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# Recent developments in uranium resources and production with emphasis on in situ leach mining

*Proceedings of a technical meeting*
*organized by the IAEA in co-operation with the*
*OECD Nuclear Energy Agency, the Bureau of Geology, and*
*China National Nuclear Corporation*
*held in Beijing, 18–23 September 2002*

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# FOREWORD

An important role of the International Atomic Energy Agency is establishing contacts between Member States in order to foster the exchange of scientific and technical information on uranium production technologies.

In situ leach (ISL) mining is defined as, the extraction of uranium from the host sandstone by chemical solutions and the recovery of uranium at the surface. ISL extraction is conducted by injecting a suitable leach solution into the ore zone below the water table; oxidizing, complexing, and mobilizing the uranium; recovering the pregnant solutions through production wells; and, finally, pumping the uranium bearing solution to the surface for further processing.

As compared with conventional mining, in situ leach is recognized as having economic and environmental advantages when properly employed by knowledgeable specialists to extract uranium from suitable sandstone type deposits.

Despite its limited applicability to specific types of uranium deposits, in recent years ISL uranium mining has been producing 15 to 21 per cent of world output. In 2002, ISL production was achieved in Australia, China, Kazakhstan, the United States of America and Uzbekistan. Its importance is expected to increase with new projects in Australia, China, Kazakhstan and the Russian Federation.

The Technical Meeting on Recent Development in Uranium Resources and Production with Special Emphasis on In Situ Leach Mining, was held in Beijing from 18 to 20 September 2002, followed by the visit of the Yili ISL mine, Xinjiang Autonomous Region, China, from 21 to 23 September 2002. The meeting, held in cooperation with the Bureau of Geology, China National Nuclear Cooperation, was successful in bringing together 59 specialists representing 18 member states and one international organization (OECD/Nuclear Energy Agency). A total of 29 papers were presented, describing a wide variety of activities related to the theme of the meeting.

Subjects such as geology, resources evaluation, licensing, and mine restoration were presented, but also heap leaching, reflecting the importance of low cost production methods during these periods of low uranium price.

The IAEA is grateful to those participants who contributed papers and took part in the discussions. Thanks are extended to the session chairmen: A. Boitsov (Russian Federation), J.M. McMurray (USA), Chen Zuyi (China) and to Weike Cong (China) for his contribution to the organization of the meeting and site visits. The IAEA officer responsible for the organization and implementation of the meeting, and for the present publication was J.R. Blaise of the Division of Nuclear Fuel Cycle and Waste Technology.

# EDITORIAL NOTE

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# SUMMARY

The Technical Committee Meeting on Recent Developments in Uranium Resources and Production, with Emphasis on In Situ Leach (ISL) Mining, was held in Beijing from 18 to 20 September 2002, followed by a visit to the Yili ISL mine, Xinjiang Autonomous Region, China, from 21 to 23 September 2002.

## Background

Why a technical meeting mainly devoted to in situ leach mining?

Despite its limited applicability to specific types of uranium deposits (sandstone deposits), ISL extraction of uranium accounted for about 18.3% of worldwide production in 2002 (6 410 tonnes of Uranium of the total world production of 36 040 tonnes). In 2002, ISL production was achieved in Australia, China, Kazakhstan, the United States of America and Uzbekistan. As of 1 January 2003, Reasonably Assured Resources (RAR) and Estimated Additional Resources-Category I (EAR-I) recoverable at costs less than US$ 40/kgU and amenable to ISL extraction amount to 526 300 tU, or 21% of the total RAR and EAR-I recoverable at costs less than US$ 40/kgU. ISL amenable resources account for nearly all of the RAR and EAR-I recoverable at a cost of less than US$ 40/kgU in Kazakhstan and Uzbekistan, which together account for about 25% of the worldwide RAR and EAR-I in this cost category. Similarly, Australia, the Russian Federation and the United States of America also have significant ISL amenable resources at a cost less than US$ 40/kgU.

In 2002, existing ISL production capability is about 10 000 tonnes of uranium. The importance of ISL is expected to increase, with new projects in Australia, Kazakhstan and the Russian Federation, as ISL has economic and environmental advantages for producing uranium from carefully selected deposits when projects are properly designed and operated by experienced personnel.

ISL mining is defined as the extraction of uranium from the host sandstone by chemical solutions and the recovery of uranium at the surface. ISL extraction is conducted by injecting a suitable leach solution into the ore zone below the water table; oxidizing, complexing, and mobilizing the uranium; recovering the pregnant solutions through production wells; and, finally, pumping the uranium bearing solution to the surface for further processing.

ISL involves extracting the ore mineral from the deposit, with minimal disturbance of the existing natural conditions of the earth's subsurface and surface. In contrast to underground and open pit mining, there are no rock dumps and tailings storage, no dewatering of aquifers, and much smaller volumes of mining and hydrometallurgical effluents that could contaminate the surface, air and water supply sources. Therefore, the impact of ISL on the environment is much less than for other mining methods as long as projects are properly planned, operated and closed using best practice.

Evaluating the suitability of an ore body for uranium extraction via ISL requires information regarding the accessibility of the uranium mineral and its solubility in a leaching solution. The ore body should be situated below the natural water table in a permeable zone, likely sandstone. This location allows for hydrologic control of leaching solution during the mining and facilitates restoration of the groundwater quality following completion of mining.

Selection of the lixiviant of leaching solution is a key factor in designing an ISL operation. This selection is driven by uranium recovery efficiencies, operating costs, and the ability to achieve a satisfactory groundwater quality restoration. The primary choice is between a sulphuric acid lixiviant and bicarbonate-carbonate lixiviant. In general, acid systems would not be considered for carboneous deposits because of high acid consumption. Sulphuric acid systems have long been used in Eastern Europe and Asia while carbonate systems are preferred in the USA. Acid systems are now employed in Australia on ore bodies, which reside in saline aquifers.

In ISL, the primary source of potential contamination is the acidic leaching solution. The low pH of the fluid results in the dissolution of various metals contained within the host rock. The combination of low pH and elevated concentrations of metals as well as radionuclides creates a risk to surface waters and soil (from spills) and a separate risk to adjacent ground waters. ISL has evolved to the point where it has been demonstrated to be a controllable, safe, and environmentally benign method of uranium mining, which can operate under strict environmental controls.

In the mid 90s, facing the challenge to meet the demand of economic uranium for the country's mid- and long-term nuclear energy development plan, the Bureau of Geology of China decided to change its exploration objectives from "hard rock" type to ISL type deposits. Exploration activities were gradually conducted in the Mesozoic-Cenozoic sedimentary basins in north and northwest China. In the past decade, uranium exploration activities have mainly been conducted in Yili, Turfan-Hami, Junggar Basins in Xinjiang Autonomous region, and in Erdos, Er'lian and Hailar basins in Inner Mongolia Autonomous Region, as well as in Songliao basin in northeast China. Four uranium deposits and a few potential occurrences have been found. In 1996 the Kujiltai deposit, in Yili basin, was put into commercial operation using ISL technology.

## Discussions

The location of the meeting in China provided an exceptional opportunity for exchange of ideas and discussion between ISL specialists from China and their colleagues from other parts of the world.

28 technical papers were presented during the meeting. They can be classified according to 7 main topics:

- General geology of China and Asia, related to potential areas favourable to in situ leach amenable uranium deposits,
- Exploration: New projects,
- Licensing,
- ISL mining,
- Heap leaching: Improvement of milling process,
- Restoration,
- Environmental issues.

### (1) General geology of China and Asia, related to potential areas favourable to in situ leach amenable uranium deposits

Northern Asia, including southern areas of the Russian Federation, Kazakhstan, Uzbekistan, Mongolia and northern China is known as an important province of uranium deposits. Most deposits in the above countries are located in the so-called "Central-Asia Mobile belt", and at the periphery of the adjacent continental blocks. There occur various types of uranium deposits, including volcanic-type, sandstone-type and metasomatite type. In addition, the region is characterized by the occurrence of large gold, copper, polymetallic deposits.

In China, most of the known ISL-amenable uranium deposits are roll-front deposits, a minority are basal-channel deposits, and very few are tabular deposits.

- *Roll-front deposits*: The mineralised zones are convex down the hydrologic gradient. They display diffuse boundaries with reduced sandstone on the down-gradient side and sharp contacts with oxidised sandstone on the up-gradient side. The mineralised zones are elongate and sinuous approximately parallel to the strike, and perpendicular to the direction of deposition and groundwater flow.

- *Basal channel deposits*: Paleodrainage systems consist of channels several hundred metres wide filled with thick permeable alluvial-fluvial sediments. Here, the uranium is predominantly associated with detrital plant debris in ore bodies that display, in a plan-view, an elongated lens or ribbon-like configuration and, in a section-view, a lenticular or, more rarely, a roll shape.

- *Tabular deposits:* Consist of uranium matrix impregnations that form irregularly shaped lenticular masses within reduced sediments. The mineralized zones are largely oriented parallel to the depositional trend.

In China, several basins present geological characteristics favourable to uranium deposits amenable to ISL mining, including the Bayantala Basin and the Ordos Basin in Inner Mongolia Autonomous Region, The Turpan-Hami Basin and the Yili Basin in Xinjiang Autonomous Region, and the Hailaer Basin in the northeast of China.

- The Bayantala basin has been subject of exploration for ISL sandstone uranium deposits. Uranium in basal channel deposit represents potential mineralization amenable to ISL mining. Features of alteration and mineralization suggest that the early stage and later stage of mineralization are related to phreatic oxidation and interlayer (roll-type) oxidation respectively. A secondary reduction is observed over the earlier mineralization, caused by hydrocarbons rising along faults.

- The Ordos Basin is a well-known “basin of energy resources” for its large resources of coal, oil and natural gas. Systematic exploration of the basin for sandstone type uranium deposits started in year 2000. Uranium related to oxidized zones occurring in mid-Jurassic formations has been discovered in the Dongsheng area. Roll shape and tabular occurrences, controlled by phreatic and interlayer oxidation, have been delineated.

- The Shihongtan uranium deposit, located in the Turpan-Hami basin, Xinjiang Autonomous Region, was discovered on the basis of previously known uranium-coal deposits. The ore body, which shows roll and tabular shapes, is associated to Jurassic loose and permeable coarse-medium-grained arkoses, attributed to a braided fluvial system. Alteration is well developed, including hematization and limonitization, originated from interlayer oxidation while mineralization is associated to the oxido-reduction front zone.

- The Kujieertai uranium deposit in Yili basin, Xinjiang Autonomous Region, is the first roll-type uranium deposit mined in China using ISL method. It is hosted in loose sandstone units of coal-bearing series (Lower to Middle Jurassic), and is strictly controlled by interlayer oxidation zones. The mineralization is associated to sandstone units of lakeshore delta facies and braided area facies.

- Numerous uranium occurrences have been found at the western part of the Hailaer basin, and uranium mineralization mainly occurs in permeable sandstone units of fluvial and fan-delta facies with high content of organic matter and sulphides. Uranium mineralization is mainly controlled by the paleo-phreatic oxidation, fault structures playing a certain role by improving hydro-geological conditions. Uranium ore bodies usually are tabular, few roll-shaped.

### (2) Exploration: New projects

In the near future, new ISL mining projects could be developed in Australia, Kazakhstan and in the Russian Federation.

