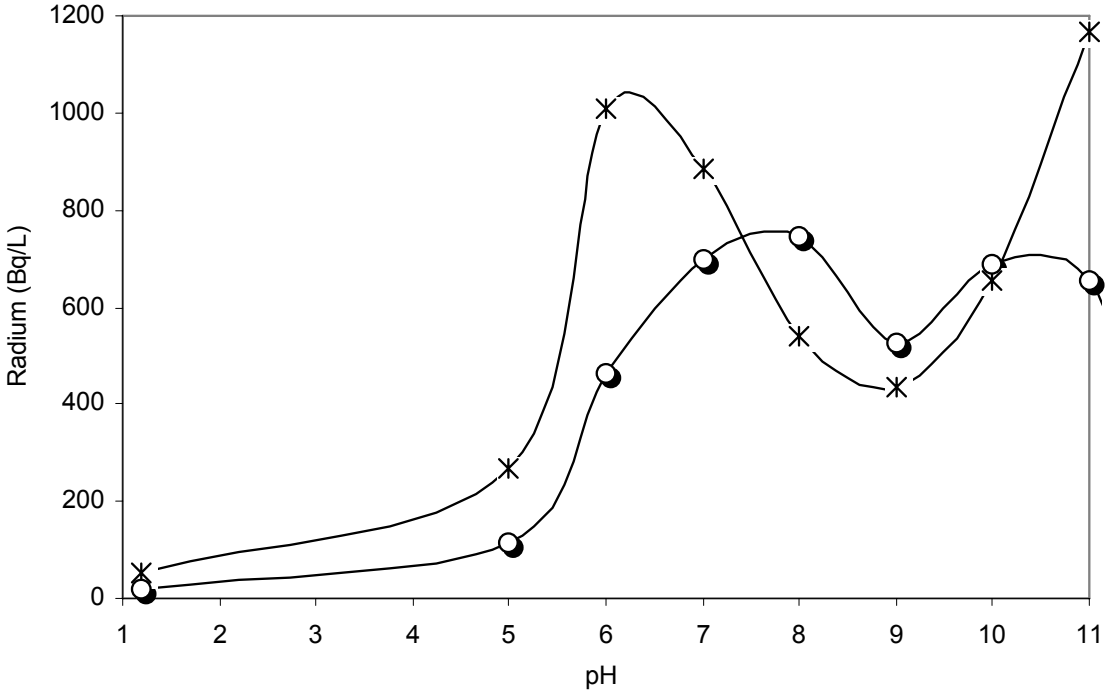

FIG. 2. Radium concentration profile in batch and continuous modes for the CCD#8 U/F slurry. Batch-scale test work is symbolized with the x points. Continuous test work is shown with the solid circular points.

In the continuous mode, the original pH of the CCD#8 U/F slurry used in the continuous scale test work was 1.72 and the initial dissolved Ra-226 concentration was 18.1 Bq/L. The dissolved radium concentration increased from pH 2 to pH 8 reaching a maximum concentration of 746 Bq/L. From pH 8 to pH 9 the dissolved radium concentration decreased to 525 Bq/L. The dissolved radium concentration subsequently increased to over pH 9 to pH 10 to 690 Bq/L and then decreased slightly to 670 Bq/l at pH 11. The continuous test work more closely represents the Key Lake mill process. Therefore, the optimum pH range to add barium chloride to the tailings slurry would be in the range pH 6 to pH 8 or pH 10 to pH 11.

The same pH profile was determined on effluent water to quantify the dissolved radium concentration profile in the absence of clay minerals present in the leach residue of CCD#8 U/F. The original pH and dissolved radium concentration of the effluent water were 1.72 and 104 Bq/L (Fig. 3). In this experiment, the dissolved radium concentration steadily decreased from pH 2 to pH 11, reaching a minimum of 2.18 Bq/L. This suggests that Ra-226 has the potential to co-precipitate with gypsum during the lime neutralization of sulfuric acid-based hydrometallurgical solutions. A concentration of 2.18 Bq/l in the effluent at pH 11 is greater than the discharge limit (0.074 Bq/l) for Ra-226 in mill process effluent. As a result, barium chloride could be added to the effluent for enhanced control on the solubility of Ra-226 in the mill final effluent.

4.2. Radium control through barium chloride addition

Next, barium chloride was added to the leach residue slurry to assess if the same reaction mechanism applies for the control of dissolved Ra-226 in the tailings pore fluids as for the treatment of mill effluent. A series of five tests were completed using the same tailings sample slurry.

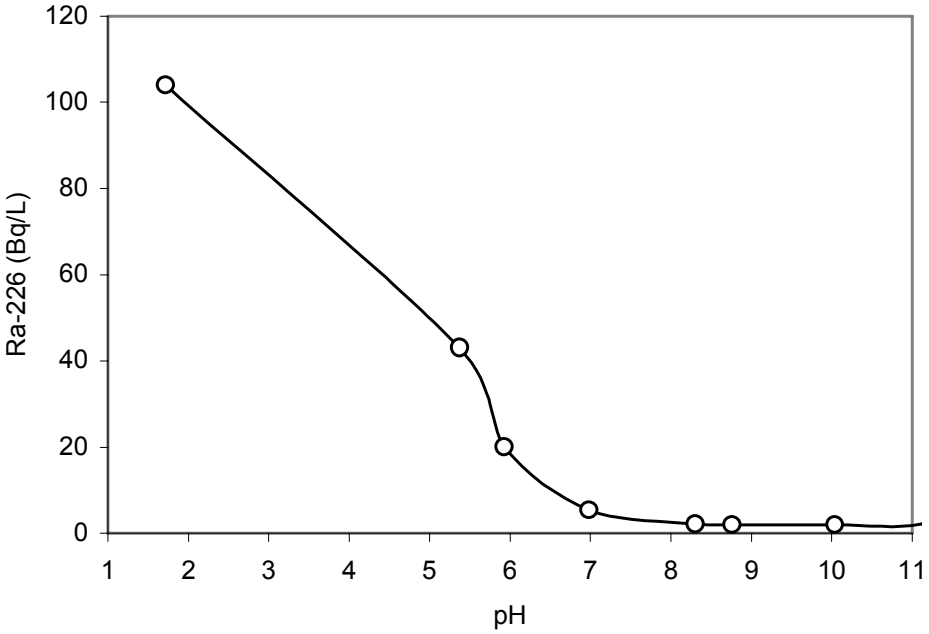

FIG. 3. Dissolved radium concentration profile in effluent water.

Table I summarizes the results of the effects of barium chloride addition to the tailings slurry and the aging tests completed on these mill tailings. Test 1 was completed as a control where the pH of the tailings slurry was increased to a final pH of 11.0 without the addition of barium. Tests 2-5 incorporated the addition of barium at a concentration of 100 mg Ba/L in the tailings slurry. In aging tests 2, 3 and 4, barium chloride was added at different pH levels (Table I) with a terminal pH of 11.0 in all three tests. In test 5, barium chloride was added at pH 6.0 with a terminal pH of 8.5. The procedure used in test 5 produced the lowest dissolved radium concentration of 64.9 Bq/L at t=0 days as well as the lowest final concentration for dissolved radium of 4.3 Bq/L at t=30 days. This was in keeping with the results discussed in section 4.1 where the concentration of dissolved Ra-226 in the tailings pore fluids was lower between pH 6 and pH8 than between pH 8 and pH 11. There is concern, however, regarding a terminal pH of 8.5 in the tailings emplaced in the DTMF. Previous drilling campaigns in the DTMF have identified a general decrease in tailings pH over time with decreases up to 3 pH units. As a result, long-term aging of tailings deposited at a pH of 8.5 may experience reductions in overall pH resulting in the potential dissolution of contaminants such as uranium and nickel. In tests 2, 3, and 4, the lowest dissolved radium concentration was noted when the barium chloride solution was added to the slurry at pH 11.0 resulting in a dissolved radium concentration of 167 Bq/L at t=0 days and an equilibrium concentration of 54 Bq/L at t=30 days.

Table I. Dissolved radium concentration in aged mill tailings. Barium chloride was not added to the slurry in test 1 (control sample). All Ra-226 values were reported in Bq/L. Barium chloride addition was at pH_i and the terminal pH is at pH_f. Aging tests were completed at 20^0C.

Test	pH_i	pH_f	Ra-226 (t=0 days)	Ra-226 (t=30 days)	Ra-226 (t=60 days)
1 (control)	11.0	11.0	428	186	194
2	6.0	11.0	249	58	68
3	8.0	11.0	227	79	75
4	11.0	11.0	167	54	52
5	6.0	8.5	64.9	4.3	5.1

Aging tests showed a decrease in dissolved radium concentrations in the tailings pore fluids with an average reduction in pore fluid concentrations of 72% (n=5; standard deviation = 14). A reduction in the dissolved radium concentration occurred in all test slurries including the control sample suggesting

secondary adsorption of radium to the tailings solids (clay minerals, ferric oxy-hydroxides, manganese oxides, or gypsum). Steady state was reached by 30 days with no further reduction in dissolved radium concentrations noted after 60 days.

Figure 4 (a-e) shows the results of aging tests 1-5 in chronological order. In each figure, the best-fit line was forced through the data points using a polynomial regression. The shape of the curves in all the figures was similar suggesting equilibrium was obtained after 30 days independent of the pH at which barium chloride was added to the tailings slurry as well as the terminal pH chosen.

Addition of barium chloride to the CCD#8 U/F slurry at a pH of 11 and a terminal pH of 11 resulted in the most efficient precipitation of dissolved radium, uranium and nickel (latter results not presented) from the tailings pore fluids. Compared to the dissolved radium concentration of the pore fluids of the control sample at pH 11 when no barium chloride was added to the above-mentioned test, there was an average decrease of 93% of the dissolved radium from the tailings pore fluids. This may be explained by the pH profile of dissolved radium concentrations in Fig. 2. De-sorption of labile radium from the grains of the tailings solids was most pronounced at pH 11. It is therefore most efficient to add barium chloride at pH 11 to realize the greatest reduction in dissolved radium concentrations in the tailings pore fluids. Dissolved sulfate concentrations in the pore fluids of the tailings at pH 11 were sufficient for the formation of the Ba, Ra/SO_4 co-precipitate.

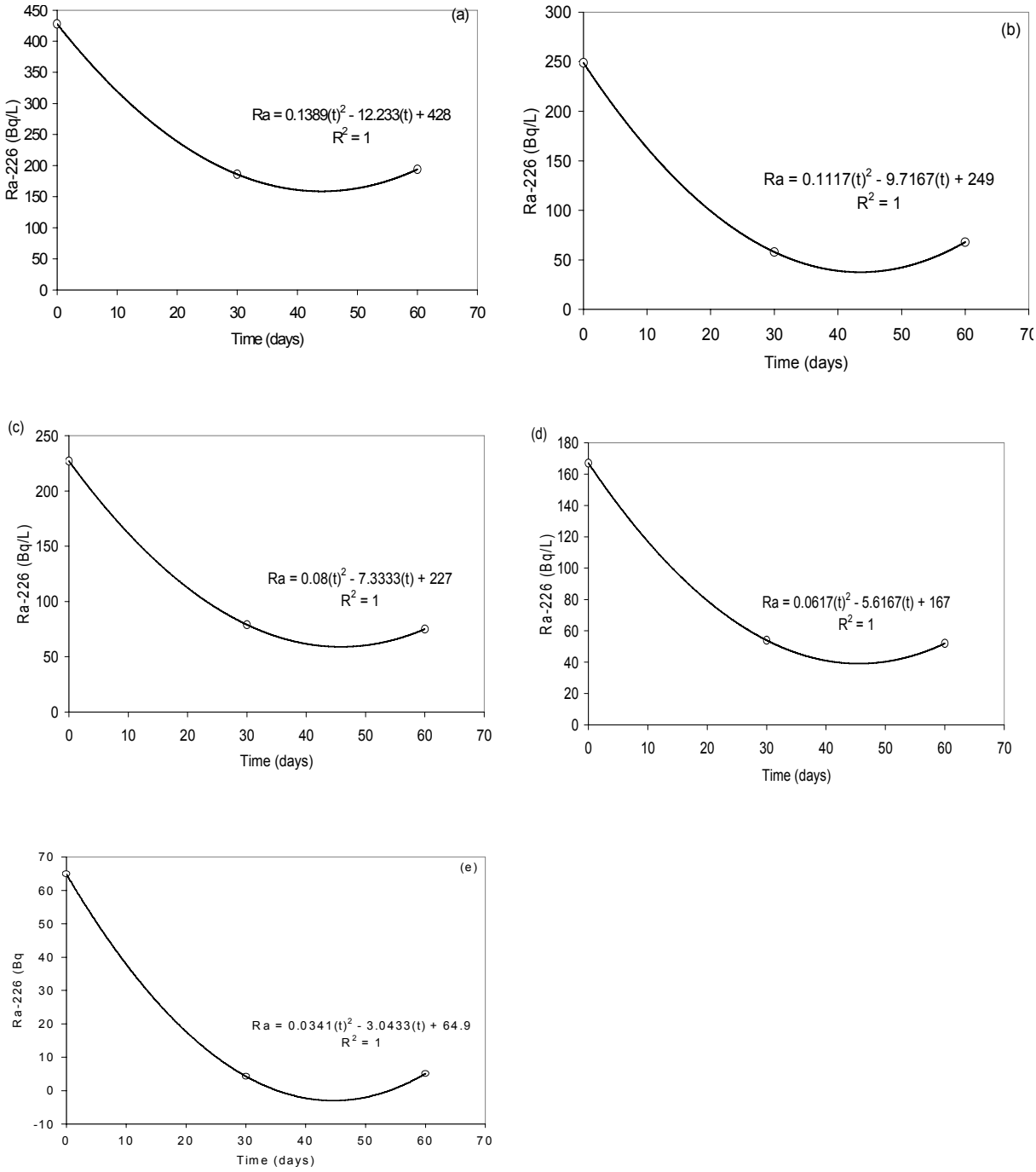

FIG. 4. Dissolved radium concentrations in aged mine tailings pore fluids. Samples of tailings pore fluids were collected at 0, 30, and 60 days after barium chloride addition. Best-fit polynomial regression equations are illustrated for each aging test.

4.3. Control of dissolved Ra-226 in the DTMF

Figure 5 illustrates the concentration of dissolved Ra-226 in the DTMF tailings supernatant solution and the associated annual production rates of uranium in the Key Lake mill. Mill data for samples of tailings supernatant collected prior to 2002 represent the period when no barium chloride was added to the tailings slurry. Samples of the supernatant solution were collected from the DTMF on a monthly

basis and the results presented are an annual average. Following the addition of barium chloride to the tailings slurry the concentration of Ra-226 in the tailings supernatant solution decreased from 280 Bq/l in 2001 to 18 Bq/l in 2004 (Fig. 5). These results confirmed that the addition of barium chloride to uranium mine tailings slurries in an effective mechanism to attenuate Ra-226 in the emplaced mine tailings thereby reducing its mobility and bioavailability. Finally, this co-precipitate was shown to be thermodynamically stable under conditions present in the DTMF.

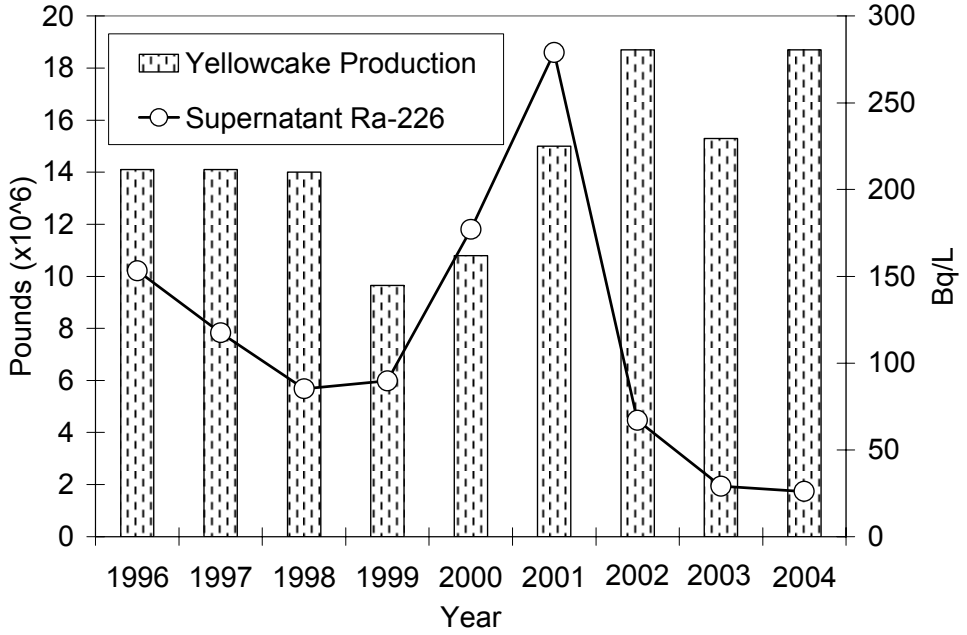

FIG. 5. Annual averages of dissolved radium (Bq/l) in the tailings pore fluid correlated to annual yellowcake production for the Key Lake mill.

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Late stage of weathering of uranium ores as a waste rock after historical silver mining, Joachimsthal, Czech Republic

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Abstract. A 450 year old dump after mining of silver ores with significant contents of radionuclides was studied as an analog of modern waste rock dumps after mining of uranium. Migration of radionuclides in the dump and underwards and radioactive disequilibrium were measured using laboratory gamma spectroscopy. The localization and bond of radionuclides were studied by means of alpha-autoradiography. Weathering of selected grains of uranyl phosphates was described.

1. Introduction

Weathering of uranium ores and migration of radionuclides were studied in the area of 450 years old waste rock dump Geister II after silver mining in Joachimsthal. The dump shows significant contents of uranium series radionuclides and the site can be regarded as an analogue of modern uranium waste rock dumps from 20th Century. It is likely to provide valuable information about process of weathering and washing of radionuclides away from it due to its long-term exposure to oxidizing conditions.

2. Radiogeochemical profiles of dump – U/Ra equilibrium

Samples of the dump horizons for laboratory scintillation gamma spectrometry were collected in digged well and also bores made with engine drilling. The coefficients of radioactive equilibrium (Ra/U activity ratios) were used to describe the changes in radioactive equilibrium within two vertical profiles. Digged well “Hermegelinda” 1.7 meter deep was placed in the slope of the dump and reached 0.4 meter under the base of the dump. It showed a strong radioactive disequilibrium. Ra activities range from 5 to 737 ppm eU. There were observed three activity maxima in the profile: in the upper horizon of the soil evolved on the dump (737 ppm eU), in the horizon of weathered waste rock (643 ppm eU) and one less distinct in the horizon of unweathered dump material (129 ppm eU). The general tendency of radium concentrations is decreasing downwards, where a clay layer under the dump is present, a buried soil and a dump subsoil (disintegrated mica schist). Uranium concentrations show an opposite trend with maximum value 1 188 ppm U in the lower horizon of buried soil under the dump. Towards the dump subsoil the activity of uranium decreases, but the background values was not found. In the upper part radioactive equilibrium is shifted strongly towards radium, the approximately balance conditions were observed only in the fresh waste rock. In the lower part of the profile radioactive equilibrium is shifted towards uranium.

The possible interpretation of this feature is that waters infiltrating through the dump caused uranium elution from the active horizons and its consequential accumulation in the weathered waste rock subsoil of the dump, mainly in the organic rich buried soil. Radium stays stable in the upper part of the dump and does not migrate (Fig. 1 and Table I).

The 3.5 m deep “Glück” bore was placed in the foot of the dump slope. The buried soil was found in the depth of 0.5 m under the horizons of soil and weathered waste rock. Then clay layers and the weathered waste rock were observed downwards. Concentrations of radium vary from 8 to

1 025 ppm eU. Elevated values were measured only in the upper part of the profile (horizon of hematite rich waste rock) and downwards the values were close to the background. Uranium concentrations are higher than equivalent radium contents in the whole profile, the values ranges between 37 and 3 679 ppm. Four main maxima were observed in the profile: the most significant in the horizon of buried soil under the dump and the other in the horizons of hematite rich waste rock and in the clay layers in the subsoil of the dump. Uranium concentrations were falling downwards. In the whole profile the radioactive equilibrium is shifted towards uranium, the approximately balance conditions were observed only in the waste rock.

It is supposed that radium is strongly bonded in the material and does not migrate from the dump material. Uranium situation is not clear in this site – its high contents are caused probably partly by washing out of the upper part of the dump and also (mainly in the subsoil of the dump) migration from the nearby U bearing vein outcrop.