In Australia, the Honeymoon project has progressed through a demonstration phase and the detailed approval process. This process is reviewed with emphasis upon the regulatory requirements, demonstration plant experience and the steps necessary to advance a new project to the commitment stage. Particular emphasis is placed upon the hydrogeological and bleed disposal aspects of the approval process. The planned ISL facility will have an initial rated capacity of 636 tonnes per year of U, and will use acid leaching and solvent extraction with bleed stream disposal to a 20g/l TDS aquifer. Cash costs for the Honeymoon deposits are projected to be below US$ 6.00 per pound $U_3O_8$ equivalent.

ISL-amenable uranium deposits were first discovered in 1971, in the Chu-Saryssu area, Southern Kazakhstan. The Zhalpak, Mynkuduk, Akdala, Inkay and Budyonovskoe deposits form an unique ore belt, which contains 800 000 tonnes of uranium, one of the largest uranium provinces in the world. Field tests of uranium production by ISL were carried at Mynkuduk, Akdala and Inkay, confirming the potential of the area.

Russia plans to increase uranium exploration and production activities in order to fulfill its planned requirements for the next 30 years. This development will be completed according to 3 axes:

- Modernization of active mining facilities, such as the Priargusky center;
- Development of new mines in Russian Federation;
- Development of joint ventures with foreign countries, Kazakhstan, Uzbekistan, Ukraine.

Current production at Priargusky is about 3000 tU per year. New developments include heap leaching and underground block leaching of low-grade ores, modernization of mining complexes and construction of a new sulphuric plant. New mines are planned to come into operation after 2010.

Currently two new mining projects are under development in Russian Federation, the Dalur deposit in the Transural district, and the Khiagda deposit in the Buryata Autonomous Republic of Russia. ISL mining tests are conducted on both projects with a production of 200 t U in 2002. Production is planned to reach 700 tU at Dalur facility by 2010.

## (3) Licensing

After exploration is conducted and the resources discovered, uranium recovery operations require extensive, time consuming permitting and licensing before operations can begin. It is reasonable to assume that to bring a new greenfield exploration project on line would require one or two decades of preparation. Even with favourable uranium prices, the steps involved in pre-production planning are time consuming and unless the preliminary work has been completed, even an economically viable project would not be able to fill requirements if there were a shortfall in world production and needs were immediate.

Regulations to assure safety to workers, to the public, and to protect the environment, are important to the credibility of the uranium mining industry, but should not impede mineral exploration and mining/milling activities.

## (4) ISL Mining

In the last 5 years, very few new uranium projects started production, including in situ leach mining.

The Smith Ranch uranium facility, located in eastern Wyoming, USA, started to produce uranium in 1997, using alkaline ISL-technology. Its design capacity of 770 tU per year was achieved in early 1999. By mid-2002, more than 1 500 tU have been produced even though production continues to be throttled at 385 tU per year due to market conditions.

Management of wellfield design, development, operation, and reclamation is the central feature of a successful ISL uranium operation. Open communications and close coordination among geologists, engineers, operations, and maintenance personnel are essential. Careful planning and scheduling of numerous diverse tasks must be interspersed with continued installation, operation, and restoration of ISL wellfields if economic production and timely closure of wellfields is to be achieved.

The Shihungtan deposit, located in the Tuha basin in Xinjiang Autonomous Region, is one of the recent discoveries made by China.

Ore has an average grade of 0.03% U over an average thickness of 7.16 m. Carbonate content in the ore is high (3.34%). Permeability is low (0.14–0.71 m/day). Groundwater is characterized by high calcium and chloride concentrations. Laboratory tests, using acid or alkaline reagents showed the amenability of the ore to leaching (67 to 93% uranium recovery).

However, two field tests, using generic acid (10-15 g/l $H_2SO_4$ + 0.3 g/l $H_2O_2$) and weak acid (1-2 g/l $H_2SO_4$ + 1.0 $H_2O_2$) showed that, due to well and ore scaling, equipment corrosion, high acid consumption, acid leaching is not economic. A third field test, using $NH_4HCO_3$ is planned. Despite a lower recovery rate, alkaline leaching may be the only usable leaching method, in order to get economical results.

In the recent years, some uranium shipments have shown excess content of U-234. All these shipments came from ISL operations, mainly those using sulphuric acid process, or from mine water recovery plants linked to remediation programmes. $U_{234}$ excess causes problems in fuel fabrication (higher potential risk for contamination). As for other undesirable elements, financial penalties may be applied to uranium coming from ISL operations, and that may have an impact on the economic amount of ISL amenable reserves and resources.

### (5) Heap leaching: Improvement of milling process

For about two decades, the world has experienced depressed uranium market prices. In order to economically recover uranium from low-grade ores, in deposits other than sandstone deposits, several countries, including Argentina, China and Romania, have been looking at low cost “milling” methods, such as heap leaching. Uranium recovered using heap leaching represented only 1.7% of 2002 production. Heap leaching was achieved in Argentina, Romania and Russian Federation.

In Argentina, after improvement of the heap leaching process, and devaluation of the Argentinean currency, CNEA is now able to produce yellowcake at a cost approximately 20% less than the spot market. At the same time, mine and mill effluents will be treated during operation to a final disposition, with the objective of water preservation, since the mine is located in a semi-arid zone.

Mining and milling methods in China includes the following four categories: ISL, heap leaching, stope/block leaching and conventional milling. Although ISL has been given priority in China’s uranium production strategy, the majority of uranium production still comes from heap leaching. Technical developments in uranium heap leaching include agglomeration of low permeable ore, bacterial heap leaching, stope leaching of blasted ore, acid curing-ferric heap leaching, and heap leaching of U/Mo ore.

Permeability of ore has a great influence on acid heap leaching. There are many types of uranium ores in China, of which 30% cannot be treated in direct heap leaching due to high clay content and low permeability. Agglomeration is one of the most effective measures to improve the permeability of ore. Intensive leaching approaches can be realized by adding lixiviant and/or oxidant when agglomerating, which will speed up leaching reaction, shorten the leaching period, increase recovery rate, reduce consumption and operating cost. Compared to direct heap leaching operation, the leaching period of agglomerated acid heap leaching is reduced from 200 days to less than 60 days, and uranium recovery increased from 40% to 96%.

Industrial-scale experiment on uranium bacterial heap leaching has been conducted in GanZhou uranium mine. Compared to conventional acid heap leaching, bacterial heap leaching reduces the leaching period by 75 days (85 days instead of 160 days), the acid consumption by 0.35%, and increases the recovery rate by 2% (92% instead of 90%).

Studies were also conducted in order to reduce mining-milling environmental impact, such as heap leaching with zero discharge of process wastewater, direct precipitation of uranium from concentrated leach liquor.

Romania conducted experiments on pelletized ore (crushed ore, agglomerated in pellets which are resistant to compression, but remains permeable to leaching reagents). The experiments showed that the ore agglomeration by pelletization increase the uranium recovery by 10–12%, with a decrease of reagent consumption.

### (6) Groundwater restoration

After ISL mining is completed, the quality of the groundwater in the production zone must be restored to a baseline standard determined before the start of the operation, so that the groundwater is suitable for any use that it was suitable for prior to mining. Groundwater restoration methods may be a combination of several methods, such as groundwater sweep, reverse osmosis, electrodyalisis, lime neutralization and precipitation, clean water injection, or in some cases natural attenuation of contaminants.

In China, laboratory tests show that restoration of affected groundwater to pre-mining conditions, using reverse electrodialysis can be economically achieved. 87% and more of the TDS content is removed in 60 to 83% of the contaminated water. Treated clean water is re-injected in the aquifer, when the contaminated brine is evaporated. Field tests are still in process, with the objective of re-injecting 90% of treated water, thus reducing the number of pore volumes to be treated as well as the volume of needed evaporation ponds.

In Ukraine, two uranium deposits, Devladivske and Bratske, were mined using the acid ISL method during the 70s and 80s. No restoration of the affected aquifer was made after mining. More than ten years after the end of mining, no displacement of the contaminated aquifer has been observed. In contrast, a process of self-restoration has been observed, with a significant decrease of U, Th, Ra, sulphates content. pH increased from 3.9 to 6.2. Self-restoration of the aquifer may be attributed to significant content in coal and clay minerals in the leached formation that promote self-neutralization of the affected aquifer.

### (7) Environmental issues

A multi-pathway, probabilistic risk model related to “undiscovered” uranium deposits in an agricultural area in Southern Colorado is compared to known uranium districts in which in situ leach mining activities are underway or planned. Favourability for occurrence of uranium deposits is based on depositional environment, alteration fronts, coincident geochemical fronts, and the presence of elevated concentrations of uranium in ground water.

Agricultural water use from these basins and aquifers are remobilizing uranium, probably radium, possibly other redox-sensitive metals (As, Se, Mo, V, etc.), and radon out of the redox zone, and distributing this material as contaminants onto agricultural crops.

High-volume pumping in the reduced zone or in the redox zone is postulated to cause oxidizing waters to flow across the redox zone, thereby mobilizing uranium in a manner similar to ISL uranium mining. Because of decades-long water use in the area, significant contaminants are likely to have built-up in soils.

The control area risk is compared to risks related to current and planned ISL mining activities in known uranium districts. A combined geological, geochemical, and geophysical programme is proposed to evaluate the extent of impact of high-volume, agricultural well use, and to develop a multi-pathway risk model.

## Conclusion

Interest in uranium activities remains high in those countries that are concerned about the future of uranium production activities. Research for low cost deposits was emphasized during the meeting by the interest of countries/companies looking for new deposits mineable through low cost methods such as in situ leach or heap leaching. But this is not without problems that will have to be solved, particularly for ISL mining of very low grade and low permeability deposits (China) or in very adverse conditions (high depth, low temperature in the Russian Federation).

Another important issue is the licensing of new projects, which is getting more and more important regarding environmental issues, and longer. Companies may have to start licensing process before completing the development of new projects, and even before favourable uranium prices are reached. If licensing is not made in advance, even economically viable projects will not be able to fill uranium requirements, if they were a shortfall in world production and needs were immediate.

# OPENING ADDRESS

**Yuming XU**
China Atomic Energy Authority

Good morning, Ladies and Gentlemen,

The International Atomic Energy Agency Technical Meetings of the Joint OECD/NEA-IAEA Uranium Group and on “Recent Developments in Uranium Resources, Production and Demand, with Emphasis on In situ Leach (ISL) Mining” open today. The meetings are organized by the IAEA in connection with China Atomic Energy Authority, and undertook by the Bureau of Geology and the Bureau of Metallurgy, China National Nuclear Corporation.

On behalf of China Atomic Energy Authority, I would like to extend my warm congratulations on the successful opening of the meetings, and warmly welcome officers of IAEA, experts and representatives of all countries, also warmly welcome experts and representatives from Chinese government organizations and research institutes.

It has been 50 years since the beginning of nuclear power utilization. And during the past 50 years, with its unique advantages of high economic value, no smash to environment and safety for operation, the nuclear power has become an un-substitutable part of the energy resources for the sustainable development of human society. At present, on the Chinese mainland, the 2 nuclear power plants (Qinshan Nuclear Power Plant and Daya Bay Nuclear Power Plant, with 3 reactors) have been in safe operation for ten years. This year, Qinshan Nuclear Power Plant (phase 2) in Zhejiang Province and Ling’ao Nuclear Power Plant has successfully been put in commercial operation. In addition 6 units under construction will go into function in succession before 2005. So we predict in the coming 10 years, the nuclear power industry in China will be developed in a relatively higher speed. With the development of nuclear power the demand for uranium resources has increased constantly, and the stable swell of the uranium resources which are economical, ISL amenable and in keeping with the environmental protection become undoubtedly the good guarantee for further development of nuclear power.