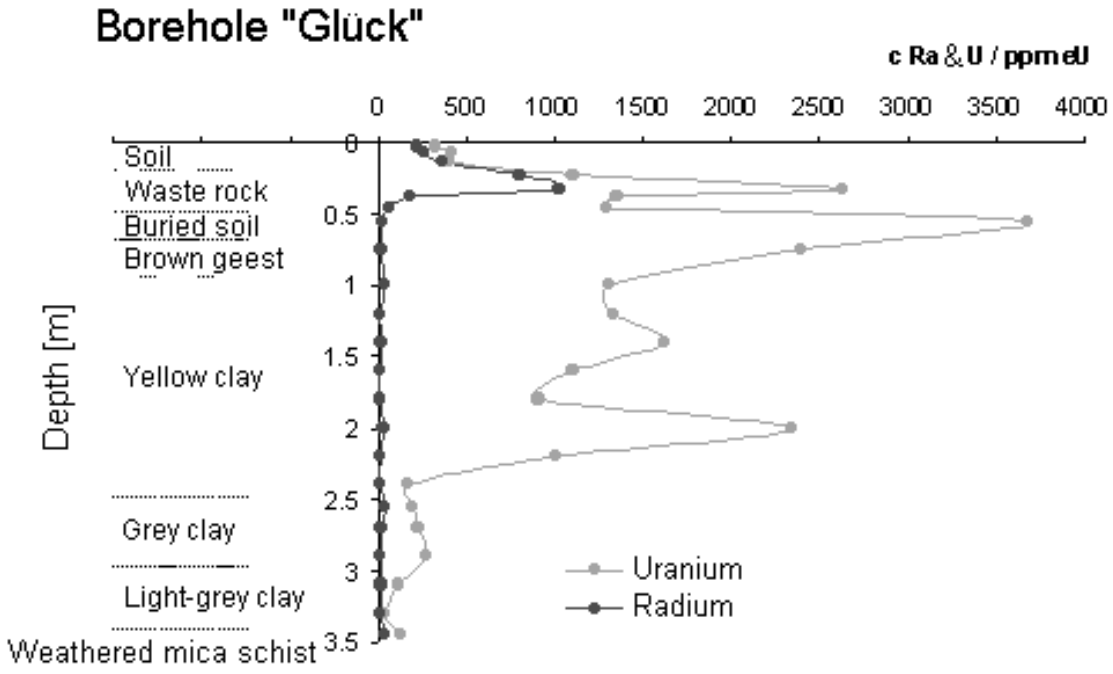

FIG. 1. Geochemical profile "Glűck" through the dump and underlying horizons.

3. Radionuclides microconcentrators. Alpha-autoradiography

Alpha-autoradiography using LR 115, type 2 film detectors was employed to study of distribution of radioactive micro-objects in the profile. Morphology and semi-quantitative chemical composition of selected objects were studied by electron microscopy and microanalysis on 3 samples from different horizons of dump and its subsoil.

Table I. Characterization of samples

depth [cm]	sample no.	description	concentration of U [ppm]	concentration of Ra [ppm eU]	coefficient of radioactive equilibrium [%]
10-20	Her 2	brown soil evolved on the dump	6.2	495.7	8034.0
50-60	Glu 8	buried soil under the dump	3679.0	19.4	0.5
140-155	Her 13	rusty coloured clay with mica schist fragments	1188.1	12.4	1.0

Her 2 sample comes from the upper part of the profile – it is a strongly weathered waste rock. Alpha activity is bonded mostly to secondary rock (mica schist) grains rims. Inside the grains are formed with quartz, feldspar, micas and apatite and rutile as accesories. The rims contain mainly micas (chloritized biotite, Fe-annite, muscovite sometimes with V or Ti), but also Fe sulfides and Fe and Bi arsenates (scorodite) were observed.

Electron microanalysis does not provide Ra concentration measurements, but localization of the active centers to the rims appointed indicates the possibility of radium bonded to grain surfaces and layered silicates. No Pb or Ba sulfates, where Ra co-precipitation was expected, were found. Isolated phases with U were observed. U is likely bonded in the form of uranyl anion to phosphates and/or arsenates with Fe, Cu, Pb, Al, Ca and Ni cations. However, U concentrations are in the range of tenth of weight %, which indicates strong leaching out of U from the new formed phases.

Glu 8 sample represents the buried soil under the dump. Rock grains (mica schist) are formed with quartz, K-feldspar, albite, micas and accesories: rutile, zircon and Al_2SiO_5. This horizon contains also a great volume of organic matter.

Uranium is to Fe and Mn oxides (1 wt. % U) and uranyl phosphates (40 wt. % U) with Ca and Cu cations. However, the most frequent is bond of U to organic matter (1-3 wt. % U).

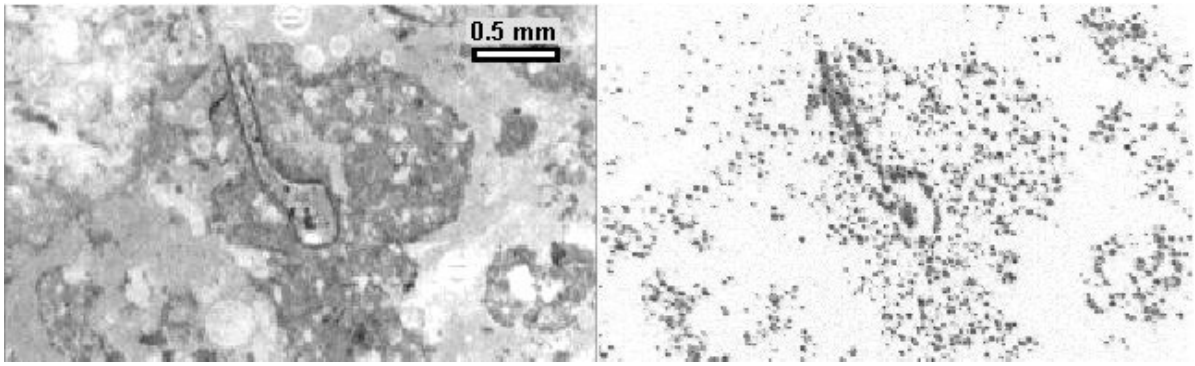

FIG. 2. Sample Her 13 (underlying soil), part of polished section (left) and its autoradiography (right). In central part a plant root with increased uranium content is visible.

Her 13 is a sample of clay with mica schist fragments from the subsoil of the dump. Similarly to the buried soil horizon the alpha activity is bound to the organic matter (roots and other parts of plants) – 2-4 wt. % U (Fig. 2). In some parts in the organic matter contains fine-grained Fe oxides.

4. U-micas breakdown during weathering ("bassetitization")

A series of secondary uranyl phosphates samples from the site in a different stage of weathering were studied.

XRD was employed for determining a mixture of uranyl phosphates:

- meta-autunite $Ca(UO_2)_2(PO_4)_2 \cdot 2\text{-}6(H_2O)$, meta-torbernite $Cu(UO_2)_2(PO_4)_2 \cdot 8(H_2O)$,
- bassetite $Fe^{II}(UO_2)_2(PO_4)_2.7H_2O$, vochtenite $Fe^{II}Fe^{III}[(UO_2)(PO_4)]_4(OH) \cdot 12\text{-}13(H_2O)$
- and oxidized bassetite $Fe^{III}(UO_2)_2(PO_4)_2(OH).6H_2O$, with XRD powder pattern comparable to that of a synthetic prepared material [1].

However, most of the corroded mineral grains, identified by XRD as meta-autunite, show a depletion in Ca (or even a nearly total absence of Ca), which is substituted by Fe. As and Cu are present in small amounts. The increasing amount of bassetite in the mixture of mineral phases corresponds to the increasing degree of corrosion of mineral grains and to increasing Fe contents. Presence of acid

solutions (pH of water leachate of dump material ranges between 3.7 and 4.5) results in the replacement of Ca by Fe and in the formation of bassetite, which can be subsequently oxidized by atmospheric oxygen. Chemical oxidation is accompanied by physical disintegration of uranium phosphate grains as evidenced by high microporosity observed on electron microscope images.

Mineral samples were studied using an optical microscopy with UV light. In several grains a transition zone between the fluorescent part and non-fluorescent part was visible. Those grains were studied by electron microanalysis in detail. It was determined that the corroded rims of the grains were depleted with Ca, U and P and enriched with Fe (Fig. 3).

Mössbauer spectroscopy was used for distinguishing of different types of Fe bond in studied samlpes and amount of phase with certain oxidation state in each sample. Goethit was determined in the mixture of secondary minerals.

By means of alpha spectrometry was found out that the studied bassetite from the dump upper layer are not in a significant radioactive disequilibrium (U~Ra), but it shows a high microporosity (Rn escape) in compare with unaltered meta-autunite.

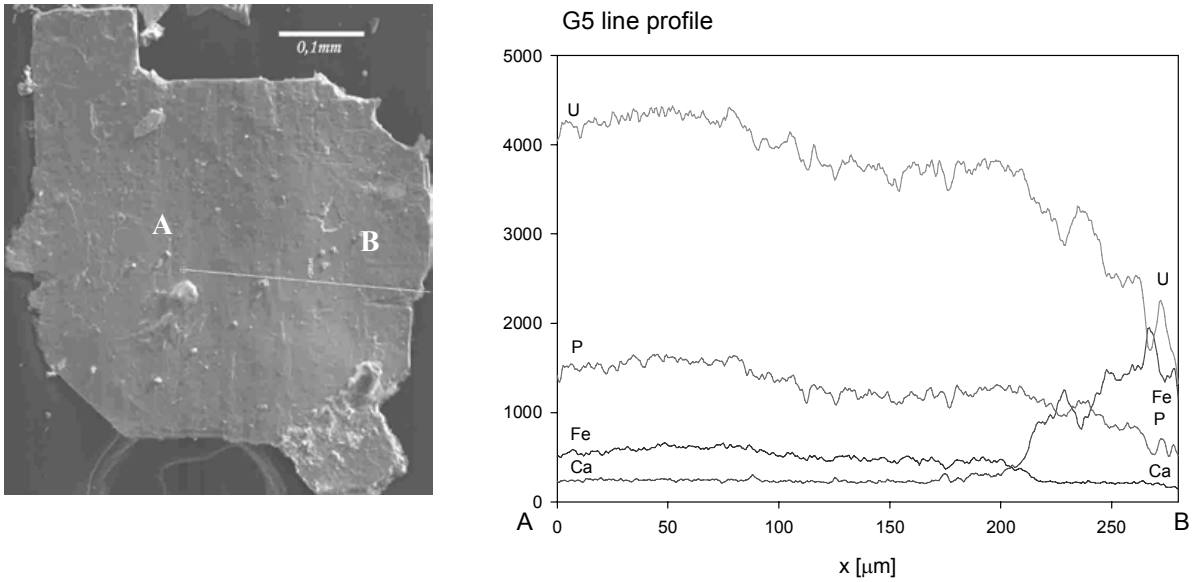

FIG. 3. Line scan of a meta-autunite grain with a corroded rim. In the direction to more corroded part contents of Ca, P and U are decreasing and Fe is increasing.

On the base of study of mineral assemblage of uranium secondary minerals from autunite group and its interaction with acid Fe^{III}-rich solutions is clear the key role in the uranium migration aspect. The following alteration succession was observed [2]: meta-autunite → Fe^{II}bassetite → Fe^{III}bassetite → total dissolving of bassetite and replacement by Fe^{III} hydrated oxides. On the other hand, radium does not migrate to the subsoil. It remains bonded to weathered waste rock and is also detectable in increased activities in the upper horizons of humus. This "upwelling" can be caused by its integration to biological cycles. Here come into account processes of radium intake by roots of plants [3] and its microbial migration similar to uranium mill tailings [4].

5. Results

The performed research showed that uranium is redeposited from the waste rock to fossil soils under the dump. In the subsoil it is bonded mainly to decomposed organic matter remainders and lesser amount is adsorbed on porous hydrated Fe^{3+} oxides, which play the role of an effective geochemical barrier. In the horizon of fossil soil the uranium concentration can reach up to 0.25 wt. %. Radium, however, is still bonded in a horizon of active dump material and comes under a partial redeposition controlled by biological processes.

It is possible to establish that the studied model mirrors the late stage of uranium migration. Leaching of uranium ore in the surface oxidizing conditions proceeded more than 450 years. Nearly total leaching of uranium from waste rock and its washing away from the dump occurred. It seems very probable, that a similar process will happen in the time horizon of several hundreds years in case of modern waste rock dumps after intensive uranium mining in other mining districts, as well. It is only a question, if there will be present effective geochemical barriers for its retain.

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Water treatment issues at the former uranium mining site

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Abstract. After the termination of uranium mining and processing among rehabilitation work water treatment issues became of first importance. Because of the location of the former mining site and drinking water catchment areas, mine water treatment and groundwater restoration around tailings ponds has priority in the remediation plans. Mine water treatment with removing of uranium in form of commercial-grade uranium peroxide and groundwater restoration is underway in industrial scale. Recently an elemental iron-base experimental permeable reactive barrier (PRB) has been built for investigation of the long-term performance of the PRB in the frame of EU-sponsored project.

1. Introduction

Water treatment issues have high priority for the company because the drinking water supplying aquifer is situated very near to the former uranium mining and milling facilities. Remediation works in this respect are related principally to mine water treatment aiming at protecting the groundwater from uranium pollution and extracting the polluted groundwater in the vicinity of tailings ponds (TPs), where a significant pollution exists (magnesium sulfate and sodium chloride). Though uranium contaminated groundwater is less important at the time being, nevertheless it is important to know how effectively the permeable reactive barriers (PRB) can be used for retardation of uranium if needed. Therefore the company took part in an EU project aiming at investigating the long-term performance of the PRB. Results of two years' experiment with an experimental iron base PRB are discussed.

2. Description of the work and results

2.1. Mine water treatment

The geological cross-section of the former mining area is shown in Fig. 1. It can be seen that the mining area can principally be divided into two parts: the **southern** part which is closely connected with the drinking water aquifer situated at foot of the ***Mecsek Hill***, while the **northern** part (northern mines) has no direct connection with drinking water aquifer.

The southern mine (shaft N^0I) was terminated in 1968. From that time, because the elevated uranium content of the water and the possible hydraulic connection with drinking water aquifer (D) a depression funnel has to be kept continuously in the shaft. The maximum permissible water level in the mine is 106 m bellow ground surface to collect the polluted mine water from the former workings and thus protecting the drinking water aquifer from escaping contaminated mine water. For this some hundred thousands m^3 of mine water per annum is being pumped out and treated for removing of uranium.

Volume of mine water significantly decreased after reclamation of the surface above the former mine workings. Over the last four years in average 450 thousand m^3/a mine water has been removed from the mine, which is app. the same volume as it was in the very beginning (1968) of the mine water treatment and half of the volume prior to the recultivation of the surface.

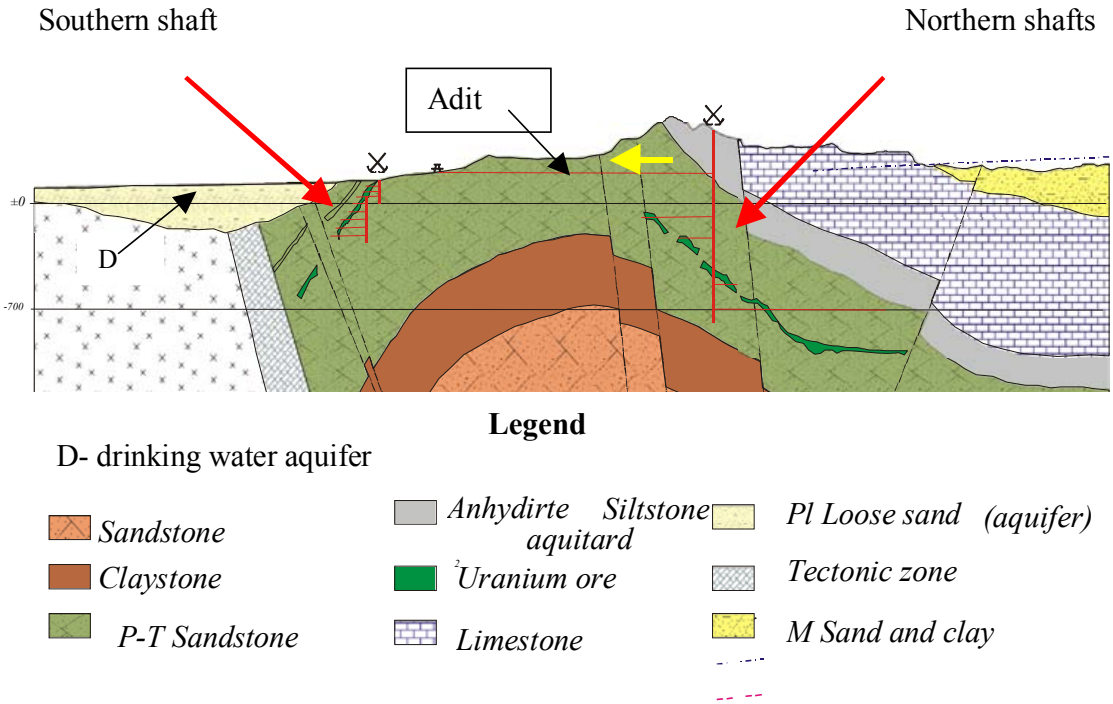


FIG. 1. Geological cross-section of the former mining site (Western Mecsek).

Historical data on uranium concentration is presented in Fig. 2. It can be seen that the uranium concentration in mine water at present is 4.5 mg/l in average, over the past four years. It is worth to mention that just after the termination of the mine in 1968 the uranium concentration was app. 7 mg/l. It means that the uranium has been decreasing very slowly in the mine water, which means that a rapid decreasing in uranium concentration is not a realistic option; therefore mine water treatment has to be continued in the future. (The higher uranium concentration between 1973-1999 is explained with the heap leaching process, because heap piles were constructed in the immediate vicinity of the former mining area and the mining workings were used as buffer for process water).

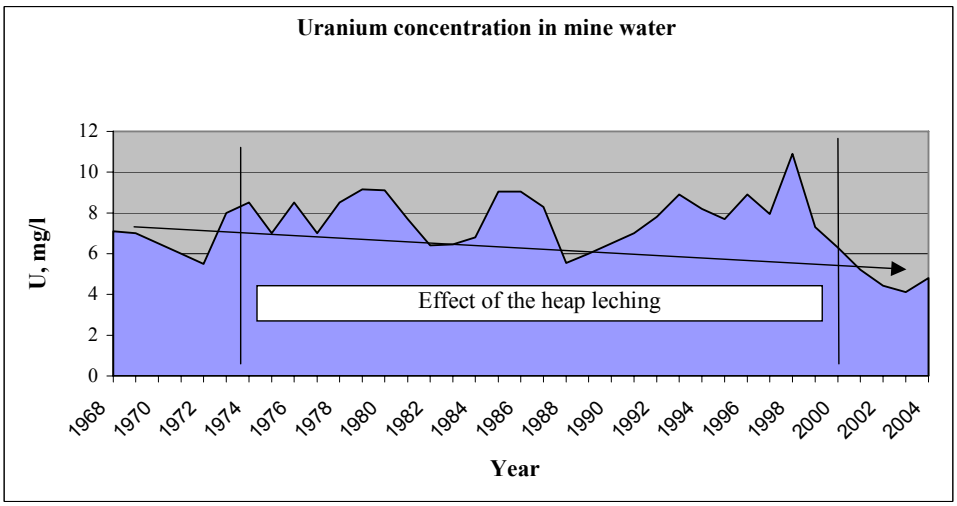


FIG. 2. Uranium concentration in mine water over the treatment period.

Mine water treatment consists of the removal of uranium from the pumped out water using anion exchange process. Uranium is obtained in form of peroxide, which is a commercial-grade product. The quantity of uranium in the peroxide is 2-2.5 t/a. The technological flow sheet of the process was presented on the previous uranium meeting in 2002 [1]. At the latest years attention has been paid to uranium in effluent. As a result of this effort uranium concentration in the effluent has decreased significantly and at the time being it is on the level of 0.2 mg/l. The mine water is slightly alkaline; the heavy metal content is low (e.g. As<12 µg/l). Nevertheless during the ion-exchange process a small amount of precipitate is formed in the columns (main components of the precipitate are iron, manganese, calcium), which is highly contaminated with arsenic (300 g/t) and uranium (3 000 g/t). It is supposed that the formation of the precipitate is due to the reduction with the iron (columns made of steal) just like the processes discussed in Chapter 2.3.

From the northern mining area at the time being only water collected with the adit enters on the surface, which does not need any treatment because both TDS and radionuclides are at low level (U<0.7 mg/l, Ra<0.6 Bq/l) in it. The northern shafts are is still under flooding. Later on (in 10-15 years) water will flow through the adit and if necessary would be treated in the existing mine water treatment station.

2.2. Groundwater restoration at tailings ponds area

Groundwater around tailings ponds is polluted with different compounds (first of all with magnesium sulfate, in less extent with sodium chloride, both originated from the mill process) because of high TDS content of the tailings water during the mill operation (22 g/l in average). Therefore it is necessary to take measures for groundwater restoration to protect the nearby drinking water aquifer. Groundwater restoration has started with building pump and treat system. The treatment process was developed partly in the frame of IAEA-sponsored project [2].

TDS in the most contaminated shallow groundwater (up to 15 m) in the vicinity of TPs is presented in Fig. 3.

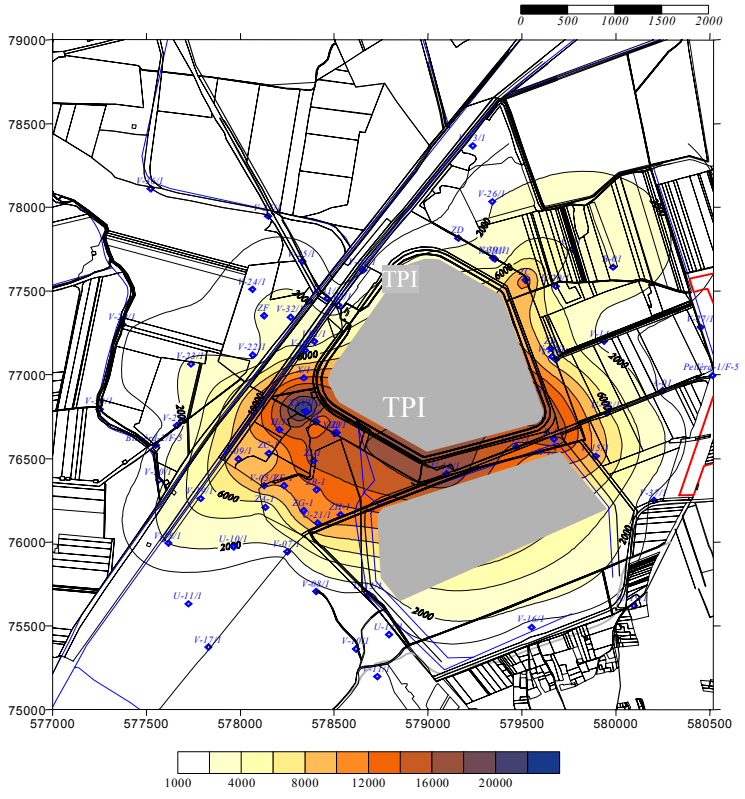


FIG. 3. TDS in shallow groundwater in 2003.

It can be seen that the TDS in groundwater in the immediate vicinity of TPs is as high as 1 618 g/l. Contamination of the deeper groundwater (15-60 m) is much less (2-5 g/l). It is worth to mention that the uranium contamination though is detected, but it is relatively low: for shallow groundwater app. 60 µg/l, for the deeper one app. 13 µg/l. In Fig. 4, uranium concentration for some selected monitoring wells (the most contaminated) are presented (average for 2001-2003) both for shallow and deeper groundwater to demonstrate the above conclusion. It is not known that the difference in uranium concentration is due to the dilution effect or in some extent to the sorption effect, too.

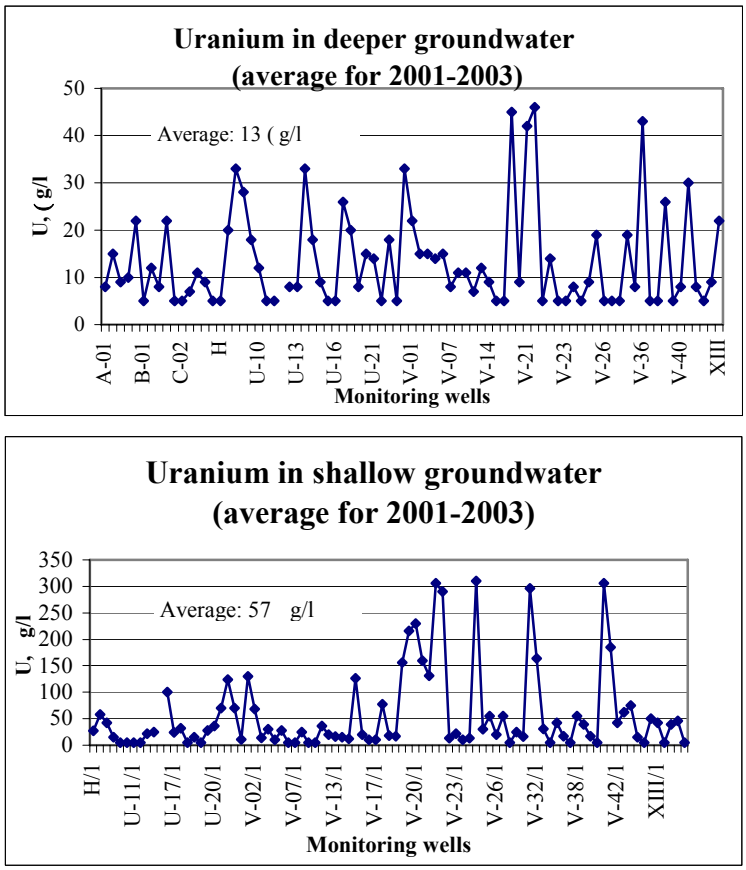


FIG. 4. Uranium contamination in the vicinity of TPs (A-shallow B-deeper groundwater).

Because of the huge contamination of the groundwater (first of all with magnesium sulfate and sodium chloride) restoration program has started. The polluted water is removed by wells (15-60 m depth) and drainage wall (6-9 m deep) constructed around tailings ponds.

The specific electric conductivity of the extracted water both for shallow and the deeper one as well as for seepage collected by toe drain of the TPs are presented in Fig. 5. It can be seen that only a minor decreasing of the contamination took place from the starting of the restoration. This is partly due to the continuing seepage from the TPs (covering of which has to be finished in next year), which still contain huge volume of former process water. This is justified by the specific electric conductivity of the seepage from toe drain (this water is practically tailings pore water).

Location of the groundwater removing system around TPs is presented in Fig. 6 (dots represent wells and lines drains). The water extracting system has been in operation from 2000 (capacity of app. 0.6 Mm^3/a), but further enlargement is needed (the enlargement was foreseen at the beginning of planning period). Therefore extracting system now is under enlarging. It is supposed that the enlarged system will be capable of removing app. 0.8 Mm^3/a of polluted groundwater, which will be treated as presently.

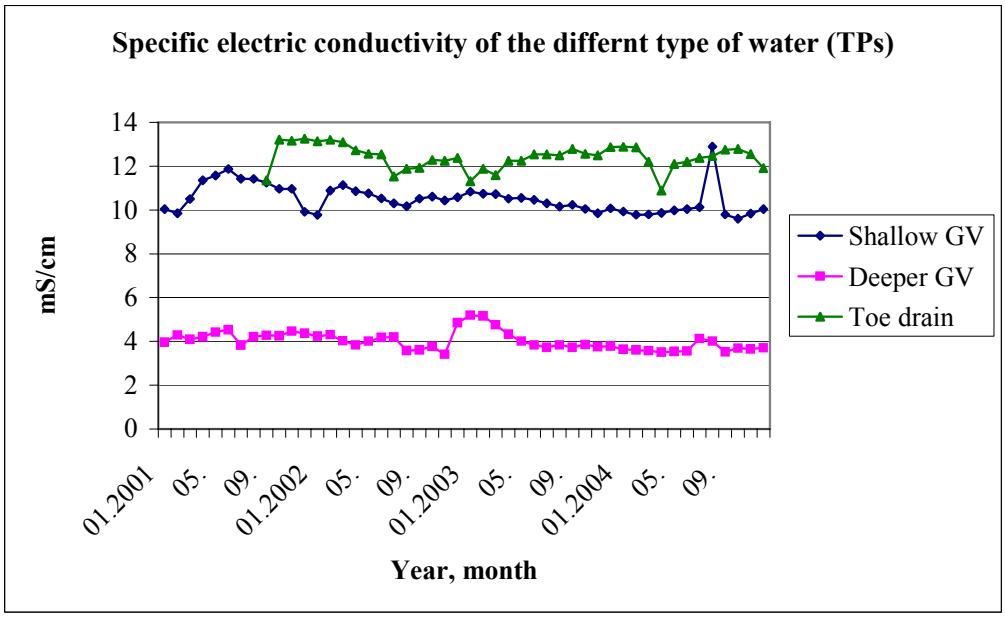
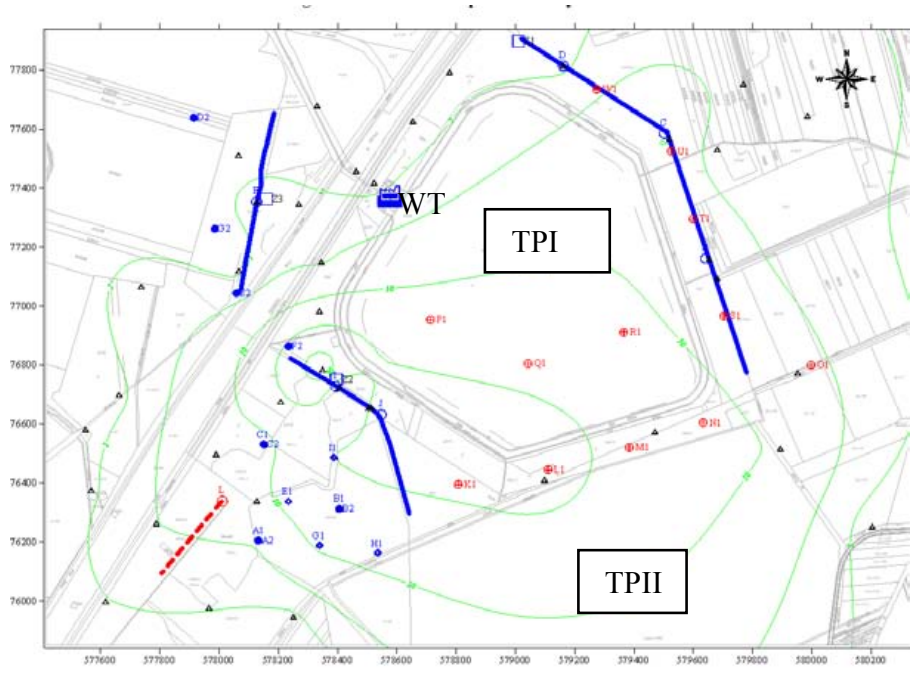


FIG. 5. Specific electric conductivity of the water treated on the water treatment station.

The used lime process (lime consumption in term of active calcium oxide is 2.25 kg/m3) is capable of decreasing the TDS to app. 7 g/l from 12 g/l. One lesson learned is that precipitation of gypsum needs longer time therefore a new additional basin has been built to increase the retention time by 2-3 hours for treated water. It is supposed that the gypsum will be precipitated more effectively and the TDS of the treated water will drop to 6 g/l[1].



Legend: WT-water treatment station
TPI, TPII tailings ponds

FIG. 6. Groundwater restoration around tailings ponds.

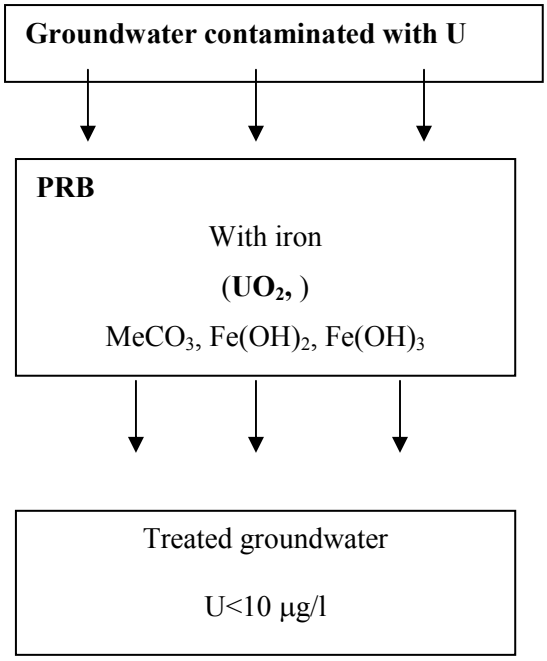
[1] The relatively high residual TDS is due to the sodium chloride content of the water (3-3.5 g/l).

The treated water from lime milk process is mixed with treated mine water and some other non-treated waters (with low contamination) and the mixed water is discharged (discharge limits are: TDS=5 g/l, U=2mg/l, Ra=1.1 Bq/l, maximum specific electric conductivity in the receiver Pécsi-víz: 2 000 S/cm). Total annual volume of discharged water is app.1.3 millions m3.

The water treatment sludge contains app. 50-55 % of water after filtration. This sludge as a waste is hauled in containers to the waste rock pile, where a storage area is allocated for this purpose. Annually app. 7 Kt. of sludge containing 3.3 Kt. dry is formed. The precipitate consist mainly of Ca~17%, Mg~17 %, SO_4~30 % and carbonate. Uranium content is app. U~70 g/t[2]

2.3. Experimental in situ groundwater treatment using permeable reactive barrier

Investigations related to the PRB started in 90-ties at the company when calcium oxide base reactive barrier was proposed for retardation of uranium migration from heap leaching residues after their relocation to waste rock pile [3]. Meanwhile an EU sponsored project (PEREBAR project) has started aiming at investigating the long-term performance of the PRB installations [4,5].



Main reactions:

$UO_2^{2+} + Fe = UO_2 + Fe^{2+}$ (1)

$UO_2(CO_3)_3^{4-} + Fe = UO_2 + FeCO_3 + 2CO_3^{2-}$ (**2**)

Supplementary reactions:

$Fe + 2H_2O = Fe^{2+} + 2OH^- + H_2$ (**3**)

$HCO_3^- + OH^- = CO_3^{2-} + H_2O$ **(4)**

$Me(HCO_3)_2 + 2OH^- = CaCO_3 + CO_2 + H_2O$ (5)

Me = Ca, Mg, Mn, Fe

$Fe^{2+} + 2OH^- = Fe(OH)_2$ (6)

$Fe(OH)_2 + 1/2O_2 + H_2O = Fe(OH)_3$ (7)

FIG. 7. Chemical processes in PRB.

The company took part in the project, providing site for field experiments. Extended site selection led to choosing a narrow valley (***Zsid-valley,*** nearby the biggest waste rock pile) linking the waste rock pile area with drinking water areas where the groundwater is slightly contaminated with uranium.

In the PRB elemental iron was used as reactive material, which proved to be effective for removing of uranium from groundwater according to publications [6,7,8,9].

From the geochemical point of view the processes taken place in iron base PRB can be presented by the equations in Fig. 7. Practically two basic processes are important: reduction of uranium into U(IV), which is less mobile because of the precipitation of UO_2 and rising of the pH of groundwater (higher carbonate ion concentration) causing precipitation of different carbonates (calcium, magnesium, iron, etc.). This latest process is undesired because it can lead to the blocking of the PRB.

[2] Some part of uranium is originated from seepage collected by toe drain (and treated together with groundwater) of the tailings ponds and not from the groundwater.

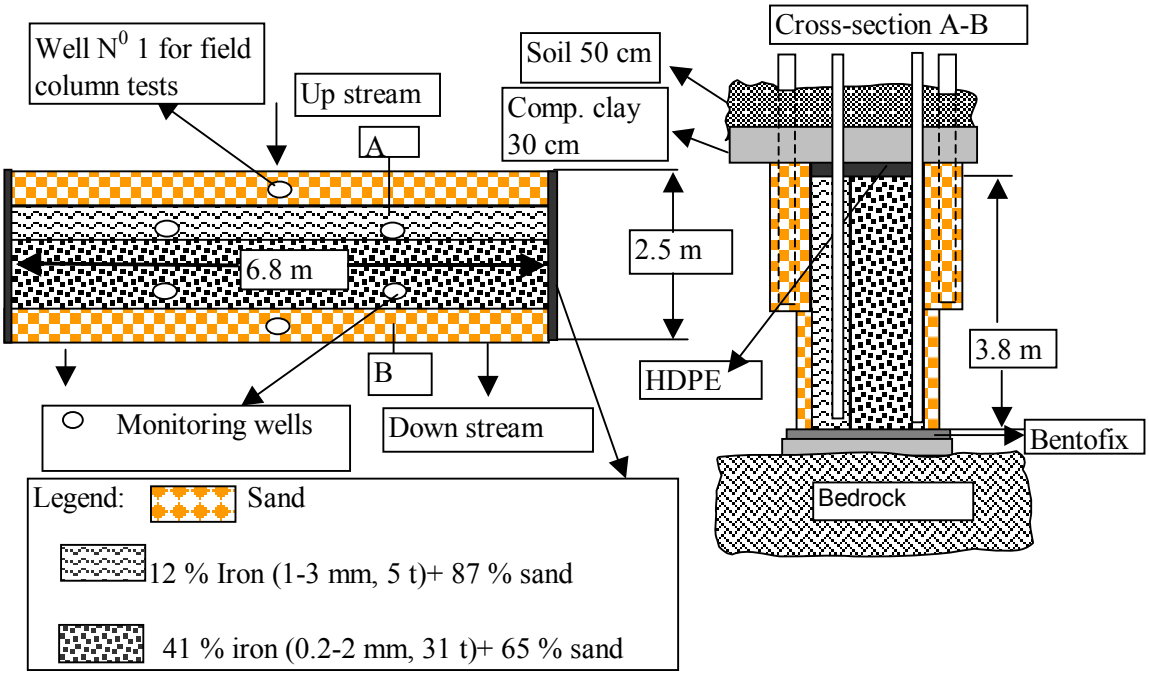


FIG. 8. Principal design of the experimental PRB.

For practical usability of the PRB their long-term performance is important. The above-mentioned EU project aimed at investigating this behaviour of the PRB. For the experiments an experimental PRB has been built. The principal design and main parameters of the PRB are presented in Fig. 8. It can be seen that the PRB consist of four layers. Sand layers are for distribution of the entering and leaving water streams, front layer with low iron content is for removing of the dissolved oxygen from the water entering in PRB, while layer with the higher iron content (iron in mixture with sand) is for retardation of the uranium.

FIG. 9. Test site with monitoring wells.

The test site can be used for additional column field experiments (investigating e.g. different reactive material) placing the columns in the well $N^0$1, which is large enough for such tests. The test site with monitoring wells is shown in Fig. 9.

Effect of the PRB on the groundwater chemistry is demonstrated by the uranium and calcium concentration distribution in Fig. 10. It can be seen that the uranium is removed with high efficiency (>95 %). Calcium concentration is also dropped to app. 50 % of the original. Uranium retention is due to the reduction of U(VI) to less mobile U(IV). Precipitation of calcium and other carbonates is related to the elevation of the pH of the water in PRB.

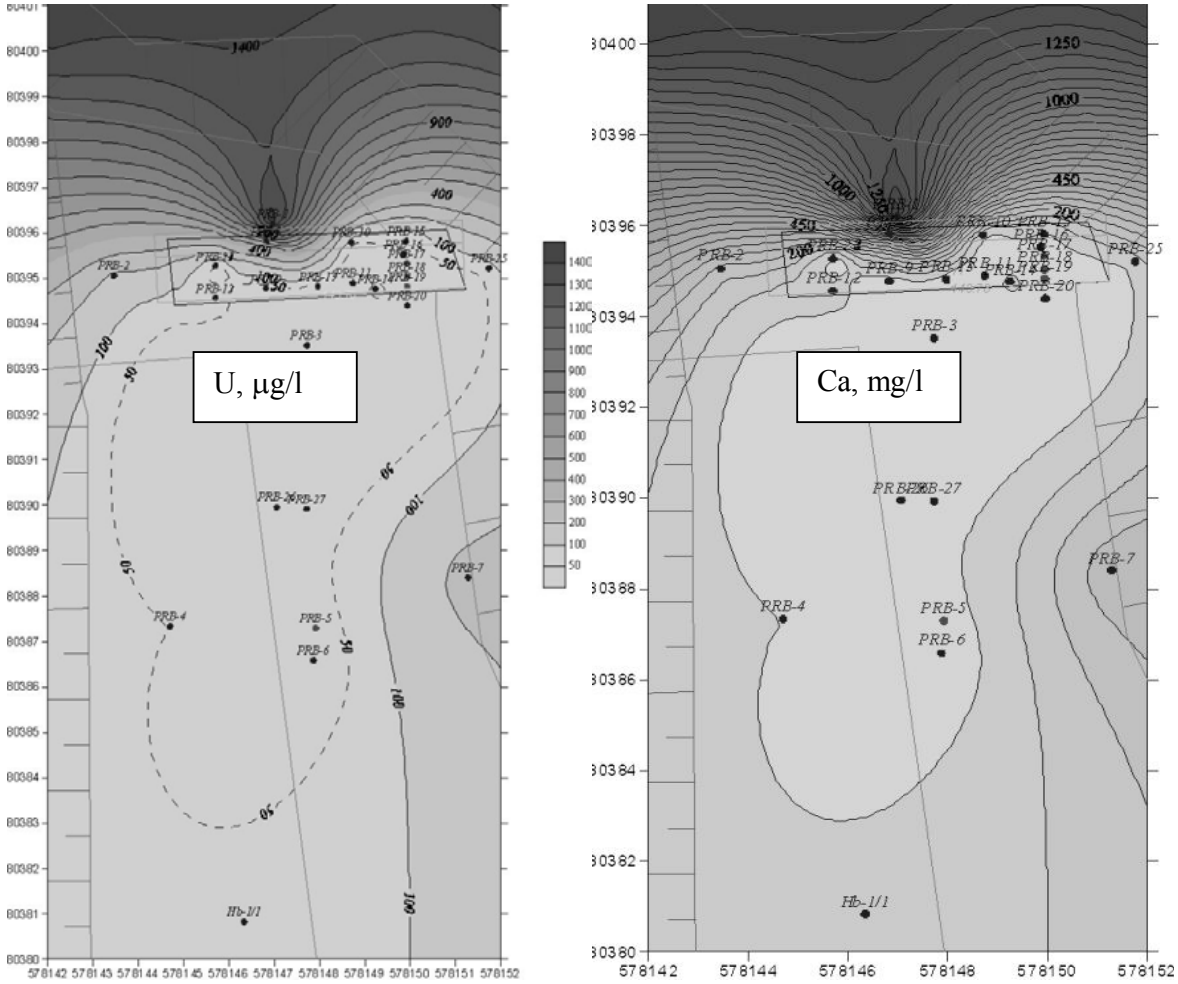


FIG. 10. Attenuation of uranium and calcium concentration in groundwater in down stream.