The Chinese Government has attached great importance to the sustainable development of uranium resources and positively supported the application of advanced uranium mining technologies, including ISL. As a result of 40 years of development, China has already established its own nuclear fuel cycle system and ensured the development of the nuclear power. In the nearest decade years, we found a batch of uranium deposits in China and set up the first ISL uranium mine. And now we are actively extending the exploring range and perfecting the ISL technology. Due to its economical and environmental superiority, Chinese Government will continue to support the development of the ISL, and also hope to cooperate with uranium organizations of all countries to accelerate the progress in technology.

Today, 80 experts and representatives from 22 countries and 2 organizations gather together to discuss the production and supply of uranium. It proves that the rational exploration and exploitation of uranium already arises international concern. I believe that during these meetings, all representatives will obtain valuable information, and also will promote new international cooperation and make great contributions to the development of the ISL technology.

At last, I hope the meetings a complete success. I also sincerely wish everyone here good health and successful work. I also wish you a successful visit to our ISL site in Yining.

Thank you very much!

# REGIONAL METALLOGENY: GEOLOGY OF URANIUM DEPOSITS

# Regional distribution of uranium deposits in Northern Asia

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**Abstract.** The northern Asia, including the southern territories of Russia, Kazakhstan, Uzbekistan, Mongolia and the northern China is known as an important distribution region of uranium deposits and occurrences. Since the 60s of 20th century, after the successful development of in-situ leach technology for sandstone-hosted uranium deposits, numerous uranium deposits previously discovered in Kazakhstan and Uzbekistan have become economically amenable low-cost uranium resources. Subsequently, prospecting efforts in Russia, Mongolia and China resulted in the discovery of a series of sandstone-hosted uranium deposits in this region. At present, most uranium deposits in above countries are located in the so-called "Central-Asia Mobile belt" and the periphery of its adjacent old continental blocks. The mobile belt is bound by the East-European and Siberian platforms from the north, and the Tarim–North-China platform from the south. Here, there occur various types of uranium deposits: volcanic-type (Streltsov, Russia), sandstone-type of interlayer oxidation zone (Kazakhstan, Uzbekistan), sandstone-type of basal-channel (Dalmatov, Russia), and metasomatite type (Elikon, Russia). It is reported, that 70–75% of uranium resources in Russia are concentrated in the mobile belt. The Central-Asia Mobile belt sandwiched in between two groups of large continental blocks experienced long tectonic evolution, including multistage extension and closure from the Baikal orogeny up to Hercynian-Indosinian orogeny resulting in the welding of the mobile belt together with the two groups of old continental blocks. Though the mobile belt experienced multiple extension, no open ocean appeared during its evolution and the belt generally represents a mature continental crust. The multiple closures led to the occurrence of numerous uranium-rich acidic-intermediate igneous rocks indicating the significant transformation of uranium and other lithophile elements towards the upper earth crust contributing to the material source of uranium ore-formation in Meso-Cenozoic basins of the mobile belt. Regardless of the occurrence of some uranium deposits in old continental blocks adjacent to the mobile belt, uranium ore-formation ages of most deposits including those located in old continental blocks show that ore-formation process occurred in Meso-Cenozoic time indicating the inherent association of uranium ore-formation with the activity of the mobile belt. The above facts suggest that the Central-Asia Mobile belt is an important global uranium metallogenic belt. Proper priority should be taken in prospecting for uranium, and special efforts should be made in locating sandstone-hosted uranium deposits amenable by ISL technology in the mobile belt.

**Key words**: Uranium deposit, Metallogenic province, Central-Asian Mobile belt.

## 1. Introduction

The northern Asia, including southern territories of Russia, Kazakhstan, Uzbekistan, Mongolia and the northern part of North-China platform is known as an important distribution region of uranium deposits. Here, many important uranium deposits of different genetic types occur, including large volcanic uranium deposits and metasomatite uranium deposits and sandstone-hosted uranium deposits. Prospecting efforts for locating sandstone-hosted uranium deposits in Russia, Mongolia and China since the 70s of 20th century have resulted in the discovery of numerous large-super-large sandstone-hosted uranium deposits. At present, the northern Asia is one of the most important uranium metallogenic belt (province) in the world. In addition, the region is characterized by the occurrence of a series of large and super-large gold deposits (in volcanics and black shale series), polymetallic deposits, massive-sulfide deposits, porphyry cooper (gold) deposits and iron-niobium deposits, phlogopite-apatite-magnetite deposits associated with peralkalic intrusive rocks etc. (Table I). These deposits of different genesis and colorful types geographically are located in an arc-shaped tectonic belt with a convex side southwards and is bound by the East-European and Siberian platforms from the north, and the Tarim–North-China platform the south respectively. This tectonic belt is named by Russian geologists as “Central Asian Mobile Belt”, and some Chinese geologists call it the “Mongolian Arc” (LI Shuqing et al., 1998) [1]. Obviously, such colorful and numerous mineral resources in the belt must be associated with the unique geologic-tectonic evolution of the mobile belt.

## 2. Characteristics of regional distribution of uranium deposits in the Central-Asia mobile belt

As shown in Figure 1, a series of important uranium deposits occurs in a wide belt sandwiched in between two groups of old continental blocks i.e. the East-European continental block (platform) and Siberian continental block (platform) from the north, and the Tarim–North-China block (platform) from the south. At the same time, in adjacent old continental blocks there exist some uranium deposits such as Elikon metasomatite uranium deposit in Aldan shield; Lianshanguan metasomatite uranium deposit; Saima uranium deposit in peralkalic intrusive massif; Guyuan and Qinglong volcanic uranium deposits at the northern margin of North-China platform. It is interesting that uranium deposits located in this uranium metallogenic belt are colorful in types, and of different sizes. Some of deposits are large, and super-large.

Main types of uranium deposits [4] in the belt include:

(a) Sandstone type, uranium deposits in Chu-Saryssu, Syr-Darya (Kazakhstan), Central Kyzylkum (Uzbekistan), Trans-Ural, Western Siberia and Trans-Baikal (Russia), northwestern China (Yili and Turfan-Hami basins), and south-eastern Mongolia (Choir and Gurvansaihan basins).
(b) Volcanic type, northern Kazakhstan (Kokchetav), Streltsov (Russia), Dornot (Mongolia), Zhangmajing and Qinglong (northern China).
(c) Metasomatite type, Elikon (Aldan Shield, Russia), Lianshanguan (northern China).
(d) Intrusive type (subtype per alkaline syenite), Saima (northeastern China).

The occurrence of so many important and colorful uranium deposits in the mobile (orogenic) belt forces most of uranium geologists to reconsider the basic distribution pattern of uranium deposits in the world.

Table I. Important gold, polymetallic, iron, REE deposits in Northern Asia

| Name of deposit | Mineral deposit (associated element) | Size (tonnage) | Country |
|---|---|---|---|
| Suhoi Log | Au (Pt) | Super-large (1200~1800) | Russia |
| Balei | Au | Super-large | |
| Olympiad | Au | Super-large (700) | |
| Soviet | Au | Large (>100) | |
| Zon Holda | Au | Large (150) | |
| Artiemov-Andreev | Au | Large | |
| Darasun | Au (As, Pb, Zn) | Super-large | |
| Bam | Au | Large | |
| Mnogovershun | Au (Ag) | Large | |
| Muruntau | Au | Super-large (4500) | Uzbekistan |
| Kokpatas | Au | Super-large (620) | |
| Dauzhestau | Au | Super-large (540) | |
| Amataitau | Au | Large (180) | |
| Zarmidau | Au | Super-large (250) | |
| Upper Kuma | Au | Super-large (300) | |
| Muiienbai | Au | Super-large (620) | |
| Arhale | Au | Large | Kazakhstan |
| Shinlonggou | Au | Large | China |
| Tuanjiegou | Au | Large | |
| Binjinshan | Au | Large | |
| Xiaoxinancha | Au | Large | |
| Kumtor | Au | Super-large (715) | Kyrgyzstan |
| Holodnin | Pb, Zn | Super-large | Russia |
| Gorevsk | Pb, Zn | Super-large | |
| Udokan | Cu | Super-large ($20\times10^6$) | |
| Jezgazgan | Cu | Super-large | Kazakhstan |
| Kunrad | Cu | Super-large ($12\times10^6$) | |
| Koksai | Cu | Large | |
| Kalapas | Cu | Large | |
| Saiak | Cu | Large | |
| Leninovsk | Pb, Zn | Super-large | |
| Zrianogorsk | Pb, Zn | Super-large | |
| Kalmakir-Dalnoye | Pb, Zn | Super-large ($16\times10^6$) | Uzbekistan |
| Kuzata | Pb, Zn | Large | |
| Kordi | Pb, Zn | Large | |
| Balekdi | Pb, Zn | Large | |
| Chaf | Pb, Zn | Large | China |
| Dongshengmiao group | Pb, Zn | Super-large | |
| Dongshan | Cu | Large | |
| Zhaodur | Cu | Large | |
| Duobaoshan | Cu | Large | |
| Tuwu | Cu | Super-large | |

| | | | |
|---|---|---|---|
| Ashele | Cu | Large | |
| Kalatunk | Cu-Ni | Large | |
| Xilin | Pb, Zn | Large | |
| Ukanshan | Cu | Large | Mongolia |
| Talov | Fe | Large | Russia |
| Garin | Fe | Large | |
| Hegang | Fe | Large | China |
| Kulundur | Cr | Large | Mongolia |
| Aunik | Be | Large | Russia |
| Jereken | Mo | Large | |
| Hancherango | Sn | Large | |
| Jinchanggou | Mo | Large | China |
| Daheishan | Mo | Large | |
| Sarytau | W | Large | Uzbekistan |
| Sautbai | W | Large | |
| Baiyun-obo | REE (Fe, Nb) | Super-large | China |
| Musugai-Huduk | REE | Large | Mongolia |

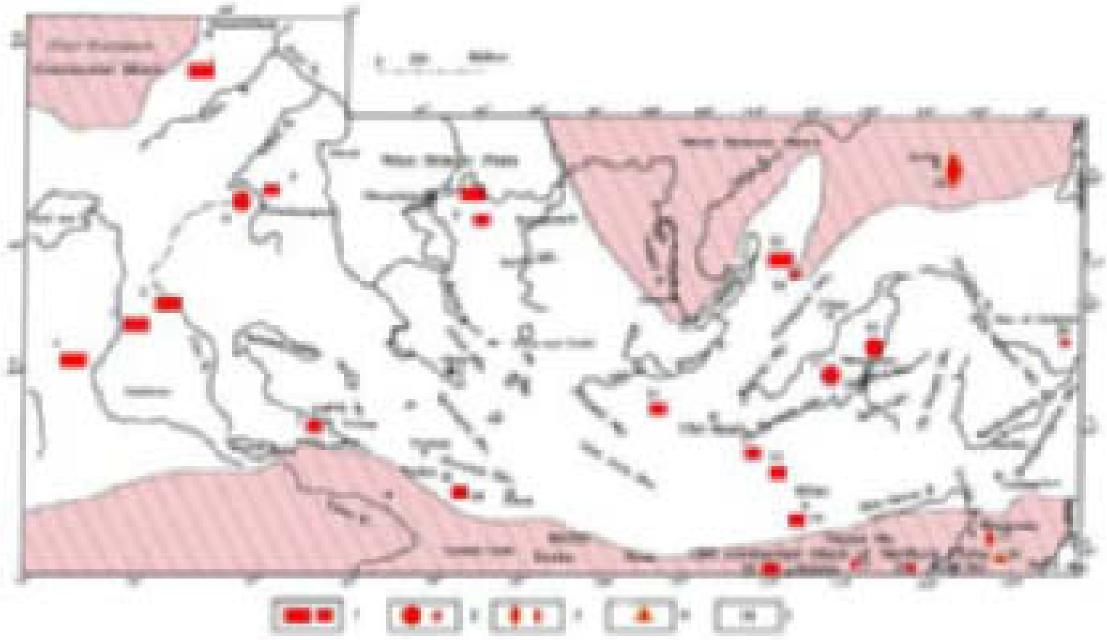

*FIG. 1. Schematic map showing the geographic location of Central Asian Mobile belt and the distribution of main uranium deposit (modified after Li Shuqing et al., 1998 and Tseisler V.M., 1984).*

*1) Sandstone-type uranium deposit >20000tU, 2000~20000tU, 2) Volcanic-type uranium deposit and orefield >20000tU, 2000~20000tU, 3) Metasomatic type uranium deposit >20000tU, 2000~20000tU, 4) Peralkalic intrusive type uranium deposit 2000-20000tU, 5) Uranium deposit (orefield).*

*Uranium orefield, deposits: 1) Dalmatov sandstone-type U-orefield, 2) Chu-Saryssu sandstone-type U-orefield, 3) Syr-Darya sandstone-type uranium orefield, 4) Central Kyzylkum sandstone-type uranium orefield, 5) Semizbai, 6) Kokchetav volcanic-type uranium orefield, 7) Yili basin group uranium deposits (Goljat, Kujertai), 8) Malinov sandstone-type uranium orefield, 9) Smolensk; 10) Shihongtan, 11) Sumin, 12) Harrat, 13) Nars, 14) Nuheting, 15) Shiagda sandstone-type uranium orefield, 16) Olov, 17) Dornot volcanic-type uranium orefield, 18) Streltsov volcanic-type uranium orefield, 19) Elikon, 20) Lastochka group volcanic-type uranium deposits, 21) Zhangmajing,* *22) Qinglong, 23) Lianshanguang metasomatite-type uranium deposit, 24) Saima per alkaline intrusive-type uranium deposit, 25) Dongsheng.*

As early as in the 70s of 20th century, Bowie SHU (1970, 1979) concluded that uranium provinces are determined by the primary distribution of uranium in Precambrian earth crust. Most important uranium deposits occur in Precambrian rocks or Phanerozoic rocks directly overlying the Precambrian basement. The Russian geologist Shuvalov in "Metallogeny of uranium in continental blocks of earth crust" (1980) [6] also repeatedly emphasized that median massifs (i.e. Precambrian blocks enclosed in Phanerozoic folded belts) are the key factor, which control the spatial localization of uranium deposits in mobile belts. Indeed, previously discovered quartz-pebble uranium placer deposits in South Africa, Sandstone-type uranium deposits in Gabon, and Nigeria confirm the inference. The sharp increase in uranium resources of unconformity-related uranium deposits again proves the judgment.

However, the discovery of numerous sandstone-hosted uranium deposits in Central Asia, Russia and Mongolia, northern China indicates, that this concept must be, in some extent, corrected, at least, for sandstone-hosted uranium deposits. Besides the geotectonic position (i.e. the location of sandstone-hosted uranium deposits on the Precambrian basement), there are lots of evidences, that uranium at sandstone-hosted deposits is originated from Paleozoic uranium-rich granites and volcanics in provenance areas (XIA Yuliang et al. 2002, This proceedings).

There are some uranium deposits in adjacent Precambrian platforms. However isotopic data show the multistage Meso-Cenozoic ore-formation ages (Table II) indicating the close association of uranium ore-formation with the activity of the adjacent mobile belt.

Table II. Uranium ore-formation ages in Siberian and North-China platforms

| Tectonic location | Deposit | Type | Uranium ore-formation age (Ma) |
|---|---|---|---|
| Alden shield | Elikon | Metasomatite | 150~130 |
| North-China platform | Zhangmajing | Volcanic ($J_3$) | 87.7; 23.6; 9.9 |
| | Qinglong | Volcanic ($J_2$) | 160~121; 87~76 |
| | Dongsheng | Sandstone ($J_2$) | 107±16 |
| | Saima | Peralkalic intrusive (240~210Ma) | 220~210 |

Moreover, Russian scholars Sherih A.S. et al. (1999) [5] propose that there exists an Euro-Asian trans-continental uranium metallogenic belt. The eastern section of this belt is coincident with the Central-Asian Mobile belt (Fig. 2). According to his statistics 50% of total world uranium resources and 70~75% of Russian uranium resources are concentrated in this trans-continental metallogenic belt.

## 3. Geologic evolution of the Central-Asian mobile belt [2]

The geologic evolution of the Central-Asian Mobile belt is characterized by two major features: (1) There occurred multiple regional extension during the evolution history from the Baikal orogeny to Indosinian orogeny , however, there never appeared a wide ocean in the region and the basement of the belt basically represents a mature continental crust. (2) Acidic-intermediate intrusive and volcanic rocks are widely distributed and occupy vast areas.

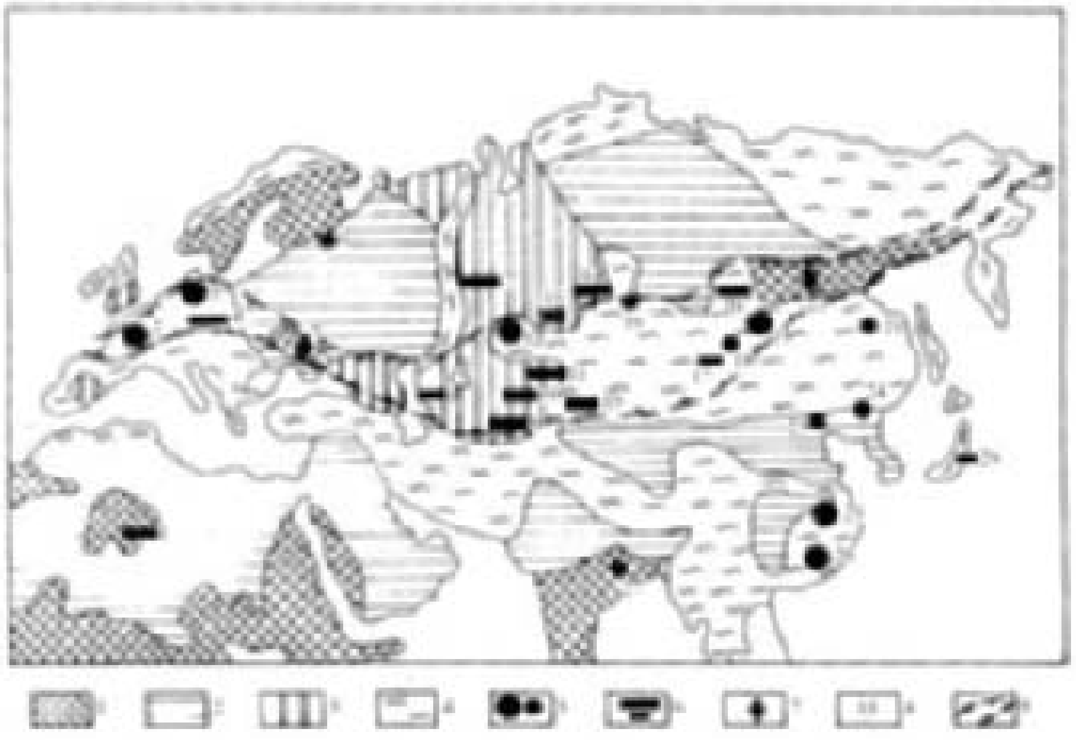

*FIG. 2. Schematic map showing the Euro-Asian transcontinental uranium metallogenic belt (modified after Sherih A.C. et al., 1999).*
*1) Old platform, shield, 2) Cover of old platform, 3) Cover of young platform, 4) Folded belt, 5) Hydrothermal vein-type uranium orefield and deposit, 6) Sandstone type uranium orefield and deposit, 7) Metasomatic type uranium orefield and deposit, 8) Boundary of Euro-Asian transcontinental uranium metallogenic belt.*
*Uranium orefield, deposits: 1) Agadez (Niger), 2) Central Massif, France, 3) Bohemia massif, 4) Lapy basin, 5) Ukraine shield, 6) Onega, 7) Transural, 8) Caspian, 9) Central Kyzylkum (Uzbekistan), 10) Syr-Darya (Kazahkstan), 11) Chu-Saryssu (Kazakhstan), 12) Kokchetav (Kazakhstan), 13) Semizbai (Kazakhstan), 14) Malinov, 15) Yili, 16) Altai-Saian, 17) Southern Mongolia, 18) Dornot (Mongolia), 19) Streltsov (Russia), 20) Shiagda (Russia), 21) Kamenychun (Russia), 22) Elikon (Russia), 23) Northern Hebei (China), 24) Eastern Liaoning (China), 25) Xiangshan (China), 26) Southern China, 27) Singbum (India), 28) Tono (Japan).*

### *3.1. Numerous old continental blocks remain in the mobile belt*

The Siberian platform itself was consolidated at 2000~1900Ma (LI Shuqing, 1998), and crystalline series with ages of 3000~2800Ma are widespread in Aldan Shield. The oldest metamorphic series in North-China platform are mica-quartz schists (3720~3650Ma) and plagioclase amphibolite (3500Ma). On Tarim old continental block, gneiss and plagioclase amphibolite with ages of 3046Ma and 3260Ma are observed. Finally, Tarim and North-China platforms were consolidated in Luliang orogeny (1800Ma). In the mobile belt sandwiched in between the above two groups of old continental blocks there still remain a lot of Precambrian blocks (Fig. 3).

On the territories north to Tarim-North-China platform there exist Yining, Junggar, Hami, Xilinshot, Songnen and Jiamusi old blocks. In general, the mobile belt is composed of a mature continental crust without obvious ocean crust composition, i.e. there never appeared a wide ocean in the mobile belt.