One of the important tasks of the continuing field test is to collect experimental data regarding the long-term performance of PRB. It is supposed that the test will have lasted by 2007. Up to now the conclusion is that the uranium removal is very efficient, but there are not enough data to evaluate the blocking effect of the precipitates formed in the process. It is supposed that in next two years (experiment will have been lasted by the 2007) this question also can be answered.

3. Conclusions

After termination of the uranium mining and milling one of the most important issues is the water treatment, for which the conventional methods can be used. The process of the attenuation of the uranium concentration in the mine water is a very slow process therefore it has to be continued perhaps for a long time. Pump and treat method for groundwater restoration is simple but some technological problems connected with the slow precipitation of the gypsum should be mentioned. Iron base PRB seems to be effective for in situ removal of uranium from groundwater, but the forming precipitate can cause decreasing of the hydraulic conductivity of the installation. In this respect our investigations are continuing.

ACKNOWLEDGEMENTS

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Treatment of mine waters discharged from underground uranium mines

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Abstract. Contaminated mine water treatment before discharging into surface water streams is mandatory for the uranium mines within the National Uranium Company SA – Romania in order to limit supplementary exposure of the population living downside the mine sites. Present mine water treatment plants have to be upgraded in order to ensure the stringent limits for uranium and radium concentrations even when processing waters resulted from the mine flooding process. Ion exchange method is used for uranium removal while radium is separated by adsorption on activated carbon. Separation process and performance are presented for the water treatment plant at an active mine and at a closed mine.

1. Introduction

The National Uranium Company S.A. is dealing with uranium ores mining and processing since 40 years. At the mine sites the treatment of mine waters to remove radionuclides such as uranium and radium is a concern for the company in order to reach the permissible values required by local environment authorityies. The decontamination methods and facilities at two underground mines, Suceava and Banat mines respectivelly, are presented. The Suceava mine is an active mine and the Banat one is closed out since 1998 and ready to be flooded during the 2005 - 2007 period.

2. Mine water treatment plant at the Suceava mines

The Suceava mines have been active since 1983 and ensure the main domestic uranium ore production. Discharged mine waters from the underground have relatively low content of radionuclides but have to be decontaminated, as a requirement of the local Environment Protection Agency. The total maximum flow of mine and seepage waters needed to be decontaminated is 2 000 m^3/day. In present there are two treatment plants with projected daily water flow of 500 m^3 and 1 500 m^3 respectivelly. The pollutant contents upside the plants are in the following range :

- U : 0.40 – 0.90 mg/l
- Ra : 0.25 – 0.60 Bq/l
- Cu : 0.009 – 0.020 mg/l
- TDS : 0.7 – 1 g/l
- pH : 6.9 – 7.5

No acid drainage was registered during the last 20 years of uranium mining within this site due mainly to 2 – 12% carbonate content of the ores and sterile rocks. The flowsheet of the water treatment involve sedimentation of fine solids, water clarifying, ion exchange for uranium removal, releasing of water into the brooks. The flowing waters are finally released into the Bistrita river. Final dilution factor is higher than 60. The planned values for decontaminated and discharged waters are 0.100 mg U/l and 0.150 Bq Ra/l , while the maximum allowed values for the Bistrita river downwards the mine are 0.021 mgU/l and 0.088 Bq Ra/l (present drinking water standard). The supplementary dose received by a

population using for drinking the Bistrita waters is under 0.10 mSv/year – person, the limit recommended by the national regulatory authority. The main characteristics of these 2 plants [1][2] are :

- old plant with 2 modules, 2 x 3 columns filled each with 2,5 m^3 ion exchange resin ; resin type anionite AM, chloride form; 12 years old ; upward flow inside columns ;
- new plant with 2 modules, 2 x 3 columns each filled with 4,5 m^3 resin ; resin type Purolite A 600 strong anion exchanger (new resin) ; chloride form ;
- both resin are in chloride form ; functional group is quaternary ammonium ; resin size is 0,70 – 1,30 mm for Purolite A600 and 0.50–1.60 mm for AM type ;
- specific loading for ion exchange resins is 12 – 18g U/l ;
- elution solution has 10% NaCl and 1% Na_2CO_3; 5 – 6 BV of eluant is used for each column elution. The first 3 BV of eluant have about 85% of the uranium recovered from the resin. The elution has an 99.3% efficiency and is undertaken in the same sorption columns without transfer of the loaded resin ;
- elution is undertaken in two steps when a rich eluate and a diluted eluate are produced ; the uranium low concentration eluate will be used as first eluant for the following loaded colum ;
- washing of resin bed is undertaken every 6 – 8 days with clear pressurized water jet in order to remove trapped fine solids.

The plant has one heated vessel (temperature up to 80^0C) for sodium diuranate precipitation from the uranium eluate processing. The filtered yellow cake (sodium diuranate having 20% moisture) is transferred twice a year to the Feldioara Milling Plant for further uranium valorization.

Uranium recovery rate is in the 90–96% range.

3. Mine water treatment plant at the Banat mines site

The Banat mines were active during the 1954–1998 period. Discharged mine waters from the underground have relativelly low content of radionuclides but have to be decontaminated. The total average flow rate of mine and seepage waters needed to be decontaminated is about 2 500 m^3/day with a maximum value of 3 300 m^3/day in rainy periods. In present there are two treatment plants with projected daily water flow of 1 500 m^3 , each one, known as Dobrei South – Lisava and Ciudanovita respectivelly. Mine water pumped from underground (inflow of the plant) has the following contents:

- U : 1,5 – 2,7 mg/l
- Ra : 0,25 – 0,60 Bq/l
- TDS : 0,8 – 1,2 g/l
- Suspended solids : 0,15 – 0,70 g/l
- pH : 7 – 7,5

Discharge effluent in the Banat area is not used in present for drinking purposes and the current treatment plant is not able to produce water that is fit for drinking, according to present romanian drinking water standard (0.021 mg U/l and 0.088 Bq Ra/l). The main objective of this plant is to ensure a low level of additional radiological risk to critical receptor groups. The underground mine water samples have a slightly basic pH (7.3–8). Derivated limits accepted by the CNCAN (national regulator) were established at 0.100 mg U/l and 0.10 Bq Ra/l, close to the drinking water standard.

The closing out programme of the Banat mines include:

- controled simultaneous flooding of Ciudanovita, Dobrei and Natra mines
- refurbishing of the Dobrei South (Lisava) water treatment plant in order to remain the single plant for the total flow of mine waters discharged from underground

- keeping the Ciudanovita treatment plant as a backup, in case of need for an over capacity or in case of over pumping within rainy periods
- ensuring a 750 m^3/day reserve capacity for uranium removal from mine water pumped in emergency cases (Ciudanovita mine)
- control and treatment of the mine discharge water until is enough confidence to allow mine water to flow directly into river Natra (after a period of minimum 20 years).

Refurbishing the Dobrei – Lisava treatment plant will completed before final level flooding of the mines and must include the following [3,4]:

- building a settling bassin of increased volume in order to enhance suspended solids separation from raw mine water
- upgrade the present plant by building 2 lines of 4 ion exchange colums each, for U removal, comparing to the total 6 existing columns
- using a new anionite resin known as Purolite A 600 or new made AM strong anion resin for uranium removal
- ensuring flow rate characteristics for the ion exchange plant similar to those of the Suceava plant
- building a complex of 2 lines x 2 columns each, for radium adsorbtion on AC

Removal of radium by adsorption on activated carbon is effective and was demonstrated by the ICP-MRR Bucharest research institute on pilot scale. This technique is proposed within the Technical Project of the upgraded tratment plant Lisava. Compared to the classical barium-sulphate co-precipitation process the Ra adsorption on activated carbon has the advantage of reduced investment and footprint for the new facility. It uses similar columns with the ones in operation today for the ion exchange process.

The time for activated carbon full loading with adsorbed radium is predicted to be 30 – 60 days. Regeneration of radium loaded activated carbon bed is ensured by radium removing when contacting with 2 - 4% hydrochloric acid aqueous solution. In order to concentrate the radium, this contaminated acid solution may be treated onsite using precipitation of the $BaRaSO_4$ complex , after pH correction and mixing with Na_2SO_4 50g/l solution, with the advantage of a low solution volume complex processing. The radioactive sludge obtained will be transfered to a safe and final disposal site, an authorized tailings pond or a national repository for radioactive solids. Radium elution may also be undertaken within another site, case when the activated carbon (AC) must be transported by truck, as a radioactive material. Investment in the radium elution facilities at the mine site will then be suspended and operating costs will be lower.

Radium adsorption on AC is suitable for low Ra content mine waters such as the ones discharged from Banat mines.

An estimated twenty years period will be allowed for the uranium and radium contents, in mine waters, to decrease to a level when treating will be no more mandatory. A longer period for the plant's life will be decided based upon long term monitoring data on the site and radiologic risk assessment.

4. Conclusions

Removal of uranium and radium from mine waters have an positive environmental impact by decreasing the risk of radiation dose increase for critical groups of population located downside the active or flooded mines.

Ion exchange on anionic resins is used in present with good recovery yields for uranium removal while radium is proposed to be separated on activated carbon and then stored under the Ra – Ba – sulphate complex after been eluted.

Recovered uranium yellow cake and radium rich sludge are transferred for valorization or safe disposal, outside de mine sites.

Transfer of uranium loaded resins from the Banat plant to an ore processing plant is foresseen when the same anionite type resin will be used on both sites.

Although costly, long term mine water treatment at uranium mines is a mandatory task for the mining company in present and near future.

Carefull planning of the flooding and long term treatment of mine waters at the Banat mines are necessarry to avoid any further suplementary contamination of the recipient surface waters, Lisava and Jitin brooks.

A first period of 20 years is estimated for treatment of pumped mine waters at the Banat site.

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TOPIC 6 - ENVIRONMENT AND REGULATIONS

Risk-based closure of uranium tailings — how to get from theory to practice - 1
Risk assessment in support of closure planning

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Abstract. Benefits of Risk-Based Closure: The risk-based approach described in this paper and the companion paper "Risk-Based Closure of Uranium Mill Tailings: How to Get From Theory to Practice**"** is being used at an inactive uranium tailings site in Canada. This paper presents the theory behind risk-based closure and illustrates the theory with examples from the case study. The risk assessment for the case study is not yet complete; therefore, examples of how the assessment methods have been applied do not extend to the end of the assessment process. However, it is hoped that the combination of theory and example presented in this paper, together with the companion paper, provide evidence of the value of the risk-based approach. The risk-based approach provides several benefits. A risk-based closure plan results in a true net reduction in risk to human health and the environment. This is in contrast to the use of generic clean-up standards, which may not be applicable to specific site conditions and which may be either over or under-protective. A risk-based closure plan also ensures that remediation actions focus on what matters; *i.e.*, the sources or pathways that produce the most significant risk to humans or the environment. Monitoring plans implemented using a risk-based approach can also be focused on the sources and pathways that remediation targeted, ensuring that risk reduction has been achieved. This is in contrast to many monitoring plans that are very broadly-based and may include the measurement of parameters that are not relevant to the evaluation of successful risk reduction. The risk assessment methodology requires input from stakeholders, including regulators and members of the public. This input is vital to the acceptance of a risk-based closure plan. Finally, a risk framework includes the explicit identification of endpoints. Endpoints are risk management statements that clearly describe when risk reduction is sufficient. In summary. risk assessment provides the opportunity to ensure that we "match the effort with the risk". This means that remediation plans are tailored to achieve a net reduction in risk by focussing on what matters and by ensuring that endpoints are met while meeting public and regulatory expectations and requirements.

1. Introduction to risk assessment

Risk assessment is widely used and recognized by regulators and the scientific community. Methods and guidance documents have been available for several years, and there is a growing body of experience in the development of risk-based remediation plans for contaminated sites.

Risk assessment is a standard procedure for answering three fundamental questions about a site:

- How safe is it?
- How sure are we?
- Is it acceptable?

2. How safe is it?

Risk assessment provides the answer to the "how safe is it?" question by proceeding through four steps:

(i) problem formulation;
(ii) exposure assessment;

(iii) effects assessment; and,
(iv) risk characterization.

2.1. Step 1: Problem formulation

Problem formulation is used to focus subsequent steps in the risk assessment. This focus is provided by a fundamental principle in risk assessment: a risk cannot occur if there are no links between sources of exposure and people, wildlife or aquatic life. In other words, three elements are required:

I. sources of chemicals must be present;
II. receptors (e.g., people, terrestrial wildlife, aquatic life) must be present; and,
III. exposure pathways must exist between the source of the chemicals and the receptors (Fig. 1).

In the absence of any one of the three elements (source, pathway or receptor), risk cannot occur.

The presence of all three elements in Fig. 1 does not necessarily indicate an unacceptable risk. Rather, source-pathway-receptor links indicate the *potential* for risk. This potential for risk is further investigated during Problem Formulation by a short-listing, or screening, to identify the following:

- **Source**: chemicals of potential concern that occur at concentrations above regulatory guidelines and/or background or reference levels;
- **Pathway**: critical pathways that serve as the primary routes of exposure to chemicals of potential concern; and,
- **Receptor**: receptors of concern that serve as representatives of the human, wildlife or aquatic communities because of their sensitivity, high level of exposure to the site, social/cultural/economic importance, and/or ecological importance.

The methods used to short-list chemicals, receptors, and pathways are outlined briefly below.

- **Chemical screening**: Chemicals and radionuclides are not evaluated in the risk assessment if concentrations or radioactivity levels in the study area are equivalent to or less than reference concentrations; if concentrations or radioactivity levels in the study area are less than applicable guidelines/criteria; and/or, if chemicals are essential nutrients or are fundamentally non-toxic. The remaining chemicals and radionuclides, which have the potential to contribute to increased health risks, are evaluated in the risk assessment.
- **Exposure pathway screening**: A list of plausible exposure pathways is developed and is then evaluated to determine whether each pathway would be operable for each receptor. For example, for the ecological risk assessment, the water ingestion exposure pathway is operable for all ecological receptors, but vegetation ingestion is only operable for wildlife species that eat vegetation.
- **Receptor screening**: A list of receptors is developed based on their predicted susceptibility to the chemical of potential concern. For the human health risk assessment, a toddler visiting the study area with adults who are at the site carrying out traditional activities, such as hunting and fishing, would be the most susceptible receptor. For the ecological risk assessment, representative wildlife and aquatic species are those that would be at greatest risk, that play a key role in the food web and that have sufficient characterization data to facilitate calculations of exposure and health risks. Species lists compiled by national or regional bodies (*e.g.*, Committee on the Status of Endangered Wildlife in Canada [COSEWIC]) are also consulted to determine whether any local species have been designated as being at risk, sensitive or threatened.

Once the screening process is complete, problem formulation continues with the production of conceptual models of the source-pathway-receptor linkages that are expected to be the primary drivers

of risk at the site. Conceptual models are usually presented as diagrams or drawings. They are a visual record of the results of the problem formulation and can be used to communicate the main themes to be carried forward into the next steps of the risk assessment.

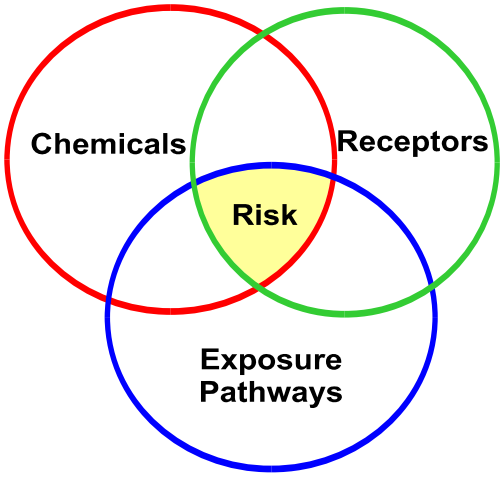

FIG. 1. Three elements of risk.

An example of a conceptual model illustrating the source-pathway-receptor linkages for the aquatic risk assessment portion of the case study is presented in Fig. 2. The thicker arrows illustrate the source-pathway linkages deemed to be the most important in driving the risk In the example, the sediments are the primary linkage.

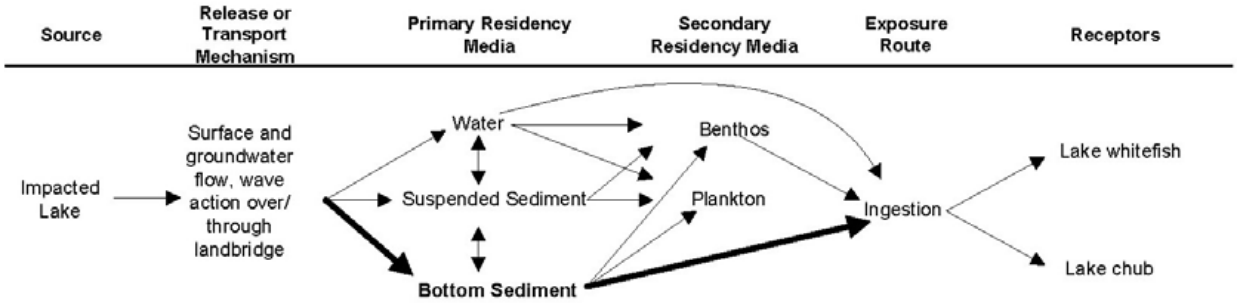

FIG. 2. Example of an aquatic conceptual model from the case study

The other principal task in a problem formulation is to establish so-called “risk management goals and objectives”, “assessment endpoints”, and “measurement endpoints”. The risk management goals and objectives are statements that describe when successful closure has been achieved. The assessment endpoint is a general statement describing what should be protected. The measurement endpoints are quantitative measures that can serve as a benchmark for determining whether the assessment endpoint can be met.

The following examples of goals, objectives, assessment endpoints, and measurement endpoints are for the aquatic ecological risk assessment component for the risk-based closure plan. The risk management goal is the same for human health, terrestrial and aquatic assessments; however, risk management objectives, assessment endpoints and measures are specific to each of the three general types of assessment.

Risk management goal

The overall risk management goal is the ultimate endpoint for the risk-based closure. The goal statement is the broadest definition of an endpoint.

" Transfer of title of the inactive uranium tailings site to the Crown can occur because it has been established that site remediation has achieved an acceptable level of residual risk to human health and to terrestrial and aquatic ecological populations and communities".

Risk management objective

The risk management objective translates the overall goal into a more specific objective derived for human health, terrestrial, or aquatic assessments. The objective for ecological risk usually includes an explicit statement regarding the level of ecological organization being protected. Individual plants or animals are seldom the level of protection, unless the receptor species is rare or endangered. The most common level of organization for protection of ecological receptors is the population.

"Acceptable risk to populations of fish or communities of invertebrates in Unknown Lake due to exposure to inactive uranium tailings site materials via reasonable, conservative exposure scenarios"

Assessment endpoints

In this example, quantifying risks to aquatic life focus on the following assessment endpoints:

- benthic invertebrate community abundance and diversity; and,
- fish populations and fish health.

Thus, benthic invertebrates and fish are the two representative groups of organisms chosen to be explicitly protected through the risk assessment.

Measurement endpoints

To assess these endpoints, exposure and effects to fish populations and benthic invertebrate communities are quantified with the following metrics:

Exposure Measures

- contaminant concentrations in sediment and water; and,
- contaminant concentrations in fish tissue.

Effects measures

- age structure of fish populations (assessed by species);
- energy storage of fish populations (assessed by species, includes condition, relative liver size, and relative egg size);
- energy use of fish populations (assessed by species, includes weight, length, size-at-age, relative gonad size, and relative fecundity); and,
- total benthic invertebrate density and richness.

Problem formulation is complete when risk management objectives, assessment endpoints, and measurement endpoints are established, the screening process is complete, and conceptual models of source-pathway-receptor links have been developed. The results of the problem formulation are

carried forward to the next two steps in the risk assessment, exposure assessment and effects assessment, collectively referred to as the risk analysis phase.

2.2. Steps 2 and 3: Exposure and effects assessment (risk analysis)

Risk analysis is a standard process for determining the exposure of a substance likely to be received by a receptor (humans, wildlife and aquatic life) and the effects that exposure may have on a receptor's health.