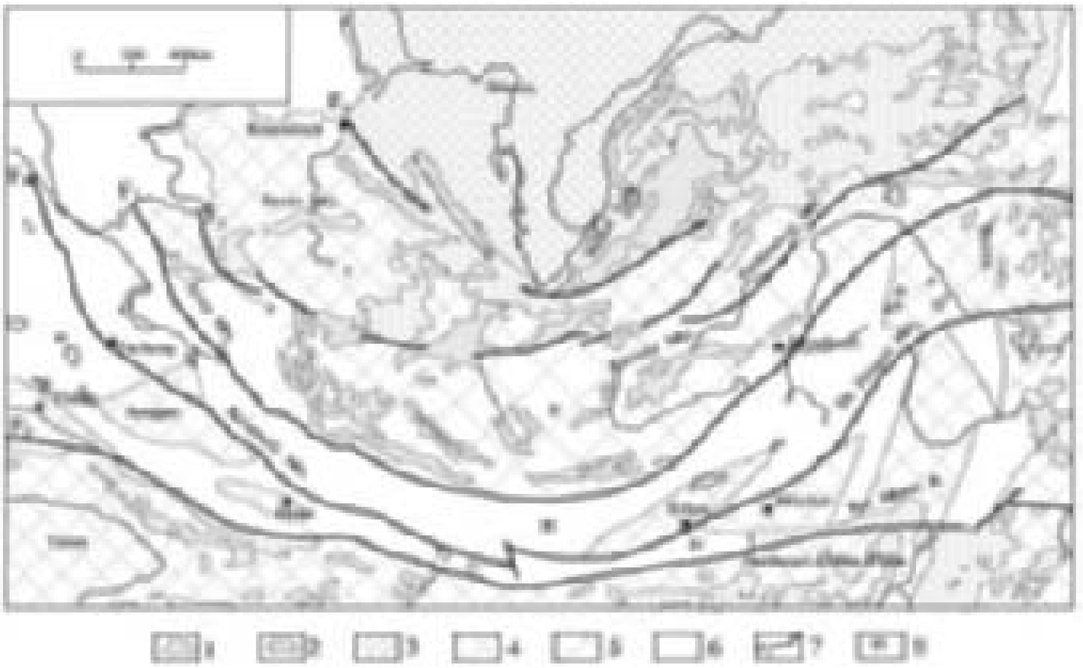

*FIG. 3. Sketch map showing the distribution of old continental blocks in Central Asian Mobile belt (after Li Shuqing et al., 1998).*
*1) Archean-Lower Proterozoic, 2) Middle-Upper Proterozoic, 3) Old continental core of Wutai orogeny (2600~2500Ma), 4) Continental blocks of Lulian orogeny (2500~1800Ma), 5) Continental blocks of Baikal orogeny, 6) Phanerozoic folded blocks, 7) Translithospheric fault zone and its number, 8) I, II, III, IV-Arcuate compressional structural zone of Late Hercynian-Indosinian stages.*

### *3.2. Wide distribution of acidic-intermediate igneous rocks*

LI Shuqing (1998) divided the igneous rocks in the “Mongolian Arc” into 4 EW-trending zones, i.e. (1) Saian Mt.-Iabulo Mt.; (2) Altai-Kent Mt.; (3) Klameili, Xing’an Mt and (4) Junggar-Xilinhot-Jamusi belts. These igneous rocks include Late Proterozoic microcline granite (1000~950Ma), Caledonian granite, grano-syenite, granodiarite (547~480Ma) (Fig. 4), Hercynian leucogranite, alkalic granite (347~220Ma) (Fig. 5), as well as Early and Late Paleozoic (D~C) intermediate-acidic volcanics and tuffs (LI Shuqing, 1998). LI emphasizes that “most acidic-intermediate intrusives are of I-type and S-type, and originated from the remelting of upper mantle and lower crust and mixing with materials of upper crust”. The evolution of igneous rocks from the mobile belt shows a trend of intermediate-acidic igneous series in the early stage (Late Proterozoic Caledonian) to acidic-alkalic series in the late stage (Hercynian-Indosinian). The widespread distribution of acidic-intermediate igneous rocks, as well as the remains of a large amount of old continental blocks once again confirm the concept, that the mobile belt itself represents a huge belt composed of numerous relicts of old continental blocks welded by many acidic-intermediate igneous masses, at the moment when two groups of old platforms are "welded" together at the end of Indosinian orogeny (Early Mesozoic). This fact is very important in the uranium potential assessment of the region.

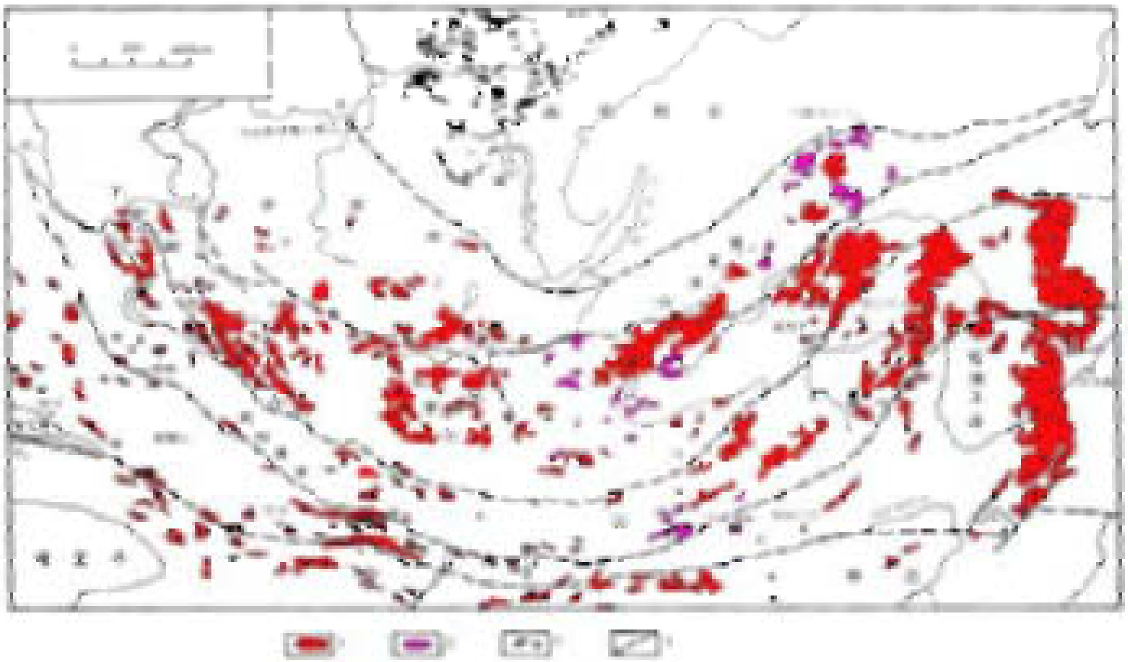

*FIG. 4. Schematic map showing the distribution of Hercynian and Indosinian granites in Central Asian Mobile Belt (after LI Shu-qing et al., 1998). 1) Hercynian granite, 2) Indosinian granite, 3) Trassic magic rocks, 4) Trauslithospheric fault.*

## 4. Metallogenic mechanism of uranium in Central-Asian mobile belt [3]

On the basis of the above analysis, it is suggested, that uranium can be originated only from the mature continental crust. The central-Asian Mobile belt is of important significance in uranium metallogeny and uranium resources just because its basement is basically composed of mature continental crust. The multiple closure of the belt resulted in repeated remelting of the continental crust leading to the appearance of acidic-intermediate igneous activities, and the migration of uranium and other lithophile elements to the upper crust and its concentration in these igneous rocks. Table III shows uranium and thorium contents in Paleozoic-Early Mesozoic magmatic rocks in territories of China, Central Asian Mobile belt.

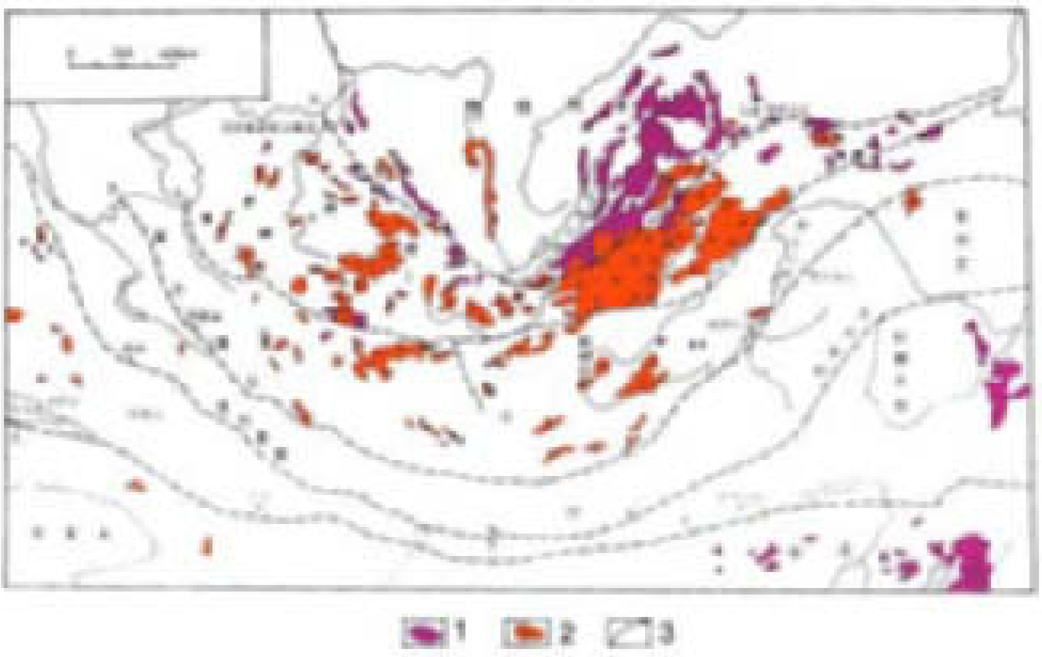

*FIG. 5. Schematic map showing the distribution of Caledonian granites in Central Asian Mobile Belt (after LI Shu-qing et al., 1998).*
*1) Granite of Luliang period (1800Ma), 2) Granite of Caledonian period (547-480Ma), 3) Trans-lithospheric fault.*

Table III. Uranium and thorium contents in some paleozoic-early mesozoic magmatic rocks, northern China

| Area | Lithology and age | U ($10^{-6}$) | Th ($10^{-6}$) | Th/U |
|---|---|---|---|---|
| Yili | Acidic-intermediate volcanics, Oymanbulak Formation ($C_2$) | 4.6 | | |
| | Acidic volcanics, Nautugay Formation, ($C_2$) | 5.8~12.9 | | |
| | Acidic-intermediate volcanics Dahalajemshan Formation ($C_1$) | 3.0~9.7 | | |
| | Middle-Hercynian granite $r_4^2$ | 3.93~5.4 | | |
| Tianshan | Late Caledonia granite $r_3^3$ | 2.9 | 11.9 | 5.3 |
| W. Tianshan | Hercynian granites ($r_4^1$~$r_4^3$) | 4.9~6.8 | 27.7~30.8 | 4.1~6.3 |
| N. Tianshan | Hercynian granites ($r_4^1$~$r_4^3$) | 3.3~3.9 | 14.7~17.8 | 4.1~7.7 |
| S. Tianshan | Hercynian granites ($r_4$) | 7.2 | | |
| Beishan | Middle-Late Hercynian granites ($r_4^2$~$r_4^3$) | 3.7~3.9 | | |
| Langshan | Hercynian granites ($r_4$) | 7.8 | | |
| | Tukmu granite | 7.71 | | |
| | Shalacha granite | 7.3 | | |
| W. Inner Mongolia | Hercynian granites ($r_4$) | 3.5~7.8 | 17.5 | 6.0 |
| Middle Inner Mongolia | Hercynian granites ($r_4$) | 3.9 | 25.4 | 6.5 |
| | Volcanoclastics, Upper Jurassic | 4.4~8 | | |

| | | |
|---|---|---|
| Erguna | Volcanoclastics, Upper Jurassic | 4.4~8 |
| | Yanshanian granites ($r_5^2$) | 2.8~5.4 |
| | Middle Hercynian granites ($r_4^2$) | 2.7~22.3 |
| Da Xing'an Mts. | Volcanoclastics, Upper Jurassic | 5.6~8.1 |
| | Late Hercynian granites ($r_4^3$) | 4.2~8.8 |
| | Middle Hercynian granites ($r_4^2$) | 3.2~4.8 |

As shown from data of Table III, except for some individual regions, the uranium content of acidic-intermediate magmatic rocks in Central-Asian Mobile belt is higher than the average one ($3.5\sim4.8\times10^{-6}$) of world acidic igneous rocks. At the same time, there is an obvious tendency of uranium increase from the early stage magmatic rocks to the late stage ones. These facts suggest that: (1) the remelted magma might be originated from a mature continental crust; (2) incompatible elements (including uranium) in basement continental crust were constantly transferred into magmatic rocks during tectonic and magmatic reactivation.