The two main components of the risk analysis, *exposure* and *effect*, as defined as follows:

- Exposure: the intake of a chemical (*e.g.,* ingestion or inhalation) for a particular time period; and,
- Effect: the adverse health effect(s) that may result from the exposure.

The *exposure assessment* conducted for each chemical or radionuclide of concern identified in the problem formulation for the case study involved the modelling of the estimated daily intake (EDI) and is typically expressed as mg of a chemical per kg of body weight per day (mg/kg-day). The EDI was calculated from: site-specific concentrations of chemicals in air, water, soil, sediment and food; the amount of time a receptor spends in the study area; and, receptor-specific parameters (*i.e.*, body weight, ingestion rates and dietary preferences). Exposure to radionuclides was estimated using a similar process; however, instead of a separate estimate for each radionuclide, the total radiation dose from all radionuclides is derived.

For aquatic life, exposure was estimated by the concentration of the chemical in water and/or sediment. For assessment of exposure, it is conservatively assumed that receptors would spend their entire life in the case study area. Exposure to radionuclides was estimated by modelling or measuring uptake into tissues and then converting to a total overall dose from both internal (via uptake) and external (from water and sediment) exposure.

The *effects assessment* involved identification of the potentially toxic effects of chemicals and determination of the dose that a receptor can be exposed to without experiencing unacceptable effects. This value is called the toxicity reference value (TRV). For human and wildlife, the TRV is expressed as mg of a chemical per kg of body weight per day (mg/kg-day). For aquatic life, the TRV may be presented as an acceptable concentration of the chemical in the media to which the receptor is primarily exposed. This is referred to as the benchmark concentration (BC).

Effects assessment for radionuclides is somewhat different because effects are assessed on the basis of total radiation dose rather than dose from each radionuclide. Another difference is that the total radiation dose to humans is compared to the regulatory threshold for acceptable radiation dose to the general public, rather than a threshold directly derived from the scientific literature. Radiation effects thresholds for wildlife or aquatic life are called “estimated no effect values” (ENEV). The ENEVs are for no effects to individual organisms; whereas ecological risks are usually assessed at the population level. Therefore, ENEVs represent a very conservative, protective guideline.

Effects assessment also included field measurements of effects on small mammals, benthic invertebrate communities and fish health. Field data provided information on the response of receptors to the mixture of chemicals and radionuclides present in the environment. Field data also provided information on the role of natural environmental factors such as soil type, vegetation (*i.e.,* food availability), water depth, and sediment texture in determining population and community characteristics such as species diversity and abundance.

2.3. Step 4: Risk characterization

Risk characterization involves comparing the estimated exposure to the TRV, effects benchmark or regulatory threshold for acceptable risk. This comparison is often presented as a ratio between estimated exposure and TRVs, usually called an "Exposure Ratio" or ER. If the ER is less than one, no health risks are expected. If the ER is greater than one, risk management alternatives are examined or the risk characterization is re-visited to ensure that the degree of conservatism used in the assessment has not produced an inappropriate result (see discussion of "how sure are we?" below). The effort extended for risk management is in proportion to the risk and is also dependent upon whether the risk is to human health (where the goal is the protection of individuals) or to wildlife or aquatic life (where the goal is the protection of populations). For example, if wildlife ER's are only marginally above one in a very small area immediately adjacent to the tailings, such that the persistence of populations of wildlife would not be at risk, then risk management effort geared to protection of wildlife would be limited. However, if ER's are much greater than one over a wide area such that the persistence of populations may be at risk, then risk management effort would be greater (and large enough to reduce risks to populations to acceptable levels).

In the case study, direct measures of effects in the field were available; therefore, a weight of evidence approach is being used to characterize ecological risk. Weight of evidence is the process by which multiple measures of risk are related to the assessment endpoint to evaluate whether there is significant risk. Weight of evidence uses explicit criteria for judging the strength of the evidence provided by each measure, including whether there is a sufficient response in the field to constitute a true "effect" and whether there appears to be a cause/effect relationship between measured concentrations of the COC and the observed effects.

3. How sure are we?

There is always some uncertainty associated with risk assessments. From a scientific viewpoint, the four potential sources of uncertainty are:

- natural variability;
- model uncertainty;
- measurement error; and,
- data errors.

These sources of uncertainty are often the sole focus of risk assessors; however, social and political uncertainty may be a more important factor affecting the outcome of a risk assessment. Risk assessors are familiar with techniques for addressing the "scientific" understanding of uncertainty. These techniques are briefly described below. Techniques for dealing with social and political uncertainty are less well-established, but some suggestions are provided.

3.1. Natural variability

Natural variability exists in both the chemical and radionuclide concentrations and in biological variability (*e.g.,* benthic invertebrate composition varies naturally in response to factors such as water depth). Site investigations often provide only one "snapshot" of conditions at the site; therefore, year-to-year and season-to-season variability is not known. Likewise, studies of terrestrial wildlife and aquatic life may not have adequately quantified the variability within and between sample locations. In this case study, maximum concentrations were used to help account for the uncertainty about the range of concentrations that could occur at times and places not included in the sampling program.

Statistical power analyses can help determine whether there has been a sufficient level of sampling to distinguish "effects" from natural variability. The study design used in the aquatic effects portion of

this case study took advantage of regulatory guidance on sample size, number of sampling locations, and response measures.

When there are enough data to be confident that natural variability, both over time and location, is adequately represented, risk assessments can make use of the full range of variability by comparing and contrasting risks from exposure to small-scale or infrequent maximum concentrations with exposure to average, larger-scale concentrations. A so-called "probabilistic" assessment can also be performed, where the assessment involves a computerized random sampling from the full data set to represent the likelihood of certain exposures happening.

3.2. Model uncertainty

Model uncertainty applies to both the exposure and effects assessments. The exposure models used in the case study used assumptions about key parameters such as inhalation rates, ingestion rates, body weights, amount of time spent in the immediate area of the tailings, *etc.* Some of these assumptions were supported by databases (*e.g.,* some wildlife receptor species are well-characterized with peer-reviewed and well-recognized exposure factors published by regulatory agencies). Other assumptions were based upon professional judgment and the limited data available from the site investigation (*e.g.,* amount of time an animal spends in the study area). Effects thresholds were derived by extrapolation from laboratory experiments with standard test animals. These extrapolations are subject to significant uncertainty.

Model uncertainty in the case study was addressed by incorporating a margin of safety through the use of conservative assumptions. For example, exposure of wildlife receptors was calculated based on conservative assumptions regarding the amount of time spent in the study area by wildlife (*e.g.,* 365 days per year in the immediate study area even though the species is known to use a large home range). Conservatively predicted concentrations in food, *i.e.,* plants and prey (including fish), at the location with the highest predicted source concentrations (*i.e.,* in air, soil, water) were used. The addition of baseline chemical concentrations in plants and soil to predicted incremental contributions from the site ensured that cumulative exposure was accounted for.

Uncertainty in the effects assessment was addressed by careful selection of TRVs after checks on the validity of the laboratory toxicity studies. The selected TRV was usually from studies where subtle, sub-lethal effects were observed from long-term exposures. Safety factors were applied (*e.g.,* dividing the TRV by 10 to account for extrapolation from one species to another) as required to ensure that the exposure threshold represents a safe dose for receptors.

The case study also addressed model error by including field measurements of exposure and effects for the aquatic and terrestrial risk assessments. These measurements added lines of evidence for the degree of exposure at the site and the presence of measurable effects.

3.3. Measurement error

Measurement errors occur because of the lack of standard sampling or laboratory procedures, the lack of proper training in these procedures, and/or the lack of vigilance in the use of procedures. Measurement error was minimized by adherence to Standard Operating Procedures (also called Technical Procedures) for all field sampling and laboratory analyses. Quality Assurance/Quality Control (QA/QC) reports from the analytical laboratories were reviewed and trip and field blanks are taken during the sampling program to indicate whether sample contamination associated with sampling or handling procedures or laboratory accuracy occurred.

3.4. Data errors

Data errors occur when mistakes are made transferring data from field or laboratory records to office records and electronic data files. Calculation errors can also occur. The following standardized quality control procedures were used to reduce data error:

- accuracy and consistency checks for all calculations;
- senior-review of all exposure calculations;
- examination of data and analytical laboratories for outliers;
- transcription error checks (*i.e.,* all data entry was reviewed); and,
- document control procedures including chain-of-custody for all samples and a project filing system that ensured that all pertinent field and communication records were filed in the Project Master file.

3.5. Social and political uncertainty

The social and political uncertainty attached to the case study was addressed by including consultations with the community and with regulators. Consultations began before the risk assessment started, to ensure that there was a good understanding of the risk-based approach and broad consensus on the risk management goals, objectives, assessment endpoints and measures. Further consultations took place at the end of the Problem Formulation stage, and additional consultations will occur when the risk-based closure plan is ready to be presented. Public involvement also included consultation and information regarding the site investigation activities. One of the early results of public meetings was the installation of wind erosion control at the site via a deployment of snow fences across the exposed tailings. This simple measure increased public trust in the intentions of the owner of the site and it is this trust that will continue to be a key to a successful outcome (see discussion of acceptable risk below).

3.6. The end result of addressing uncertainty

Risk assessments that use conservative assumptions to address natural variability and model error produce risk estimates with many layers of safety embedded within them. Thus, if the ER is less than one, we can be confident that risks can be ruled out because of all of the layers of safety incorporated into the assessment. If the ER is slightly greater than one, risk management should only be considered after the conservative assumptions have been critically examined and the potential for the use of more realistic inputs reviewed.

ERs greater than 1 indicate the potential for effects on *individuals*. The objective in an Ecological Risk Assessment (ERA) is to protect populations (unless the receptor is endangered). Therefore, in an ERA, an ER greater than one is only one step in understanding whether there may be risks to populations. Further steps include estimating the proportion of the population that may have an ER greater than one. This is often done by estimating the number of home ranges of each receptor where ERs greater than one may occur.

The overall result of the use of conservative assumptions is *confidence that risks have not been underestimated.* Often, more extensive (and expensive) probabilistic risk assessments are not required if risk management can be based upon conservatively based risk estimates without undue attention paid to risk estimates that are only marginally exceeding effects thresholds.

Risk-based decisions made in the face of uncertainty can be checked by monitoring. For example, we can check on the effectiveness of a remediation measure taken to cut off an exposure pathway by monitoring chemical concentrations at the end of that pathway (*e.g.,* at the original entrance for seepage into a lake). We can also monitor chemical concentrations in food items such as plants or fish.

4. Is that acceptable?

4.1. Acceptability of guidelines and toxicity benchmarks

The guidelines and toxicity benchmarks used in risk assessments have been determined by regulatory agencies to be acceptable based on a combination of scientific information and public acceptability.

Science provides the understanding of the consequences of exposure. Public opinion has determined the level of protection that must be built into the guidelines and toxicity benchmarks.

4.2. Broader definitions of acceptable risk

Science is not the only basis for the definition of acceptable risk. Other important considerations are whether:

- risks are voluntary;
- processes are fair;
- control or scrutiny by public is possible;
- actions are morally correct;
- there are visible benefits; and,
- the situation is familiar and we know how to manage the risks.

These broader criteria can be discussed throughout the risk assessment process. It is important that the risk assessors understand the wider context for discussions of risk acceptability, since, as scientists, they are often prone to more narrowly defined acceptable risk.

Discussions with community members and regulators have been a regular feature of the risk-based remediation planning project for the case study. These discussions have, and will continue to, contribute to the study team's understanding of the broader definitions of acceptable risk for the site. For example, direct involvement of community members in site investigation activities and in monitoring has increased the sense of control and fairness.

5. Linking risk assessment with closure planning

The results of the risk assessment are being used to provide the focus for the closure plan for the site. This focus is on the "risk drivers"; *i.e.*, the sources and pathways contributing the most risk to receptors. The risk assessment is allowing the closure plan to "match the effort with the risk". Details of this process are presented in the companion paper.

Radiation doses to members of the public from the Olympic Dam operation

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Abstract. The Olympic Dam project is a large underground mine with associated processing plant and smelter, producing copper, uranium, gold, and silver, and is located at Roxby Downs in central South Australia. Results from the monitoring of airborne radionuclides have been reviewed to estimate the doses to members of the public living at Olympic Dam village, approximately 4 km south of the edge of the operational area, arising from project operations. The results indicate that the doses are very low, with an upper bound on annual effective dose from radon decay products of approximately 20 μSv, and approximately 3 μSv per annum from inhalation of radioactive dusts.

1. Introduction

The Olympic Dam project is situated in central South Australia, and commenced production in 1987: this study reports conditions following a major expansion completed in 1997. It comprises an underground mine, with associated processing plant, including a copper smelter. The principal product is copper with approximately 250 000 tonnes being produced annually (from approximately 11 million tonnes of ore). In addition uranium oxide is produced, with a capacity of over 4 000 tonnes per annum, making it one of the largest uranium producers in the world. The project is currently owned and operated by WMC Resources Pty Ltd, and further significant expansion is contemplated.

The region is arid, with low relief, and sparsely populated. Evaporation significantly exceeds mean rainfall in every month, and there is no established drainage pattern. The main population centre is the township of Roxby Downs, 14 km south of the operational area with a population of about 4 000. Olympic Dam village, a camp approximately 4 km south of the operational area, has a variable population (of adults) which can range up to a thousand or more during construction or major maintenance activities. Apart from a very few pastoral workers, there are no other residents within 25 km of the project.

The regulatory regime governing the radiological aspects of the project is rather complex, but includes requirements to comply with the currently recommended ICRP dose limits, and requirements to monitor radiation exposures arising from project operations. In particular, a program to monitor the exposure to members of the public is required, and has been in place since the commencement of operations. Although other parameters are monitored, the only significant pathways for project generated radiation exposure are airborne ones: inhalation of radon decay products, and inhalation of long-lived alpha emitting radionuclides in dusts. There are no aquatic pathways.

This report concerns doses to residents of Olympic Dam Village. As Roxby Downs is three times further away from project operations, doses to those residents will be significantly smaller.

2. Radon decay product monitoring

For this study, radon decay products (RnDPs) were monitored continuously at four sites: NBS - approximately 6 km north of the processing plant, EBS - approximately 8 km east of the plant, ODV - Olympic Dam village, and RDS - Roxby Downs township. These sites, and their relation to operational areas are shown in Fig. 1. The monitors used continuously draw air through a filter, which collects the radon decay products. The alpha particles resulting from the decay of these RnDPs are counted continuously with a solid-state surface barrier detector, and the counts recorded for each hour are stored, and downloaded weekly [1]. The instruments used in this study are AlphaNuclear Prism 560 "continuous working level monitors". As these instruments do not separate the alphas emitted by "thoron" (Rn-220) decay products from those of Rn-222, (the isotope of interest in uranium mining), the results will overestimate the true Rn-222 decay product concentration [1]. Hourly wind speed and direction data was also collected at a meteorological station near the processing plant.

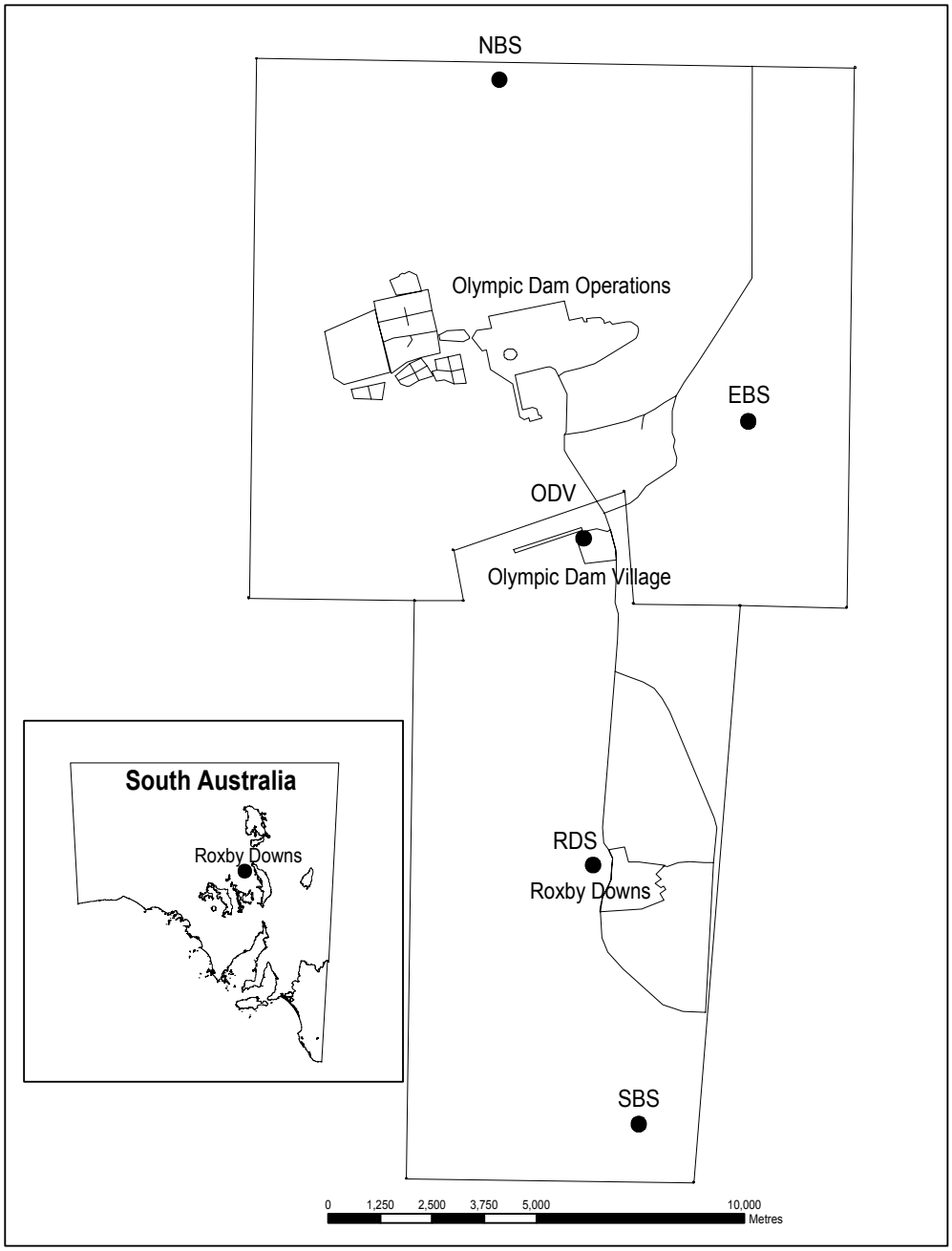

FIG. 1. Olympic Dam project area and monitoring locations.

The natural background RnDP concentration at a site is highly variable, as is illustrated in Fig. 2. Variations arise principally from variations in meteorological conditions, with concentrations during calm night-time conditions frequently peaking (usually pre-dawn) at a factor of ten or more above typical daytime concentrations. This makes the separation of the contribution of the project generated RnDPs from the natural background concentration at a particular location difficult. Using wind direction data, two general techniques are available. Firstly, one can measure the concentration at a site when the wind is blowing from the operational area, (which will include both background and project contributions) and compare that with the concentration at that site at times when the wind is blowing from other directions, (that is, background only). The second method is to have several detectors, located so that when one detector has the wind blowing from operational areas, and is thus recording background and operational components, the other(s) are recording only background. The first method has the implicit assumption that the background concentration is independent of the wind direction, and the second has the implicit assumption that the natural background at all sites is the same. As we shall see, neither of these assumptions is necessarily true, but elements of both approaches were used here.

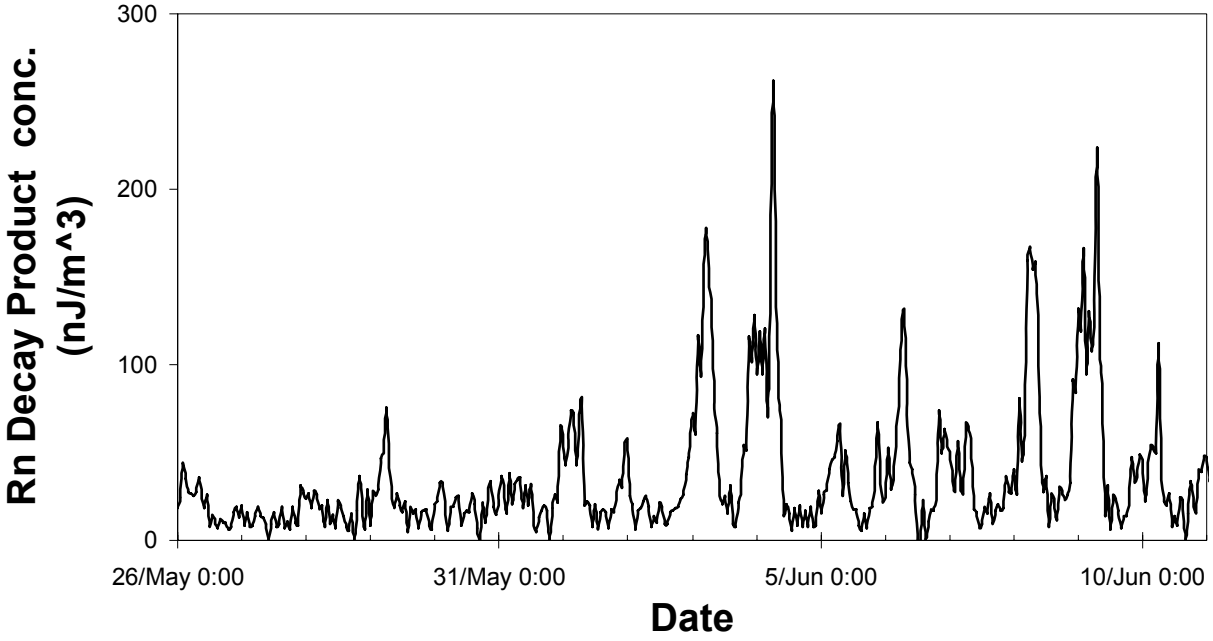

FIG. 2. Typical variations in radon decay product concentrations (EBS site).

The RnDP data set used in this study was established by selecting the results from all hours between February 1999 and June 2002, where reliable data was available from all four sites - a total of 18 079 hours. This data matching is important as it ensures that when project doses are calculated by subtraction of concentrations at different sites, variations caused by meteorological effects will largely cancel out. The meteorological data was used to sort the data into 24 wind direction sectors, and the mean RnDP concentration for each site and each sector was calculated. The results are shown in Fig. 3 – sector 1 is North. Note that when the wind speed fell below the minimum for which the wind direction could be measured, the last valid direction was used. The doses are derived using a dose conversion factor of 1.1 mSv/(mJ·h·m^3) - adults at home [2].

There is good general agreement between the sites, but there are significant differences, with the mean of NBS being some 15% higher than the other sites. It is also clear that the concentrations are not the same for all wind directions – concentrations at all sites are some 40% higher when the wind is from the north (this is expected as radon concentrations are higher in “continental” air than “oceanic” air, and southerly winds at Olympic Dam will contain a greater proportion of oceanic air). Thus neither of the implicit assumptions mentioned above are met: different sites have different (mean) concentrations, and concentrations are not the same for all wind directions.

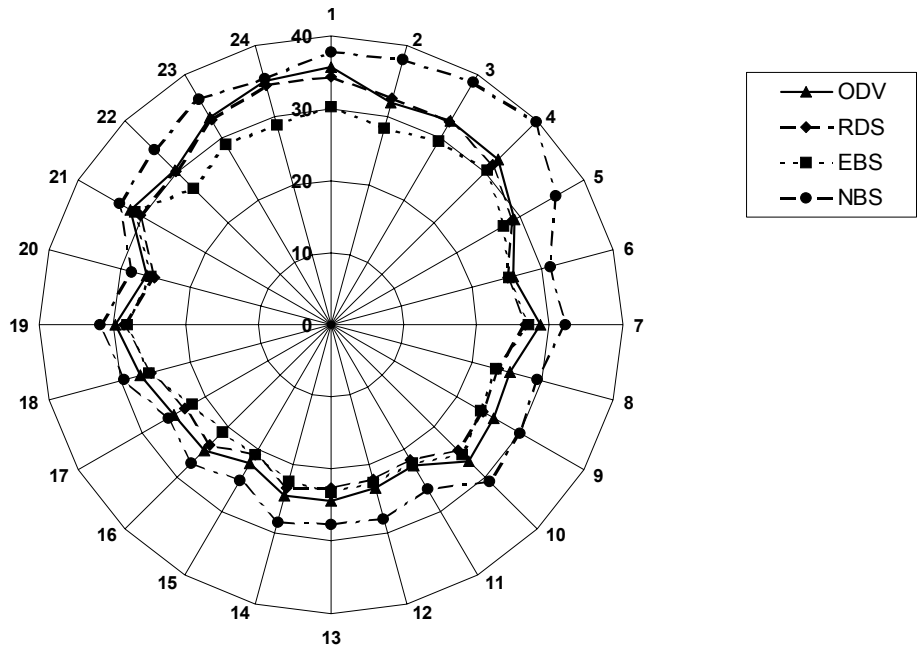

FIG. 3. Radon decay products at four sites by wind direction (microsieverts per year).

Further insight can be gained from Fig. 4. This contains the same data as Fig. 3, but normalised so that the mean RnDP concentrations at all four sites are the same. This figure confirms the very good agreement of the "shape" of the distribution – no site value departs from the mean of the other sites (for that wind sector) by more than 7.5%. While there is some suggestion that concentrations might be higher when winds are from operational areas (i.e. sectors 21-24 and 1-3 for ODV, 23 and 24, and 1-3 for RDS, and sectors 19-22 for EBS), any such increase is small. There is no indication of any increase at NBS when winds are southerly (sectors 11-16).

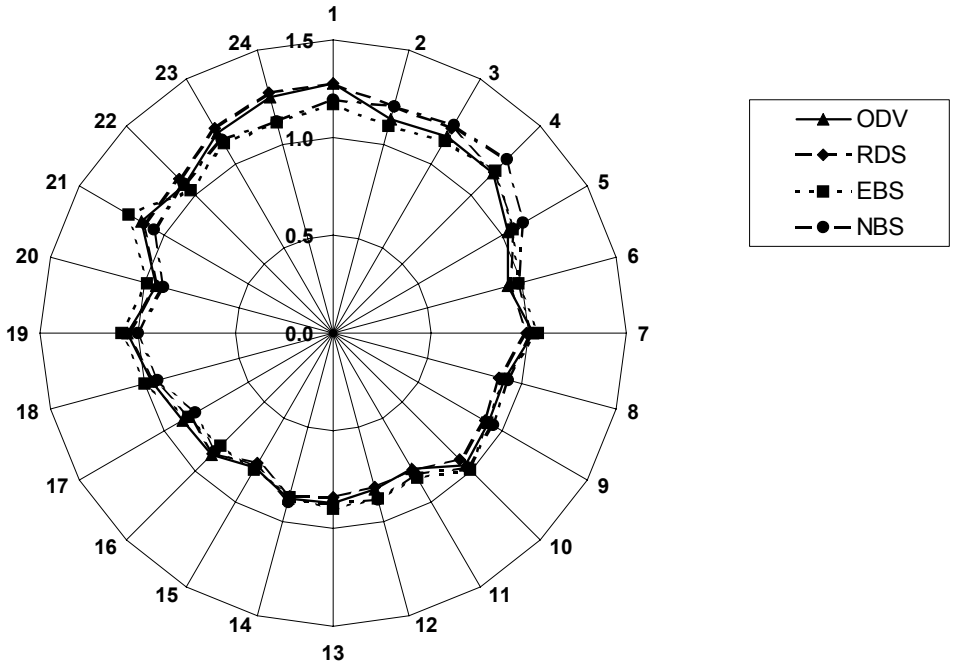

FIG. 4. Normalised radon decay products at four sites by wind direction.

An estimate of the resulting project related dose can be obtained from these results. The annual dose from RnDPs derived from the monitoring results at ODV, including contributions from all wind directions and both natural and project related sources, is approximately 340 μSv. The dose contribution (at ODV) arising when the wind is from the operational area only (that is, northerly) is

approximately 66 μSv per annum, and again this includes natural and project sources. It is clear from Fig. 4 that any enhancement over background levels (represented by the concentrations at NBS and EBS during northerly winds) cannot be greater than about 30%. This corresponds to an annual dose of about 20 μSv, and this then represents an upper limit on the project related dose.

3. Radon decay product modelling

RnDP concentrations resulting from project operations have also been estimated by atmospheric modelling. The overall radon release was estimated at about 6 MBq/s, (mainly from mine exhaust raises and the tailings storage facility, with a smaller contribution from the plant) [3], and these sources were used as inputs to the CalPuff atmospheric dispersion model [4]. The resulting average annual dose at ODV over the years 1999 – 2001 (approximately the period covered by the data above) was 24 μSv.

4. Radioactive dust monitoring

Dusts are monitored at three sites: ODV and RDS as above, and SBS, approximately 21 km south of the project area (Fig. 1). Standard high volume samplers are operated continuously at approximately 70 m^3/h, with filters collected weekly and monthly composites analysed. Standard radionuclide analysis techniques are used to determine the U-238, U-234, Th-230, Ra-226, Pb-210 and Po-210 concentrations, which are corrected for decay since sampling, and these are then used to derive resulting doses from inhalation using standard dose conversion factors for adults [2].

The average annual dose (project related plus background) for each radionuclide at the three sites over the seven-year period 1997 – 2003 is shown in Table I, together with the "World Average" [5] for comparison. The difference between the total doses at ODV and SBS was calculated for each year. The average difference was 3.1 μSv, (SD = 0.7 μSv) and this difference can be interpreted as the project generated component at ODV. Even in the extreme case where all radioactive dust recorded at ODV is assumed to be project generated, the annual dose is still less than 7.5 μSv.

Table I. Doses from dust inhalation (microsievert per year)

	SBS	RDS	ODV	Av,[a]	S.D.[a]	%	World Av.
U-238	0.06	0.11	0.42	0.20	0.17	4%	0.02
U-234	0.08	0.13	0.48	0.23	0.19	4%	0.03
Th-230	0.12	0.19	0.67	0.33	0.26	6%	0.05
Ra-226	0.39	0.41	1.13	0.64	0.41	12%	0.03
Pb-210	3.24	2.46	3.50	3.07	0.67	59%	4.0
Po-210	0.43	0.52	1.23	0.73	0.47	14%	1.2
Total	4.33	3.82	7.43	5.19	1.73	100%	5.8

[a] Av. and S.D. are average and standard deviation of annual doses for the three sites from that component

5. Conclusions

Despite running a comprehensive monitoring program using appropriate equipment, no increase in radon decay product concentrations resulting from the project operations could be measured. This is not a result of any defect in the program or its implementation, but arises from the relative magnitude of the natural background, and its variation.

The monitoring *does* establish that the annual effective dose arising from project operations is very low: an upper limit of approximately 20 μSv per annum from radon decay products, and approximately 3 μSv from dust inhalation.

Other estimates can be made based on various very conservative assumptions. For example, the dose calculated if it is assumed that all of the radon decay products and dust measured are project generated is approximately 350 μSv, and when it is assumed that all of the RnDPs measured when the wind is from the north, and all of the dust, are generated by the project the estimated dose is approximately 75 μSv. These estimates are all significantly less than the 1 mSv annual limit recommended for members of the public. The relative magnitudes of doses calculated under these various assumptions, are shown in Fig. 5.

Atmospheric dispersion modelling supports the conclusion that the dose from project generated radon decay products is very low.

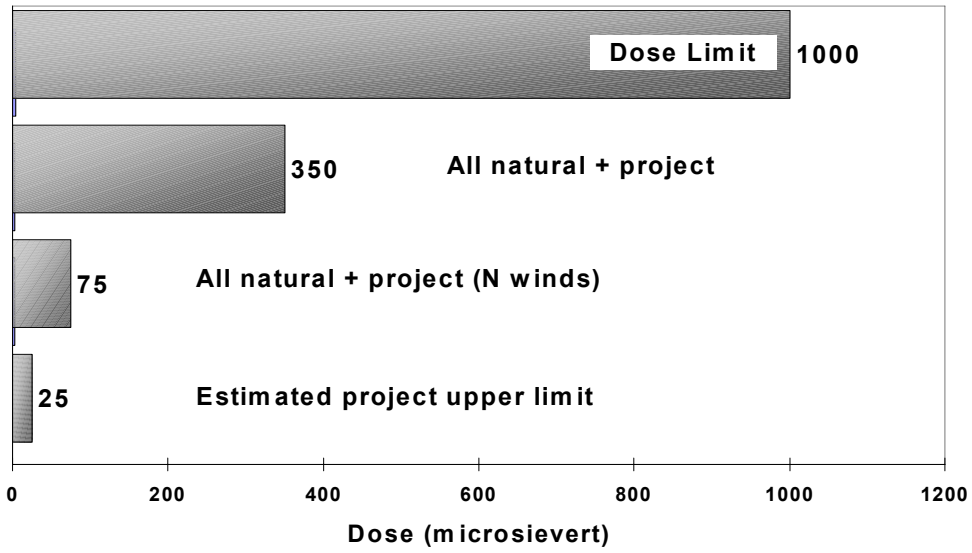

FIG. 5. Member of public doses calculated under various assumptions.

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Environmental monitoring in radiation field in uranium mines of Niger

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Abstract. In Niger, uranium (yellow cake) has been produced since 1968 and 1978 by respectively SOMAÏR (Mine Society of Aïr) and COMINAK (Mine Company of Akouta) both situed in the Region of Agadez (north of the country). This paper deals the radiological impacts from the uranium production activities of these societies on the population and the environment.

1. Introduction

During the last years, SOMAÏR and COMINAK have developped environmental policies in addition to the requirements of national regulations in mining field to ensure human and environment protection.

2. Institutional and regulatory framework

2.1. Institutional framework

The two institutions in charge of control and follow of mining activities in Niger are:

- Ministry of Mine and Energy (MME),
- National Center of radioprotection (CNRP).

2.2. Regulatory framework

The most important national regulation for uranium production acitvities is the order n°3/MME/DM of 8 June 2001 which concerns protection against radiation in mining sector. The section 6 of this order (from article 40 to article 48) deals with monitoring of environment in radiation field. Thus, the article 45 limited the effective dose above natural level at a mean value of 1 msv per year on five consecutive years without exceeding 5 msv by year for public exposure.

3. Impacts on population and environment

To assess the radiological impact from uranium production activities on population and environment, SOMAÏR and COMINAK have established measurement systems of radiation in air, water, soil and vegetables.

For this respect, the following risks are evaluated (and relevant units conversion assumptions made) [1][2]:

- external γ exposure (msv);
- internal α exposure by inhalation of short lived decay products of :
  - radon 222 (1,1 msv per $mJ.m^{-3}.h$),

- radon 220 (0,39 msv per $mJ.m^{-3}.h$);
- internal α exposure by inhalation of dusts (from uranium chain) with long lived α emitters ($1,4\ 10^{-2}$ msv/Bq);
- internal exposure by ingestion of radium 226 ($2,8\ 10^{-4}$ msv/Bq);
- internal exposure by ingestion of uranium 238 ($4,5\ 10^{-5}$ msv/Bq);
- internal exposure by ingestion of lead 210 ($6,9\ 10^{-4}$ msv/Bq);
- internal exposure by ingestion of polonium 210 ($1,2\ 10^{-3}$ msv/Bq);
- internal exposure by ingestion of thorium 230 ($2,1\ 10^{-4}$ msv/Bq).

The following Table I and II give exposures from respectively SOMAÏR and COMINAK mines [2].

Table I. Exposures from SOMAÏR mine in 2003 [1][3]

Exposures	Mine	between mine and town of Arlit	Arlit
γ ($nG.h^{-1}$)	210	170	150
Radon 222 ($nJ.m^{-3}$)	165	122	76
Radon 220 ($nJ.m^{-3}$)	38	40	29
α from dust ($mBq.m^{-3}$)	1.00	<1	1.41
Radium 226[1] (Bq/l)	-	0.09	0.02
Uranium 238[1] (mg/l)	-	0.09	0.03

Table II: Exposures from COMINAK mine in 2003 [1]

Exposures	between mine and Akokan	Arlit
γ ($nG.h^{-1}$)	150	135
Radon 222 ($nJ.m^{-3}$)	184	140
Radon 220 ($nJ.m^{-3}$)	37	49
α from dust ($mBq.m^{-3}$)	<1	<1
Radium 226[1] (Bq/l)	<0.02	<0.02
Uranium 238[1] (mg/l)	0.02	0.02

In Table III, we have the contribution of COMINAK and SOMAÏR in the exposure of the members of the critical group.

TABLE III: SOMAÏR and COMINAK mines exposures for critical groups [1][2][3]

LOCATION	ANNEE	SOMAÏR	COMINAK
EXPOSURE OF CRITICAL GROUP	2003	0.26 mSv	0.49 mSv
	2004	0.47 mSv	0.93mSv

From Table III, we can see that the impacts on environment (calculated from water, soil, air and vegetable) have decreased:

- for COMINAK, from 0.93 msv in 2002 to 0.43 msv in 2003,
- for SOMAÏR, from 0.47 msv in 2002 to 0.26 msv in 2003.

This is the result of the actions undertaken by COMINAK and SOMAÏR to reduce the negative impacts on the environment.

The values of environment exposition from COMINAK mine for 2001, 2002 and 2003 are given in the following Fig.1 [2].

[1] From drinking water.

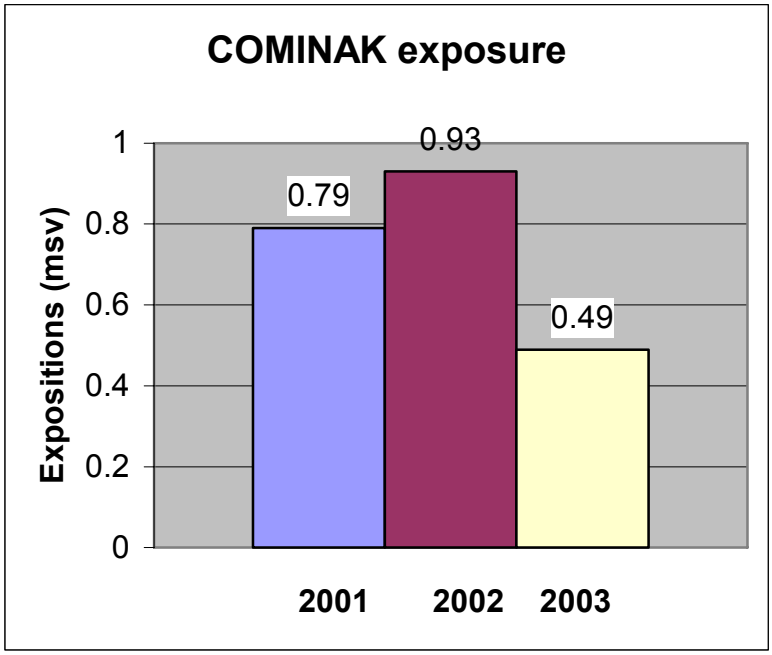

FIG.1. COMINAK mine exposure on environment for 2001, 2002 and 2003.

4. Conclusion

SOMAÏR and COMINAK contribution (on natural level) in environment exposures are in compliance with national order n°3/MME/DM of 8 June 2001 (less then 1msv).

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Ecological problems related to uranium mining and uranium processing industry in Ukraine and restoraion strategy concept

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Abstract. Ukraine's uranium facilities are located in the central part of the country, in urbanized districts with a high population density and intensively developed industry and agriculture. Nearly 50 years of uranium mining and milling at these facilities have caused radioactive contamination of the environment. This paper is devoted to identification of the main sources of actual and potential releases of radioactive materials to the environment, assessment of the radiological and environment risk as a basis for remedial measures. Choice of the best strategy for site restoration are described in this paper.

1. Introduction

Since the end of the World War II, the Ukraine as a part of former USSR has exploited the mining and milling of uranium ores with its own territories and also transporting ores from Central Europe for its processing on chemical and hydrometallurgical plants situated in Zhovty Vody and Dniprodzerzhinsk towns in order to develop nuclear industry and weapons programs of former USSR. The operation of uranium facilities in Ukraine during former USSR era was as usually close to public environmental control. Therefore it appears that most of these former mining and milling operations have been conducted without sufficient and adequate care for environmental consequences or for their impact on the human health of the locally involved population as well as ecosystem compartments. Preliminary environmental impact assessment carried out during recent decade based on the results of experimental studies and other expertise show that actual negative impact of the most of uranium facilities are exist as result of leaching of contaminated water from ore processing tailing, wasting mine water to the rivers, groundwater contamination, erosion and air dust re-suspension. The main chain of naturally occurs TENORM radionuclides from the uranium facilities is the following ^{238}U, ^{228}Th, ^{226}Ra, ^{222}Rn, ^{210}Pb, ^{210}Po. These facilities and relevant fluxes of toxic and radioactive substances may create a real potential ecological risk for the district. The aim of the problem description in this study was to disseminate a present understanding that the problems of former uranium production in Ukraine have to be properly studied and to be a basis for regional restoration program to be implemented.

Uranium exploration started in the Ukraine in 1944 and led to the discovery of the Pervomayskoye deposit in 1945 and the Zheltorechenskoye deposit in 1946. Other ore bodies were subsequently discovered within the boundaries of the Kirovograd, Dnipropetrovsk and Nikolaev regions. Many of the deposits are within the watershed of the Dnipro Basin while some are within the basins of the

Southern Bug or Severskiy Donets rivers. Figure 1 shows the sources of radioactivity at the Dnieper River basin in Ukraine [1].