Moreover, Russian geophysicists Sherih A.S. et al. (1999) [5] come to the same conclusion by processing the aero-gamma-spectrometric survey data (Table IV).

Table IV. Statistics radio-geochemical data of the Euro-Asian transcontinental uranium metallogenic belt.

| Radio-geochemical parameters | U ($\times10^{-6}$) | | Th ($\times10^{-6}$) | | K (%) | | Th/U | | U×K/Th | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 | 1 | 2 |
| Average value | 2.9 | 1.6 | 7.2 | 6.3 | 2.0 | 1.3 | 2.7 | 4.0 | 0.8 | 0.4 |
| Mean square deviation | 1.30 | 0.54 | 3.41 | 2.31 | 0.88 | 0.45 | 1.71 | 1.80 | 0.51 | 0.21 |
| Variation coefficient | 0.45 | 0.34 | 0.47 | 0.39 | 0.46 | 0.36 | 0.46 | 0.43 | 0.76 | 0.54 |
| Asymmetry | 1.73 | 1.24 | 1.43 | 0.83 | 1.12 | 0.86 | 1.12 | 0.91 | 2.22 | 1.57 |
| Excess | 4.50 | 2.4 | 3.35 | 1.20 | 1.60 | 1.54 | 1.71 | 1.85 | 6.47 | 3.69 |

1) Euro-Asian transcontinental radio-geochemical belt, 2) Euro-Asian continent (after Sherih A.S. et al., 1999).

As shown from data of Table IV, contents of uranium, thorium and potassium in Central-Asian Mobile belt are much higher than the averages of Euro-Asian continent. But in Central-Asian Mobile belt the Th/U ratio is less, and variation coefficient for above elements is higher. These facts indicate the concentration of radioactive elements in the belt, making the distribution of above elements more heterogeneous. Sherih A.S. et al. (1999) also emphasize that the range of the metallogenic belt is corresponding to regional gravimetric lows or the down-warped bottom boundary of the earth crust (from 38~40km to 42~60km). Tectonically, the radio-geochemical belt is identical with the regional magnetic anomalous belt and regional folding and faulting trend. Geophysically, it is a low-density and high-permeability zone in the earth crust. The above-listed characteristics result in the multistage magmatic activities and the occurrence of colorful ore-formation processes in Central-Asian Mobile belt.

As mentioned above, uranium deposits located both in the mobile belt, and in adjacent old continental blocks were formed mostly in Mesozoic time. For those of endogenic genesis, the uranium ore-formation process was triggered by magma-hydrothermal activities associated with the tectonic evolution of the mobile belt. For those located in Meso-Cenozoic basins, the uranium ore-formation was genetically associated with the tectonic reverse, i.e. the transformation of basin structure to a sub-orogenic area of the region, making the ore-hosting sandstone units tilted, and the infiltration of oxygen- and uranium-bearing groundwater into ore-hosting sandstones.

## 5. Conclusion

(a) The northern Asia, especially the Central Asian Mobile belt is a geotectonic unit with its unique geologic-tectonic environments. It is such an intercontinental orogenic belt different from both the ocean-continent collision belt and the continent-continent collision belt. In fact, it is a huge super-province for uranium, gold, polymetal, REE mineral resources etc. Uranium deposits of different types and with different ore-formation ages are distributed concentrated in the super-province, especially the sandstone-hosted uranium deposits in the province account for important proportion of world uranium resources at present.

(b) The northern Asia, or the so-called Central Asian Mobile belt contains such abundant geochemically different mineral resources, including those of siderophile, the chalcophile and lithophile elements for it is characterized by its unique geologic evolution, i.e. it was sandwiched in between two groups of old continental blocks-the East-European and Siberian platforms from the north, and the Tarim-North-China platform from the south, and experienced multistage extension and compression (orogeny).

(c) It is true that uranium ore-formation is genetically associated with the development of the mature old continental crust. However, unlike most uranium deposits in African and American continents where uranium deposits tend to be located at/near Pre-Cambrian blocks, most uranium deposits in northern Asia, especially those sandstone-hosted don’t show such features obviously. It seems that the uranium for ore-formation may be originated (derived) not only from Pre-Cambrian old continental crust, but also from those uranium-enriched acidic-intermediate magmatic rocks (especially for sandstone-hosted uranium deposits). Sometimes, the later (they may be called transmitted uranium source) may play direct control upon uranium ore-formation and the localization of uranium deposits.

(d) The investigation and research on this huge metallognic belt is only in the preliminary stage, and to strengthen the overall research and to take active prospecting measures are necessary for deeper understanding and achieving new progresses in metallogenic theory and prospecting.

In a word, there is great potential of uranium resources in northern Asia (Central-Asian Mobile belt) and important progresses in prospecting and scientific research expect to be obtained.

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# ISL-amenable sandstone-type uranium deposit: Global aspects and recent developments in China

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**Abstract.** It is concluded that most of known ISL-amenable uranium deposits are attributed to roll sub-type, a minority to basal-channel sub-type, and a few to tabular in case that redistribution of U occurred. Such a classification and related explanation are beneficial to exploration in China. However, there exist significant differences between deposits in Central Asia and those in Wyoming in aspects of tectonic background, scale and shape of host sandbodies, and attitude of ore bodies though all are attributed to the same roll sub-type. Similar situation is presented for deposits of basal channel sub-type. So, it is proposed to establish deposit model and model series, providing guidelines for exploration. Four model series and eleven models have been tentatively formulated, including: 1) Central Asia-South Texas series (Chu Sarysu-Syr Darya, Central Kyzylkum, Yili and South Texas models) where hosts are large-scale tabular sandbodies, usually developed on the slope parallel to the long axis of the basin and orebodies have a "C" shape with convex surfaces perpendicular to the long axis of the basin; 2) Wyoming series (Shirley-Wind River-Powder River and Great Divide models) where hosts are moderate/small sandbodies forming a wide ribbon, deposited in compressive foreland basins while ore bodies occur on both margins of ribbon-shaped sandbodies with the convex surfaces directed outwards; 3) Grants series (Grants-primary and Grants re-distributed models) where host sandstones were deposited as channel fill within a large-scale humid alluvial fan, containing plenty of organic matter, and orebodies are mostly tabular in shape, transformed locally into roll form; and 4) Siberia-Bohemia series (West Siberia, Trans-baikal-West Yunnan and North Bohemia models) where U concentrations occur in, on, and/or adjacent to detrital plant debris within the channel sandstone, filling incised valley. Besides, recognition criteria are briefly explained. On the other hand, the sandstone-type uranium metallogenetic prospect of China is discussed with special attention to the Northwest Territory of China that could be considered as the east extension of a giant uranium super-province, stretching from Central Asia eastwards. The territory includes four domains and thirteen sub-domains different in uranium endowment. Meanwhile, the features of six selected deposits/mineralized areas are described in brief, including the Kujie'ertai, roll sub-type, hosted in tabular sand-bodies ($J_{1-2sh}$); the Shihongtan, roll sub-type, hosted in ribbon-shaped sand-bodies ($J_{2x}$); the Dongsheng, tabular sub-type with local U redistribution, hosted in ribbon-shaped sand-bodies ($J_{2z}$); the Nuheting, tabular sub-type, hosted in ribbon-shaped sand-bodies ($K_{2e}$); the Bayantala, basal channel sub-type of Mesozoic ($K_{1bs}$) age; and the Chenzishan, basal channel sub-type of Cenozoic ($N_{2m}$ age). Finally, it is emphasized that China, especially the Northwest Territory of China, remains highly perspective, having only minor exploration in the past.

**Key words:** Sandstone-type uranium deposit; ISL-amenable; Deposit model and model series; Recent developments in China.

## 1. Introduction

First report on sandstone-hosted uranium mineralization came from the Colorado Plateau, USA [3], where carnotite-type sandstone deposits were discovered prior to 1880 in what later became known as the Uravan Mineral Belt, Colorado-Utah. Since then, sandstone-type uranium deposits have become one of the most important types of uranium deposits in the world. However, most conventional mines working sandstone-type U deposits were closed since the mid 1980 (the last US conventional mine in 1992) in response to declining uranium prices while in-situ leach (ISL) U extraction from suitable sandstone-type U deposits remained competitive. It is predicted that ISL output is expected to increase remarkably during 2000-2015, accounting for 15% in 2000 and 21% in 2015 of the world annual production [6,10,7,13].

In China, exploration for sandstone-type uranium deposits began in 1950s and became the major target for exploration by the end of last century when ISL mining technology has been successfully introduced. So far, a series of uranium ore deposits have been discovered in Yili, Turfan-Hami, Ordos, Eren, and other basins.

## 2. Distribution of sandstone-type uranium deposits and identification of mineral deposit models/model series [1]

### *2.1. Time and spatial distribution*

Sandstone-type uranium deposits can be timely divided into pre-Mesozoic and Mesozoic-Cenozoic with respect to ISL amenability. ISL-amenable deposits occur especially in post-Triassic basins where host sandstones are non-deformed and permeable. Pre-Mesozoic uraniferous basins mainly occur in Africa. The Mesozoic-Cenozoic sandstone-type uranium deposits or showings are widespread all over the world. However, those of commercial significance are restricted to distinct geological regions: the West of U.S., including Wyoming Basins, Colorado Plateau and South Texas coastal plain; the North Bohemia of Czech Republic, extending into Germany; the Central Asian basins, including Chu Sarysu-Syr Darya Basin in South Kazakhstan, Central Kyzylkum basins in Uzbekistan [8,11], Junggar, Turfan-Hami and Tianshan intermountain basins (such as Yili and Kumishi basins) in northwestern China; the southwestern margin and southeastern margin of West Siberian Basin; the Trans-Baikal, including a series of valley basins in Vitim area. Among them, the Central Asian basins and the West U.S. are of more importance. Besides, there may exist a sandstone-type uranium super-province, which extends from Trans-Ural eastwards, passing through Central Asia and Mongolia-Inner Mongolia into Trans-Baikal, having a geographical coordinate scope of N56º-39ºand E63º-113º (Fig. 1). This is a giant arcuate tectonic belt with a southward arc apex and frontal arc in Mongolia and Inner Mongolia of China, termed "Mongolia Arc". The Belt was formed from the end of Late Paleozoic to Triassic Period, covering the southern margin of the Siberia Continental Block (platform) as its northern part, the northern margin of the Tarim Continental Block and the northern margin of the Sino-Korean Continental Block as its southern part and Paleozoic fold belts between these blocks.

The uraniferous basins display some similarities elsewhere in the world. On the other hand, some differences in tectonic evolution have been revealed (Table I). In Central Asia, host sediments were deposited under an intracratonic subsidence or post-orogenic strike-slip mild-extensional regime while ore was formed in association with mild compression (so-called sub-orogenic event). It means that a tectonic reversion happened between the sedimentation of host rocks and the ore formation. However, such reversion is absent in South Texas, Wyoming and West Siberia. The tectonic evolutionary pattern of uraniferous basins, the scale and the shape of host sand-bodies exert an obvious influence on the attitude of ore deposits and the mode of ore-forming process.

*FIG. 1. Generalized map showing Central Asian sandstone-type uranium super-province (Modified after Li Shuqing et al, 1998; Chen Zuyi, 2002).*

*1) Basal channel sandstone-type, 2) Tabular sandstone-type, 3) Roll sandstone-type, 4) Volcanic-type, 5) Vein-type (in metamorphosed rock), 6) Peralkalic intrusive-type.*

Table I. Evolutionary pattern of basins and lithology of host sediments in selected regions.

| Region/Basin | Underlying rocks | Tectonic regime during | | Lithology of host rocks |
|---|---|---|---|---|
| | | Deposition of host rocks | Ore formation | |
| Chu Sarysu-Syr Darya | Late Paleozoic passage layer | $K_2$-$E_{1-2}$, intracratonic subsidence | $E_3^2$-$N_1$, mild compression | Gray clastic rock series with low content of carbon debris |
| Central Kyzylkum | Late Paleozoic foldbelt | $K_2$-$E_{1-2}$ , mild extension | $N_1$-$N_2$, mild compression | Gray (locally red) clastic rock series |
| Yili | Late Paleozoic foldbelt | $J_{1-2}$, post-ogogenic mild strike-slip extension | $N_1$-$N_2$ , mild compression | Melanocratic coal-bearing rock series |
| South Texas | Paleozoic passage layer | $E_3$-$N_1$, mild extension, along passive continental margin | $N_2$-$Q_1$ ,mild extension | Grayish clastic rock series, poor in carbon |
| Wyoming | Paleozoic passage layer | $E_2^{1-2}$, compression | $E_3$, compression | Gray clastic rock series with carbon debris |
| San Juan basin, Colorado Plateau | Paleozoic passage layer | $J_3$, intracratonic subsidence | $J_3$, cratonic subsidence for primary ore; $N_1^2$-$N_2$, regional uplift for re-distributed roll ore | Melanocratic clastic rock series, enriched in extrinsic carbon |
| Trans-Ural/West Siberia | Late Paleozoic foldbelt | $J_3$-$K_1$, intracratonic subsidence | $J_3$-$K_1$, mild compression after intracratonic subsidence | Melanocratic clastic rock series with carbon debris |
| Trans-Baikal | Paleozoic granitoid | $N_1^2$, compression | $N_2$-$Q_1$, mild extension after compression | Melanocratic clastic rock series with carbon debris |
| North Bohemia | Pre-Cambrian crystalline rocks | $K_2^1$, mild extension after uplifting | E, extension | Gray carbonaceous clastic rock series of alluvial fan/bog/delta/ littoral facies |

### ***2.2. Ore deposit modeling and ore formation mechanism***

Ore deposit model is a standard form to characterize similar ore deposits on realistic description with subsidiary inference. Meanwhile, similar ore deposit models can be incorporated into an ore deposit model series. In such a way, twelve models and four model series have been tentatively established on the essential features of a number of known sandstone-type uranium deposits (Table II). Most of above-mentioned deposits are of exogenous-epigenetic origin. However, ore formation mechanism is not all the same:

(1) The deposits of Central Asia-South Texas series [14] are characterized by that mineralising solutions (oxygenated uraniferous water) flowed down the regional dip of large- to moderate-size tabular sand bodies and crescent-shaped U deposits occur along the boundary between unaltered sandstone and altered sandstone. Germanov [4], as early as in 1960, firstly described ore bodies at the deposits of this series that are irregularly scattered along a wide regional redox front (Fig. 2). Curving parts of the front seem to be more favourable sites for the deposition of ore than straight parts, but ore does not occur on all curves and it does occur on some straight parts. Within the Central Asia-South Texas series, the Yili and South Texas models are characteristic of self-reducing barrier (carbon debris) and allogenic reducing barrier (extrinsic sulphide) prior to ore-forming intra-layer oxidation respectively. It is not clear whether the allogenic reduction is also typical for the Chu Sarysu–Syr Darya and Central Kyzylkum models.

(2) The movement of mineralising solutions along the strike of a ribbon-like sandstone body is typical for the deposits of the Wyoming series. As pointed out by Frank C. Armstrong (1960) that “ore bodies might approximate mirror images of one another and would lie along opposite margins of the flow path” with outwards-directed convex surfaces (Fig. 3). Sweetwater Mine Area, central Great Divide Basin [12], provides an example where ore bodies lie along two opposite margins. However, in most cases ore bodies are predominantly developed along one margin, as shown in Shirley Basin where sandstone bodies strike NNW-ward and ore bodies occur mainly on their western edges with westwards-directed convex margins.

(3) In the deposits of Grants series, uranium was concentrated together with humate during diagenesis to form blanket and elongated tabular ore bodies. Early interlayer oxidation and late interlayer oxidation is locally characteristic for this series. The Crownpoint and Churchrock deposits are the examples where tabular ore-deposits were subsequently transformed into roll type by the early interlayer and the late interlayer reduction. It is reported that both deposits will be developed, using ISL mining techniques (McCarn, 2001) [9].

(4) Within the Siberia–Bohemia series, the deposits of Siberia and Trans-Baikal-West Yunnan models [2] were firstly formed as the product of phreatic oxidation. Then, they were possibly superimposed by interlayer oxidation immediately after the host sandstone was covered by a confining bed and the oxygenated water could flow inwards to form roll-shaped ore-bodies with inward convex margins facing one group to another. Tertiary magmatism might be involved in the ore-forming process as a heat source for the North Bohemian model.

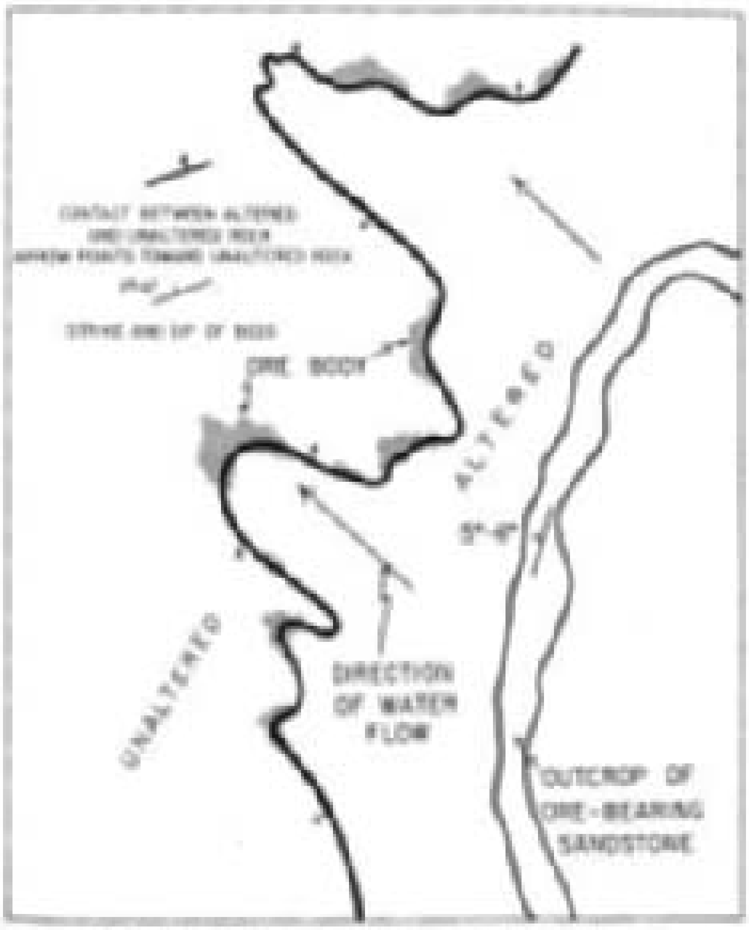


*FIG. 2. Sandstone type uranium deposit in former USSR (After Germanov, 1960; No scale given).*

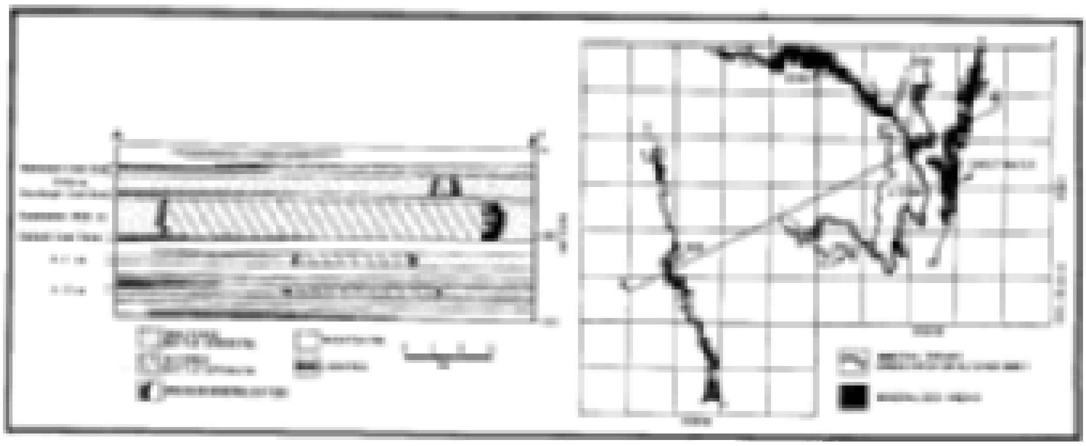


*FIG. 3. Generalized uranium trend map, with associated stratigraphic section (A-A$^{'}$) of the Sweetwater Mine area, central Great Divide Basin, Wyoming (After Sherborne et al., 1980).*

## 3. Tectonic delimitation of Mesozoic-cenozoic basins and their exploration perspective

The tectonic framework of China exhibits a pre-Mesozoic basement divided by meridional lineaments into several blocks and three Mesozoic-Cenozoic structural regions of latitudinal direction; the three regions correspond to both the recent landform and the morphology of mantle top surface identified by various geophysical measurements. Furthermore, eight structural sub-regions could be divided in three regions by the limits of pre-Mesozoic blocks (Fig. 4). The evolutionary patterns vary in certain extent between the Mesozoic-Cenozoic basins located in different regions and even between those in different sub-regions of the same region. In China, above-mentioned Mongolia Arc occupies northern sub-region of the north region, northern and middle sub-regions of the middle region, named also as "Northwest Territory of China". This territory, north to the Kunlunshan-Qinling Mountains and west to Daxing'anling-Taihangshan Mountains, hosts most of known sandstone-type deposits in China except Qinglong ore-field and Chengzishan deposit. It could be divided into 4 domains and 13 sub-domains (Fig. 5). In the territory, known productive layers are attributed to $J_{1-2}$, $J_2$ and $K_1$.