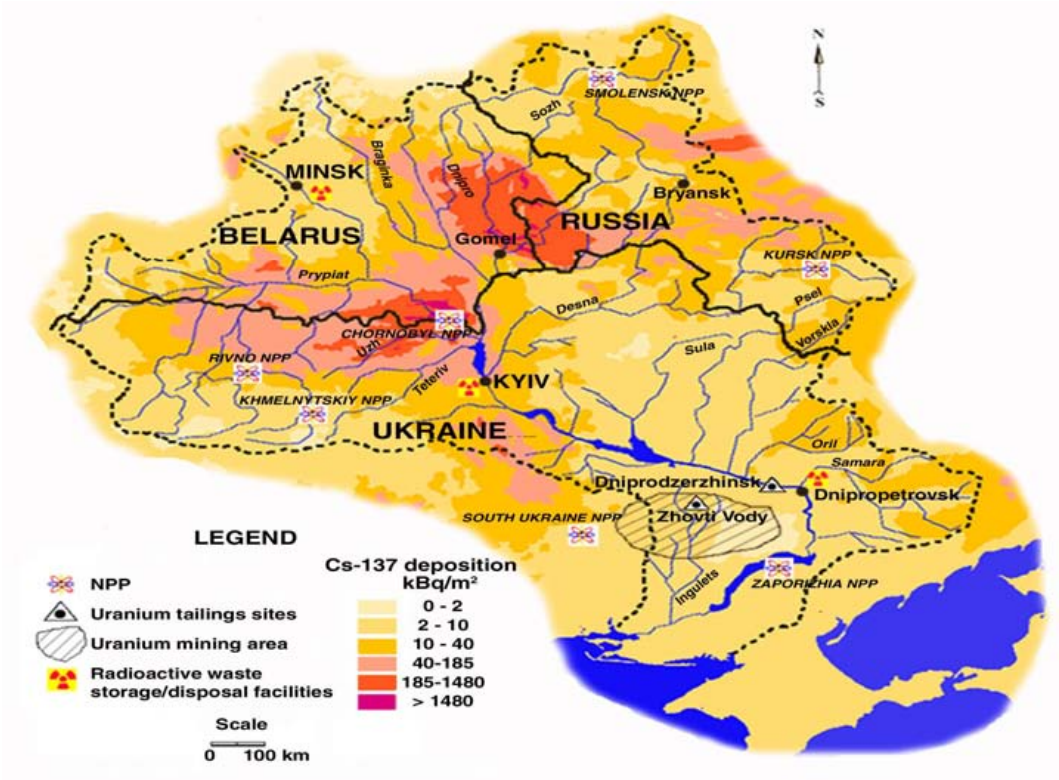

FIG. 1. Sources of radioactivity at the Dnieper River basin (Zhovty Vody and Dniprodzerzhinsk) in Ukraine.

2. Identification of the main sources of actual and potential releases to the environment

The first uranium processing plant in Ukraine was the Pridneprovsky Chemical Plant (PCP), which started up in 1948 using ores shipped from former USSR and Eastern Europe. The PCP is situated near the Dnipro river in the city of Dniprodzerzhinsk. From 1948 until its closure in 1991, about 42 million tones of uranium tailings and other radioactive wastes with a total activity of 3.2 x 10^{15} Bq (86 000 Ci) were generated (Fig. 2).

The Zhovty Vody Hydrometallurgical Plant has processed ores from southern Ukraine since 1959. It is located at a former iron ore production site near the centre of Ukraine's main uranium province. It is operated by the Eastern Mining and Concentrating Mill (named VostGOK). Currently, most of the production (about 1 000 tonnes uranium per year) is coming from the Ingul'skii mine developed on the Michurinskoye deposit. There is also a small amount of production from the Smolino mine developed on the Vatutinskoye deposit [1]. There are about 90 millions tons of uranium tailings and associated wastes in Ukraine.

The main environmental impact of the uranium industry into the environment are wasting of mine water into the river without sufficient cleaning, seepage and leaching of radionuclides and other toxic substances from the tailing into the surface and groundwater. The common problem for all these cases are impacts the environment due to exhalation of ^{222}Rn and radon dispersion within the air to the

surrounding areas, radon releases from mines, waste rock dumps and mill tailings piles, and also erosion of tailings leading to dispersion of its covers material by wind and water.

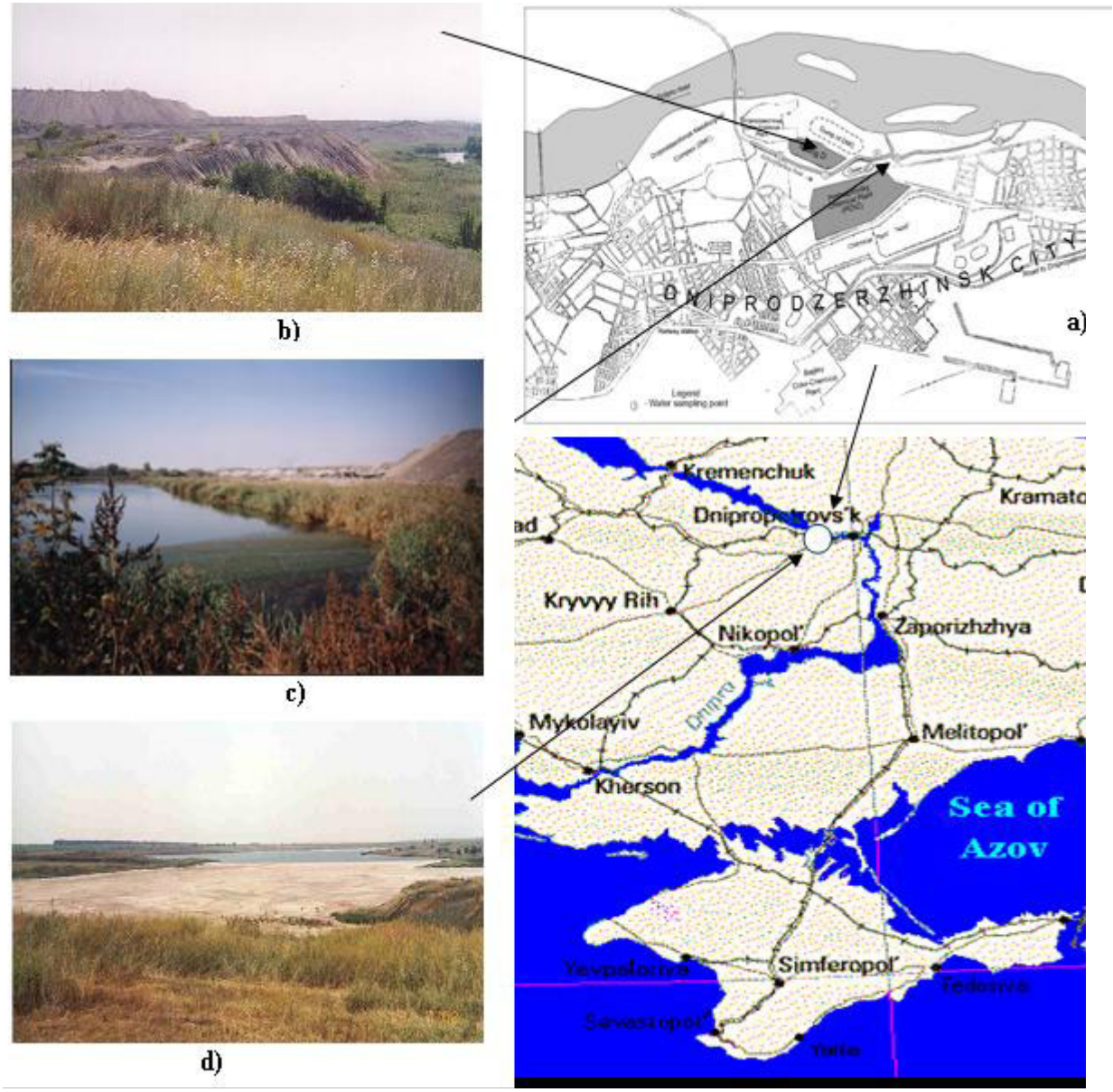

FIG. 2. Situation of Dnieprodzerzhinsk town 35 km away of Dniepropetrovsk (a); Uranium tailing "Dnieprovskoe" (b), settling pond at Konoplyanka River (c), and Sukhachevskoe tailing pond no longer in operation (d).

Preliminary Pathway Analysis and Radiological Assessment of the actual sources and pathways show that among of potential sources of uranium product pollution the main impact to the environment occurs by uranium tailing dumps and releases from radioactive waste disposal sites located in Dniprodzerzhinsk town and also from the mining water to the rivers near Zhovty Vody town.

The impact of tailing "D" is detectable at the distance of about 80 km from the release points. In particular relatively high Uranium concentrations in water (0.2 – 0.7 Bq l^{-1}) were found in water of Konoplyanka River near inlet to the Dniprovsky Reservoir. In the reservoirs itself the averaged concentration during 2003-2004 are varied from 0.03 to 0.06 Bq l^{-1} . The typical natural levels of uranium content in the river's water of the not contaminated regions are usually lower 0.01 Bq l^{-1}. The uranium-238 concentration in silt fraction of the bottom sediment in the reservoir are varied in range 150-200 Bq kg^{-1} while at the not contaminated area its activity were found in range 20-40 Bq kg^{-1} 1 [2].

High concentrations of ^{238}U (in range of activity values up to 1.0-2.5 Bq l^{-1} that is coresponding to the values 0.08 – 0.2 mg U per liter) occurring in Zhovta River downstream of waste water released from the mines in Zhovty Vody. The Dose Assessment derived from prior studies [2] lead to several conclusions.

3. Radiological and environment risk assessment as a basis for remedial measures

The highest levels of human exposure, which potentially obtained by citisens of the settlements located on the banks of the Zhovta River and downstream of Konoplyanka River mouth. The estimates based on some conservative scenarios of water use for irrigation, drinking from the wells at the riverbanks remain close to those found for the content of radionuclides in the rivers and in fish. The annual worst case scenario individual doses rates for adult population were estimated as 0.03 mSv and 0.05 for childrens in case of water use from Konoplyanka River and 0.12-0.15 mSv for inhabitans of Annovka settlemet in case of using water from Zhovta River near the town of Zhovty Vody.

In fact, these streams are relatively small and are highly polluted with various contaminants. Therefore, this water should be used not for drinking, or preparing the food and for any other domestic consumption. Nevertheless a worst case scenario figures for direct water use from these streams were included to conservative estimates and as a basis for justification of potential strategy on further action on the environment rehabilitation and to mitigate actual and potential releases from the uranium mines and tailing dump in the region. These results show that the calculated dose rates exceed the Radiation Safety Standard of Ukraine (NRBU-97) value of 0.05 mSv for water use (based on a limit of 5% of 1 mSv for the water usage pathway). For comparison the annual dose rates are about at the level (0.1 mSv per year) recommended by WHO as the maximum permissible for drinking water.

Moreover according to numbers of study appeared during recent decades it was concluded that for uranium, the chemical toxicity needs also to be considered. In some recommendations such as the addendum to the WHO Guidelines (1998), a health-based guideline concentration of urenium was established as of 0.002 mg per litre. Some other studies in Canada and USA a health-based concentration of uranium in water estimated in range about 0,03, which is well below the limit based on radiological considerations and those values of uranium concentration in water of Zhovta River (0.08-0.2 mg l^{-1}) and in some cases for Konoplyanka river (up to 0,05 mg l^{-1}), which took place in 2002.

4. Selection of the best strategy for site restoration

It makes reasonable to provide some possible actions aiming to reduce or at least to control TENORM radionuclide flux to the Dnieper ecosystem. Basic strategic directions of the activities conserning the rehabilitation of uranium tailings in the city of Dniprodzerzhinsk were described many times in proceedings of authorized Commissions and scientific workshops. The most radical of these were developed in the Ukrainian Institute of Industrial Technology (Ukrpromtechnologyi). That is an option of full relocation of the content of several uranium tailings (for example tailing “Dniprovske”) to the other tailing of Suchatschevske, which located 14 km far from Dnieprodzerzhinsk town. This tailing has additional space to accept the wastes and is better adjusted for safe storage, bacause the bad of this tailing is arranged with special engineering facilities of anti-filtration glay barrier.

Some number of the buildings at the contaminated territory of Pridneprovsky Chemical Plant (PCP) was proposed for dismantling with further decontamination of the territory. According to the plan for the year 2002 decontamination should cover locations previously used for uranium ore storage at the territory of PCP and inforcement of the other tailings with anti-erosion measures and reconstruction of drainage systems. Conservation of the surface of tailings or arrangement of additional coverage were defined as measures that decrease exhalation component of radon irradiation of the population in the area under impact of uranium facilities situating in the city of Dniprodzerzhinsk and in Zhovty Vody.

Whereas, the contaminated mine water releases to Zhovta River is today more acute ecological problem for the neighbouring population, the problem of waste management and complete solution of

the ecological problems for the town of Zhovty Vody are considered as a separate clause in the integrated program. It was taken into account that the VOSGOK enterprise continues its operations and this gives more opportunities for economic assistance in solving this problem.

The government has identified a priority task of ecologically sound solution for Dniprodzerzhinsk Site for the period of 2005-2020. A potential danger of this object was taken into account in connection with the accumulated large amount of radioactive wastes (more than 100 thousand tonns [1]) and taking into account that after suspension of operations at PCP some ON-SITE facilities are recognized as having a threat of the accident.

Recommendations of the experts of IAEA having a statement that «in any rehabilitation plan, particular attention should be given to Tailings "D" and the Konoplyanka river which is acting as a conduit for transfer of pollutants from the tailings impoundment into the Dnipro river» were also taken into account.

Evaluations of the efficiency of the consolidated measures proposed with respect to the strategic plan of the year 2002 for this site were 35 man*Sv for the estaimated life span dose of the irradiation of population and personnel that continues to serve at the territory of former PCP. At the same time total costs of measures suggested for realization of this plan during 15 years were found as 350 million UAH – the amount which should not be considered as reasonable in respect of risks averted for the population coming out of uranium facilities environmental impacts in their current state.

The solution as a primary task was recommended as follows – to organize a continuous system of observations at the site and in the zone of influence with the elements of ecological control and complex monitoring.

The Concept of monitoring of the contamination sources and environment in the zone of influence of former objects of the PCP was developed in the year 2004 [3]. This Concept and elaborated program for monitoring and surveillance of residues from the mining and milling of uranium ores is based on IAEA recommendations [4] and an experience received during implementation of real practice for management of radioactive waste and establishing a radioactive substancies monitoring programs at the Chernobyl sites.

The main objective of the organizing the system of monitoring and carrying out an observations was identified aiming to assess an actual impact of uranium facilities on the environment and to estimate the actual and potential risks for the population and ecosystem. Only after conducting a necessary scientific research and monitoring of the state of environment and the contamination source a partial role of uranium containing facilities on the environment should be evaluated with regards of their influence on ecosystem and health of the population.

As based on this approach during the nearest 2—3 years a new plan of rehabilitation measures with more justified strategy should be identified using not only radiological criteria but also social and economic issues. Such a plan of measures is currently under development, however it is obvious today that the removal of wastes from "Dniprovske" tailings to any other location outside the PCP industrial site does not meet feasibility requirements and economic considerations to realize this idea.

Taking into account relatively small releases of uranium in seepage water and with aerosol fluxes running off the existing edges of the site, it was proposed as optimal plan to preserve the tailings through surface coverage over existing phosphogipses and establishing a certain geochemical and engineering barriers along the mainstreaming contaminated groundwaters.

Removal of the high polluted mud in settling pond on Konoplyanka river, arised to the river with the contaminated waters from tailings and industrial territory of former PCP, may become appropriate measure if costs are feasible.

Phytorehabilitation measures to cover surrounding wetlands intended to regulate uranium fluxes occurring as annual removal and burning of some part of biomass (reed and rush) composed of water associated higher plants, planting the hygrophilous arboreal plants such as cloned populus is considered as likely measure.

Main attention is paid to the rules of handling and behaviour of the workers who might operate on radioactively contaminated territory of former PCP developing adapted radiation-hygienic standards for management of radioactive and other waste acumulated at the uranium facilities – these standards are not established in Ukraine untill now, providing objective and complex control of the state of these objects.

The enterprise responsible for handling uranium tailings (State Enterprise "Barrier") will have more effective control in minimizing the radionuclide fluxes running off the site where the established borders of sanitary-protective zone act as quite reliable barrier on the way of radionuclide distribution in to the envvironment.

Adequacy and effectiveness of this simple set of measures have to be confirmed by independent observations on the annual basis at the state system of ecological monitoring networks regarding to monitor the contamination of atmospheric air, surface and groundwaters, and also agricultural production grown in the nearest zone with the impact of uranium facilities.

The restoration of drainage systems is recommended for the other former uranium facilities located at the site of PCP, being arranged with several anti-erosion measures, to operate a reconstructed control and observation wells for surveillance of the state of groundwaters in accordance with the requirements for the network of radiation monitoring, to remove chemical production wastes from a surface of uranium tailings, to conduct preparatory works on the conservation of these facilities.

Experience of conservation of similar facilities in Canada (CAMECO Corp., COGEMA Resources Inc.), Czech Repuplic (DIAMO, State Enterprise), Germany (WISMUT Gmbh), Hungary (Mecsek Environmental Corp.), [5-7] and the experiens of phytorehabilitation technologies with reference to its applications for Chernobyl zone [8] should be very helpful.

It is also visible restoration strategy has to be based on the results of Uranium and Uranium daughters and chemical elements transport modelling and in particular through aquatic and, where appropriate, aerial (Radon, windblown radioactive particulate) and food pathways.

Conceptual design of the proposed remediation of the PCP site and for uranium facilities in Zhovty Vody site have to based on internationally accepted practice with justification of the “best suitable” remediation concept.

It was recommended that current and future operations need to be carried out in accordance with an environmental plan that includes funding provisions to ensure progressive rehabilitation of closed mines, dumps and other facilities.

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PANEL DISCUSSION

The panel was introduced by C. Ganguly, who explained that the composition had been intended to reflect the wide range of interests being debated at the symposium. Specifically the members were identified with uranium in the fuel cycle as representing the supply industry, consumers (in the form of utilities), the demand analysts, the fuel producers, exploration and resource development, marketing, and mining and production. The moderators for the discussions were S.W. Kidd of the World Nuclear Association and F.M. Killar of the Nuclear Energy Institute, both institutions being cosponsors of the symposium.

The panel members were invited to make short opening statements to indicate which part of the fuel cycle they were representing:

A. Boitsov, TVEL Corporation, Russian Federation — a supplier of uranium and fuel fabrication services — the main interest is in supply and demand and how the gap between these two may be developing and options to fill it.

J.P. Malone, Exelon Generation Co. Ltd., United States of America (USA) — a consumer as a power generating utility — as the owner and operator of nuclear power plants their interest is in guarantee of supply, especially when there is talk of a growing gap between supply and demand. They believe that the demand is growing and more mines are needed as well as improvements in fuel fabrication and reductions in tails assay.

S.W. Kidd, World Nuclear Association — representing the analysis of the demand side — mainly involved in research of the demand side but interested in supply, from both mines and secondary sources.

F.M. Killar, Nuclear Energy Institute — looking at the supply and demand equation — some mining interest but mostly concerned with fuel fabrication.

G. Capus, Cogema (Areva Group), France — geological exploration and resource development — noted that only 16% of the papers were on production from mines; if there is a gap between supply and demand where is it and are there enough in-ground resources to meet the demand?

J.C. Cornell, RWE NUKEM, Inc., USA — one of the largest intermediaries in the world uranium market, in effect a virtual mining company with interests in central Asia — how is the so-called gap defined and by whom? The interest should be in uranium production minus reactor demand not reactor requirements — the gap is flexible.

R Gupta, Uranium Corporation of India Ltd. — uranium mining — increased uranium production is a major objective for India to meet the growing demand for electricity to support ongoing industrialization and to reduce dependence on fossil fuels. He sees India as a growth market and would like to host the next symposium!

The debate commenced by considering the “gap” between supply and demand and the suggestion that there were two factors to consider when trying to establish demand for uranium: the forecasts of increasing generation capacity and the reactor load factors. Only these could establish future demand accurately. The problem is how to get accurate and independent forecasts especially when the demand for power is rising quickly and generating capacity is also increasing, but less quickly. There was discussion of how utilities are trying to manage demand by improving tails assays — for example, one company had reduced its demand from 11–11.5 million pounds to 8–8.5 million pounds in this way. It was also pointed out that a utility must be able to sell its product competitively in the market. Improvements in fuel design may make only marginal increases in production, but these could be very

significant commercially. Thus, improved economics could actually result in a reduced demand for uranium.

Again it was pointed out that there are many new reactors being discussed around the world and this will lead to increases in exploration as producers try to improve long term market security of supply. The resurgence of interest in nuclear power as a consequence of growing concerns about the "greenhouse effect" will probably lead to many of the presently "deferred" NPP projects getting development approval. As the price of the uranium raw material increases so the search for new resources will expand. All members of the fuel cycle are in the game together and have a vested interest to make nuclear power more efficient, attractive and publicly acceptable than it is today.

As it takes up to 60 years to plan, develop and operate a reactor over its full lifetime, we should be able to plan well ahead. New uranium mines also need long lead times to reach full development. Last year's uranium production rose from about 35 000 t to more than 40 000 t with little effort but nobody is sure of the estimate for the coming year. If the enrichment capacity keeps pace with demand then it could lead to a depression of the market for the producers.

The meeting was reminded that a realistic scenario for the true market demand is essential to forward planning for all parts of the fuel cycle. Some of the present scenarios are unrealistic, but in both directions. The issue of efficiency and longevity of secondary sources has to be agreed. Availability of secondary sources will be a function of current uranium market prices. For example, the OECD price estimate for uranium from MOX fuel was 2.5 times that of reprocessed uranium. There was also potential to obtain supplies from further processing of depleted uranium. Also what will happen in respect of processing HEU after 2013 when the present agreement between USA and Russia expires? The potential to loose 900 t per year on the supply side could lead to another price hike.

Questions from the floor were varied:

There was a question about the increasing price of oil impacting on uranium as a competitive source of power generation. Some participants thought the concerns about price stability could be well founded. In particular it was felt that while there would be no short term impact on the uranium industry, volatile oil and gas prices could, in future, encourage utilities to prefer nuclear power options based on a more stable supply and prices for uranium. Other observers felt that there would be some long term impact on the uranium industry from rising gas prices but there was a need to stabilize the marketing of secondary sources and stockpiles of uranium.

There was a question about the ability of government policies in the USA and Russia to influence the uranium price downwards. It was felt that governments can indeed affect prices and the US Congress was being lobbied by industry to act in the interests of a stable uranium market.

It was observed that the industry is unique in that only 60% of the annual reactor demand comes from primary sources, thus the gap is between primary production and the annual requirements. The floating secondary supply sources are what fill the gap at present. In the past 5 years the commercial stockpiles have been run down but there are still significant secondary sources available; for example tailings from earlier operations — there are 15 million pounds of uranium contained in tailings in the USA and even more in Russia. It was also possible the USA would obtain permission to remove 100t HEU from safeguards control to be used for dilution to fuel supply grades. It was stated that the US Government has 60 million pounds equivalent of uranium surplus to requirements, which it would like to sell in accordance with the timetable recently established by Congress.

It was thought, however, that secondary sources will continue to be an important supply option for some years to come; even by 2020 there could be up to 10 000 t of surplus uranium available.

The wisdom of making decisions on the basis of today's spot prices was questioned but mining companies want better prices to help recover full production costs, including exploration and resource development. The present price is stimulating the idea of assaying and extracting uranium from tailings, but this will drive down demand for new uranium and mine development. The forward price for uranium today is little more than half the spot price and it is not anticipated that much will sold at that price — most will be lower. As electricity prices are not fixed and frequently fluctuate, uranium could become a more expensive option with full price recovery. Both sides of the equation (supply and demand) would require a stable pricing structure to get fair deals.

The supply is thought by some to be tight now and secondary supplies are an important source, but as secondary supplies are capped new production is thought to be essential. The talk of global expansion in exploration was strongly welcomed, and better supply conditions would surely help to stabilize prices in the long term.

There were questions about the validity of statements that had been made on long-term prices when compared to present spot prices. Also, it was clear that there was a lot of uranium resource available at a recovery cost of less than $40 per kg. This raised the question of the accuracy of the data published in the IAEA/OECD-NEA Red Book as some thought that using this data could be misleading. The meeting was advised that a study of the accuracy of predictions in the Red Book was underway to look at data from the past and up to 2050. To date the discrepancy between the Red Book projections and the actual rates of exploitation had been small except in some specialist categories.

This lead to a discussion as to how much present production facilities could expand. Although this would require some increased investment some "new" production should be possible. With such increased investment increased production would be possible, but perhaps not a great deal as production centres were reaching available capacity. However, new production will also have to take account of the need for (and costs of) remediation — an activity not always practised in the past. Income from production must be used to support exploration. Exploration should be increased, or at least maintained, as additional reserves are needed. It could be that reprocessing of residues and reopening of closed facilities might be profitable in some cases. However, money had been wasted in the past by premature remediation. Such outcomes are frequently associated with volatile market prices. Centres that were previously considered to have high production costs may now look economically attractive.

The true level of new production needed after discounting secondary supplies was questioned. Also the matter of whether "new" production to fill the gap should be in old or new facilities. The true availability of resources should be established and in particular their recovery cost. Even at a recovery cost of $40 per kg a producer might have to sell at around $70 to be profitable. Also it is questionable if production can actually be increased fast enough to meet demand. To meet the projections for uranium up to 2050 would seem to require development of resources that are not yet proven and new production centres will be needed in less than 20 years — and the lead time for some developments has been that long!

It was commented that there is a need to take two main factors into account. These are the significantly variable estimates of demand and the extent to which estimated uranium resources in the ground could be turned to "yellowcake in the can".

At this point in the debate Mr McMurray made a short presentation on the ongoing Red Book project and showed the graphs derived from work done so far. Taking the "reference case" projection, it was shown that reasonably assured resources (RAR) would be sufficient to meet demand until 2040. If inferred resources were to be included then production would be adequate to meet demand to 2050. However, this depended on the success with which uranium in the ground could be converted to "uranium in the can" as previously remarked. This would be something that would involve a lot of

work and was very difficult to predict with certainty. It showed that supply could be doubled in the timescale but the loss of secondary sources, in particular HEU, made it difficult to see how increased primary production could be avoided. This would mean new mines and exploration activity ought to be underway now.

It was stated that if all the NPP and new reactors listed as "possibles" went ahead then new mines are essential to meet demand. India in particular would need several mines, even if the increased power requirement to 2020 was modestly put at 20 000 MW. Exploration was proceeding nationally for this reason. In Russia it was considered that production after 2020 could be problematical once stockpiles and secondary sources are run down.

There was some discussion of former mines being redeveloped in some more remote areas and how these sources could be producing up to 3 million pounds annually within 2–3 years if investment was forthcoming. The profits from these "quickstart" operations could finance other smaller mines in nearby locations and so contribute to overall production increases.

There were questions raised again about the relationship between resources measured in the ground and the final amount produced. The gap here is significant in many cases and work must be done to reduce this gap. It was highlighted that we have several high technology mining methods to deal with difficult sites, for instance: very deep mining and new technologies to deal with poor ground conditions and similar factors limiting production. The increased risk of worker radiation exposures with higher grade deposits being worked also had been addressed. An outstanding issue, ironically, is the exposure of workers in low grade mines. Here workers are in close contact with the ore and consequently occupational exposures are more difficult to control. Some of the problems in low grade mines are being dealt with through the introduction of in situ leach (ISL) methods, where this is possible. In medium grade mines, heap leaching is being practised. This led to discussion of the similar issues in relation to ISL mining, where environmental concerns relating to residual effects of mining on water quality are often creating difficulties for resource development. It was noted that ISL deposits are not found everywhere and some may be in areas that are environmentally too sensitive to be considered for development.

The issue of the activity of the big 3 developers/producers of uranium controlling the market meant that the position of smaller producers was very important to reduce the economic vulnerability of the consumers. It was also commented that it was possible for resource appraisal biased, although the Red Book is drawn up on the basis of governments' figures and should be unbiased because it was free from commercial influences. The Red Book projections seem to lie evenly between the extremes shown in projections of other groups. Opinion was that resources were most likely to be underestimated and production could be overestimated.

The meeting considered that the uranium industry is well endowed with technology and uses it well. The shortfall may be in working with the regulations and situations that prevent resources from being developed. Jabiluka in Australia was quoted as an example. Such resources could be over 200 000 t countrywide. It was pointed out that in Australia there are a number of local situations that have created these conditions and they may not be universal.

There were comments that the IAEA should be producing more guidance for countries trying to develop uranium resources, especially with new technologies such as ISL. Comparison was made with the level and style of guidance documentation produced by the IAEA in relation to nuclear power plants (NPPs). It was pointed out that much guidance information on radiological aspects of uranium mining and waste management is available but Member States must make their own decisions. In all countries, regulation locally is an issue for government and industry, and is not the responsibility of outside agents. Also it should be remembered that some issues hindering resource development are

generic to mining rather than specific to uranium, and these broader issues will take longer to resolve. Also such issues are not the responsibility of the IAEA to solve.

There was also a comment that more attention should be paid to development of smaller resources rather than to maintain reliance on a few existing large deposits. Some observers considered it unlikely that there would be new "mega" deposits in future and so these smaller resources should be regarded as more significant than they appear to be at present. Such developments may require new techniques, and development might be better organized on a regional basis.

There was a comment that Australia has particular issues to consider as a major uranium resource holder but having no nuclear power programme of its own, as well as specific local political concerns. Again the issue of objections to mining generally as opposed to uranium specifically was mentioned and the need for regulating agencies in Member States to sort out such issues which are clearly not the responsibility of external agencies such as IAEA. It was agreed by another participant that these points were well made and similar situations existed in other countries, including Brazil and the USA. It was important for the industry to show good stewardship of land and resources in order to avoid gaining a bad reputation. This in turn would be another obstacle to overcome in the path of resource development.

It was argued that there needed to be new exploration efforts worldwide and that the issues of large versus small deposits would have to be debated. There was also little doubt that new techniques might have to be developed to exploit some of the smaller resources. There was then a discussion on developments in uranium exploration geology with the debate centring on the second day's activities concerning types of deposits and plans for future exploration and exploitation. This was discussed in some detail with India as a case study.

The meeting then turned to discuss new exploration more generally and it was agreed that finance for exploration was the prime concern. The present high price on the spot market could take 2 or 3 years to bring a change in long term contract rates, and this would affect the ease of obtaining finance from institutions. However, it was agreed that a rising spot price does help when trying to obtain exploration finance. There may not be so many new targets but there was a hope that more resources would be identified for appraisal using some of the new exploration technologies discussed at the meeting. In particular the advances in data processing and improved results from computer-based mapping were seen as advances that would lift efficiency of exploration.

Another speaker commented that traditional methods and technologies were doing well enough but there would be a need to introduce better systems and tools as deposits became harder to find. The major concern was the dwindling human resources with skill and experience that would be available to undertake the necessary resource location and development studies. There are very large areas of some countries that are presently unexplored, e.g. Siberia, and these would have take a new approach if exploration was to be successful. The lack of a skills base was an international issue and should be addressed at the international level. The long lead time of 15 years or more to obtain skilled staff must not be forgotten and action should be started soon.

There was a question about what was happening in China. The answer from a delegate was that there was a programme in China that set out targets up to 2020. The prime concerns were safety of NPPs and the assurance of uranium supply for these plants. There was no doubt that local uranium production would not meet NPP demand in the short or long term and so exploration had begun again in earnest, also training for exploration personnel including geologists. Work was commencing in the south east of the country with volcanic and granitic type deposits. There is also a proposal to seek overseas joint venture partners to assist in these programmes of exploration and resource development.

Finally the issue of human resources was raised. Many of the participants were concerned that the uranium industry was not attractive to young people for a variety of social and philosophical reasons and so there was a real danger of there being insufficient experience and skill in the future to maintain the industries of the fuel cycle.

In the CIS, the meeting was told, there are also concerns about training levels and human resources availability. There is no doubt that uranium geology does not attract many new people, especially amongst young professionals. The CIS is actively planning to implement new courses and attract new people.

In the USA the situation is similar, with decreasing numbers of experienced human resources, and efforts are being made to stimulate the whole nuclear energy sector at all stages of the fuel cycle.

In Canada, the problem for mining companies is not only staff for themselves but also for contractors who are needed to operate facilities. In many areas of operations, support contractors cannot supply enough well-trained staff and this situation is getting worse as fewer and fewer young people are attracted to the industry. All resource industries are now competing for a decreasing human resource base, and uranium is apparently less attractive than the rest. Even basic geology is not attracting sufficient new people. It seems that not even greater salaries and conditions are sufficient incentives, as delegates from both Brazil and Australia commented that offering to pay more did not appear to attract any more people. Also the private sector is perhaps less speculative nowadays and so perhaps governments need to do some of the initial groundwork to encourage resource companies to follow up on new deposits.

The meeting was advised that the Uranium (Red Book) Group was planning to look at this issue during their meeting set for the following week. Also it was possible that NPP operators were getting into a similar situation after the effective moratorium on many new developments. If there is to be a renaissance for NPP development then the lack of experienced human resources could become a significant constraint. The need for a wider base in nuclear educational opportunities was seen as apparent and the new nuclear university was mentioned as one possible way to solve the issue.

It was observed that China is also planning to increase the numbers of new students in uranium geology greatly in the next few years.

The international shortage of uranium geologists was exemplified when a delegate stated that there are perhaps less than 10 such senior staff in the field in Australia, a major resource country. Again it was noted that there is a social stigma attached to uranium above all the other resource industries, and new professionals prefer not to be working in remote areas under conditions of hardship. This industry cannot compete with other, service-type industries when it comes to attracting new young professionals. This was also stated to be the case in Indonesia.

Many delegates suggested that the IAEA might be able to help in organizing training for some countries which could help overcome these problems.

One observer stated that we need to identify some basic issues; in particular that young professionals are now more environmentally aware and that with the industry having a poor environmental image with the public it is not attractive to new graduates. The industry must work hard to overcome the prejudice arising from the legacy of earlier times and to ensure that there is no new adverse legacy for future generations to deal with. The importance of the environmental issue should never be underestimated. Small mines will be important in the future and they may be a larger environmental challenge.

One speaker suggested that the IAEA could help by encouraging industry members to offer more studentships, internships and vacation employments. Experience suggests that many students will

follow careers where they had good experiences in such employments. There needs to be a longer term approach to resource development “from cradle to grave” and, if the IAEA could continue to support such efforts and provide best practice guidance and if industry members remember to make operations more transparent and consult more with stakeholders, then things should improve.

The final comment before conclusion of the panel discussion was that environmental issues are important and should be integrated into all aspects of resource development from the earliest stages of exploration to the end of remediation, but as a standard activity not as a special one!

The debate was closed by C. Ganguly just before midday, after which the meeting president thanked the delegates for their efforts and bade them farewell.

CONCLUDING REMARKS OF THE SYMPOSIUM PRESIDENT

M. Tauchid, Canada

Ladies and Gentlemen,

I have renamed the president title to glorified observer because my job is basically observing.

First, when you come to a big meeting like this you wonder, particularly for the organizer, if it is going to be a good and successful meeting. Listening to comments from the participants, it appears that it has been a great meeting. The interest, as reflected by the number of participants coming from different parts of the world, suggests that this probably is one of the most successful meeting in this area of interest during the past few years organized by the IAEA.

The scientific programme covered all themes of importance in the uranium production cycle and the related areas, environment in particular. The quality of papers and posters presented were excellent. It is obvious through this meeting that we all learned from one another. This brings me to one of the main role of an organization like the IAEA as being a unique international body for this type of gathering. It provides a neutral venue and a forum where experts from all over the world can come and have a dialogue and discuss matters that are of mutual interest and benefit.

However, it is up to you to say that.

I would like to briefly comment on two completely separate aspects of this gathering. First, what have we learned from this meeting, and secondly, what is the role of IAEA on some of the questions raised.

Related to the first question, I do not wish to bore you by repeating on what has been presented or discussed during the past four days. Everybody heard the various papers twice, three times, and even more. I think it is sufficient to say that the question of supply and demand had been thoroughly addressed and will need further analysis in order to come with a more accurate projection, thus avoiding over optimistic figures which had driven the price skyrocketing in the 1970's. In the uranium production side, it was noted that there are basically two issues, the existing and the planned facilities. It is quite reasonable to think that production increase from the existing facilities will be limited and will not be able to meet demand on the short term. On the planned facilities, they will face a number of challenges and constraints. Probably one of the most important points that have to be taken into consideration is the frequently mentioned long lead time of 10 to 15 years before the first yellowcake can be put into a drum. The nagging problem of liability management and negative public perceptions are two issues that require serious attention. There are a number of places in the world where the legacy of old uranium mining remain a troublesome issue requiring proper decommissioning and remediation. Regardless of their geographical locations and who were responsible, they represent black marks in the uranium industry. This leads me to the question of the generally negative public perception toward the uranium industry. Of course this negative perception applies to all that are nuclear related. On the first day, Mr. Gerald Grandey mentioned the need to promote our industry not only to the outside world, but also within our own organization. How true. I still recall when I was still at the IAEA when uranium price was at the lowest point in the early 1990's, everybody that bumped into me at the corridor always asked:" Mohamad are you still here". Uranium geologists and miners were endangered species by then. It appears that these species are now again in demand.

As reflected in the number of papers presented at this meeting, because of their lower production cost, the uranium deposits that are of interest at present are the high grade unconformity related and the sandstone type that are amenable to in situ leach production. Obviously the key point is economics. If the uranium market is stabilized around the present level, other uranium deposits, such as the vein and volcanic types might become attractive again.

We have seen a number of graphs showing how exploration expenditure closely followed uranium price. One can easily add two more lines on those graphs. The first is on the new resources that were discovered, and the second is on the increased uranium production that followed. Stockpiling by utility companies was not far behind. Everybody still remembers what happened next. It is hoped that we all learn from the past and try to act more rationally as partners in this rather complicated business.

Looking at past exploration expenditures during the past 30 to 40 years indicate that the amount of money spent per square km was highest in Western Europe, followed by North America and Australia. It is not surprising that despite of its small size Western Europe, in France, Spain and Portugal, had sizeable uranium resources. South America, Africa and Asia are regions where exploration expenditure per square km was very low. These are also areas with limited uranium resources. Obviously favourable geology has something to do with it. However, looking at the geological map of the world, one can speculate that similar geology does occur in these areas where different types of uranium deposits might be found. In this connection I personally think that we need to re-examine the existing uranium deposits classification and develop good sets of favourability criteria that are useful for the exploration geologists. The use of different exploration techniques are generally dictated by the type of deposit sought and the geological environment noted in the favourable criteria, as well as those learned from known areas. An example is the successful use of deep penetrating electromagnetic system for very deep target in Northern Saskatchewan noted in one of the paper. It is also worth stressing that it takes time to find a new deposit. That is if you are lucky. As most exploration geologist knows, money alone is not a guarantee for success.

I now like to go back to my second question in relation to the role of IAEA on the various points noted during this meeting. First of all, repeating to what was said by Mr. Grandey on his keynote address, a role to help promote the uranium industry. Simple but useful illustrated information that addressed the public at large on the various aspects of the uranium production cycle and its environmental impacts is probably an area where IAEA, through the channel of its 138 Member States, can play an important role. Another point raised frequently during the symposium was about the shortage of trained personnel. IAEA through its interregional/regional training courses and fellowship programme under its Technical Co-operation system can definitely help. Assistant to Developing Member States in these various fields of activities will probably be needed as well.

It is hoped that this gathering has enriched us and that the various players in the uranium areas of activities will find a point of equilibrium to assure a long term supply demand relation with minimum disturbance.

With this I would like to leave and thank you all for your participation.

LIST OF OTHER PAPERS AND POSTERS PRESENTED (available in pdf on CD only)

TOPIC 1: URANIUM SUPPLY & DEMAND

An Analysis of Historical Data on Uranium Exploration Expenditures and Price
R.R.Price

TOPIC 2: URANIUM GEOLOGY & DEPOSITS

Overview of the Maybelle River Uranium Mineralization, Alberta, Canada
K. Wheatley, C. Cutts
Felsic magma-related Uranium Deposits in Southern China
Xiadong Liu, Weixun Zhou
Uranium Mineralization in Oxidised Fractured Environment of the Giant Volcanic Related Uranium Field from the Krasnokamensk Area
V. A. Petrov et al.
Formation Conditions and Origin of Dongsheng Sandstone Type Uranium Deposit in Inner Mongolia, China
Ziyling LI et al.
Sandstone Type Uranium Deposits in NW China
Weixun Zhou, et al.

TOPIC 4: URANIUM PRODUCTION

Extraction of U(VI), U(IV) and Th(IV) from Nitric Acid Medium by CYANEX 272, CYANEX 301, CYANEX 302 in Kerosene
J. A. Daoud et al.
Wastes of the Uranium Industry – Valuable Raw Material for Reception of UO_2 and U_3O_8
U. Mirsaidov, N. Khakimov
Improving uranium extraction efficiency of yellow cake production from one shale deposit by acid pugging and curing with D263B resin adsorption
Zhang Jianguo, Niu Yuqing, Chen Mingyang, Wu Peisheng

TOPIC 5: WASTE MANAGEMENT

Water Management Methodologies from Mining and Milling Activities in Argentina
A. Asenjo
Low-level Radioactive Waste Disposal in the USA – Use of Mill Tailings Impoundments as a New Policy Option
C. W. Farrell

TOPIC 6: ENVIRONMENT & REGULATION

Licensing on Exploration of Nuclear Ore in Indonesia
A. Muktaf Haifani, Suniindyo Surio Herdredi

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S.W. KIDD	World Nuclear Association (WNA)
Topic 5:	**Waste Management**
F. KILLAR	Nuclear Energy Institute (NEI)
J. JARRELL	Canada
Topic 6:	**Environment and Regulations**
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PANEL DISCUSSION ON “HOW TO FILL THE GAP?"

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