*FIG. 4. Distribution of tectonic elements in China (Compiled with references to Li Chunyu, et al., 1982; Cheng Yuqi, et al., 1994; Wang Hongzren and Mo Xuanxue, 1996).*

*1) Siberian Plate, 2) Kazakhstan Plate, 3) Northeast Asian Plate, 4) Karakum-Tarim Plate, 5) Sinokorean Plate, 6) Yangtze-Qangtang Plate, 7) Turkey-Central Iran-Gondise Plate, 8) Southeast Asian Plate, 9) Indian Plate, 10) West Tectonic Domain, 11) Middle Tectonic Domain, 12) East Tectonic Domain, 13) Boundary between Plates, 14) Boundary between Tectonic Regions, 15) Strike-Slip Fault.*

Table II. Tentative ore deposit models and model series for sandstone-type U deposits.

| Model Series/Model | Principal Recognition Criteria | Examples |
|---|---|---|
| 1. Central Asia-South Texas Series: Hosts are large-scale tabular sandbodies, usually developed on the slope parallel to the long axis of the basin. Orebodies have a "C" shape with convex margin perpendicular to the long axis of the basin. | | |
| 1.1 Chu Sarysu-Syr Darya | Host sandstones were deposited in intracratonic basins poor in organic matter. Ore formation is closely related to the regional redox interface with a length of >200 km | Inkay, Uvanas and other deposits in South Kazakhstan |
| 1.2 Central Kyzylkum | The same as 1.1 with the exception that the ore formation is related to small-size local redox interface | Uchkuduk, Sugraly, Kyzylkum, Uzbekistan |
| 1.3 Yili | Host sandstones were deposited in post-orogenic strike-slip extension basins, enriched in organic matter. Ore formation is related to local redox interface | Kuji'ertai, Zajistan, North Xinjiang, China |
| 1.4 South Texas | Host sandstones were deposited in continental marginal environments with lack of organic matter and syn- and dia-genetic pyrite. Ore formation occurred after the introduction of extrinsic sulphide | Rosita, Rhode, Ranch, Texas, USA |
| 2.Wyoming Series: Hosts are moderate/small sandbodies forming a wide ribbon, deposited in compressive foreland intermontane basins. They are distributed from the basin margin inwards perpendicular to its long axis. Ore bodies occur discontinuous along curvilinear redox interfaces at the front end of alteration (oxidation) tongues developed on both margins of ribbon-shaped sand bodies. | | |
| 2.1 Shirley | U-bearing basins are the so-called "arid" basins, lacking lacustrine and deltaic deposits with a few turfs at the bottom of the basin filling sequence | Deposits in Shirley Basin and Wind River Basin, Wyoming, USA |
| 2.2 Powder River | The same as 2. 1 with the exception that the deposits occur not only in Paleocene (in the southern part) but also in Eocene (in the northern part) | Highland and Smith Ranch in southern part, and Christensen Ranch in northern part, Powder River Basin, Wyoming, USA |
| 2.3 Great Divide-Turfan | U-bearing basins are well-developed "humid" continental basins. U concentrations occur within the transitional areas between alluvial-fan and fluvial system where uraniferous sandstone is intercalated with discontinuous coal, mudstone or siltstone | Crooks Gap, Sweetwater, Great Divide Basin, Wyoming, USA. Shihongtan, Turfan-Hami Basin, N.Xinjiang, China |
| 3. Grants series: Host sandstones were deposited as channel fills within a large-scale humid alluvial fan, containing plenty of organic matter. Uranium is primarily closely connected predominantly with humate | | |
| 3.1 Grants-Primary ore | Ore colour is of dark grey to black. U was concentrated together with carbon during diagenesis to form blanket and elongated tabular ore bodies, and during early (pre-fault) oxidation to form roll-like ore bodies with quite wide limbs. | Most deposits in the Grants Uranium Region, Colorado Plateau, USA. Kharat, Mongolia. Nuheting, Inner Mongolia, China |
| 3.2 Grants-Redistributed ore | Ore colour varies from dark brownish grey to light grey. U was redistributed, separated from carbon on the basis of pre-existing ore during later (post-fault) oxidation. Ore bodies have the form of a roll or occur stacked along faults. | Church Rock, Crownpoint, Grants Uranium Region, Colorado Plateau, USA. Dongsheng Area, Ordos, China |
| 4. Siberia-Bohemia Series: U concentrations occur in, on, and/or adjacent to, detrital plant debris within channel sandstone. The sandstones were deposited under low-stand conditions, located at the bottom of the basin fill. Ore bodies are lens-like or tabular, less frequently having a form of an elongated roll. The roll-shaped ore bodies were developed from both flanks of the belt-like sandbodies with the convex margins directing inwards, seldom forming X-shape as a twin combination. | | |
| 4.1 West Siberia | U-hosting sandstones are distributed within incised valleys, developed on a plain. The sandstones eroded into either basement or underlying depositional sequences. Ore bodies are n km long, 50 m to n×100 m wide and 1-10 m thick | Dalmatovskoye, Trans-uralsk; Malinovskoye, SE part of W Siberia, Russia. |
| 4.2 Trans-baikal-West Yunnan | U-hosting rocks are distributed in tributary valleys, converging into valley basins that are formed on uplifting highland. The sandstones are confined to Neogene-Quaternary age due to erosion, underlain unconformably by the basement (granitic rocks). Ore bodies are a few km long, n×10 m to 400 m wide and up to 20 m thick. | Khiagda, Trans-baikal, Russia. Ningyto-Toge, Japan. Chenzishan, W Yunnan and other deposits and occurrences in Inner Mongolia, China |
| 4.3 North Bohemia | U-hosting rocks are distributed in the lower parts of Mesozoic marine sequences, consisting of alluvial-fan-fluvial-lacustrine conglomerates, sandstones, siltstones, mudstones and littoral quartzose sandstone containing rutile, monazite, zircon. Ore bodies have the shape of a lens and a flat flag. The mineralization age of 24 Ma to 74 Ma roughly corresponds to the age of Tertiary basaltic magmatism. | Hamr, Straz, Czech Republic.<br>Koenigstein, Germany |

*FIG. 5. Tectonic delimitation of Mesozoic-Cenozoic basins in Northwest Territory of China (Compiled with references to He Dengfa, et al., 1999; Ji Rangshou, et al., 2000; Ren Jishun, et al., 2000).*
*1) Sedimentary basin, 2) Caledonian suture zone, 3) Hercynian suture zone, 4) Indo-Sinian suture zone, 5) Yenshanian suture zone, 6. Thrust zone, 7) Basin domains and their number.*
*I. Junggar-Tarim Domain: $I_1$: Junggar Sub-domain; $I_2$: Tienshan Sub-domain; $I_3$: Tarim Sub-domain;*
*II. Altun Domain: $II_1$: Badain Jaran Sub-domain; $II_2$: Beishan Sub-domain;$III_3$: Dunhuan Sub-domain;*
*III. Alxa–Qaidam Domain: $III_1$: Alxa Sub-domain; $III_2$: Corridor Sub-domain; $III_3$: Central Qilian Sub-domain; $III_4$: Qaidam Sub-domain;*
*IV. Eren-Ordos Domain: $IV_1$: Eren-Hailar Sub-domain; $IV_2$ Yingshan Sub-domain; $IV_3$: Ordos Sub-domain.*

The Junggar-Tarim Domain borders on the east of Chu Syr Darya-Kyzylkum Domain of Middle Asia and on the west of Altun strike-slip fault system, having a relative high uranium endowment. The domain is composed of 3 sub-domains as shown in Figure 5. The Tianshan Sub-domain includes the Yili Basin that is well known for the discovery of the Kuji'ertai and Zajistan deposits. The sub-domain was involved by post-orogenic strike-slip extension and consists of a group of intermountain basins. Recently, exploration was also implemented at Kumishi Basin situated to the east of the Yili Basin. The Junggar Sub-domain includes the Junggar, Turfan-Hami, Buerjin and other relatively small basins around the Junggar Basin. Shihongtan is a newly discovered deposit located at the southwestern margin of the Turfan-Hami Basin. A certain amount exploration work has been done in the Junggar Basin with attention to $J_{1-2}$ and K strata but no commercial deposit has been found so far. It is supposed that Paleogene sediments may be more promising than $J_{1-2}$ in the northern Junggar Basin (Dingshan Area) and the Buerjin Basin where a low-angle southwards-dipping slope was developed during Paleogene period from the Altay Mountains (northern boundary mountain for the Junggar Basin), upon which favorable, alternating sand-pelitic sediments were deposited. The Tarim Sub-domain contains the only basin of the same name that covers an area of 560,000 km$^2$. This is a hydrocarbon-bearing basin and U-promising areas are known in its northern part where Bashibulak deposit was found in $K_1$ melanocratic bituminized sandstone-conglomerate, and in its northeastern part where Kongque River low-angle slope as a target area developed on the south edge of Kuluketak Precambrian massif. The Altun Domain has its name from Altun sinistral strike-slip fault system. This fault system was active since the Jurassic with highest intensity in Early Cretaceous. No drilling program has been conducted specially for uranium there. The domain consists of 3 sub-domains (Fig. 5). The Dunhuan Sub-domain, NE-striking, comprises the Dunhuang and two other basins. The Dunhuan Basin is developed on a stable Precambrian massif and is filled with Jurassic coal-bearing clastic rocks. The sediments are less deformed and show a certain potential for uranium exploration on its northern low-angle slope. The Beishan and the Badain Jaran sub-domains occur within a Late Palaeozoic fold belt that was intensely overprinted by early Yanshan orogenic movements so that the Jurassic coal-bearing clastic rocks are deformed and lost exploration value. The Beishan sub-domain is located at the site where the Altun fault system turns from NE- to EW-trending. It includes 8 small-sized intermountain basins, such as the Gongpoquan, the Zongkezi, and so on. The sub-domain was uplifted for a quite long time since the end of $K_1$ with omission of $K_2$-$N_1$ deposition so that Lower Cretaceous productive layers are relatively shallow-buried. A testing drilling program for uranium will be conducted soon in the Gongpoquan Basin where drilling for coal revealed several sections of U-mineralised sandstone. The Badain Jaran Sub-domain, generally EW-striking, is presented by a medium-sized basin filled with J-E sediments of more than 4000m in thickness, covered mostly by desert deposits. This sub-domain is considered to be relatively less productive. The Alxa-Qaidam Domain consists of 4 EW-trending sub-domains from north to south: the Alxa, the Corridor, the Central Qilian and the Qaidam. It is indicated that the deformation of $J_2$ and $K_1$ productive layers is getting more intense southwards due to northward push of Indian Plate. The Alxa Sub-domain includes the Huahai-Jinta, Chaoshui and Yabulai basins that were developed on the basis of Alxa Precambrian massif (a western extension of Sino-Korean Continental Block). The Chaoshui Basin has been selected for prospecting with special attention to the north monocline (Taobei Slope) where several low-grade sandstone- and coal-type U deposits/occurrences were discovered in $J_2$ and $K_1$ clastic rock formations during the 1950s-1980s. The Corridor Sub-domain, a lowland corridor between the Longshoushan-Alagushan Mountains and the Qilianshan Mountains, is a transitional element between Sino-Korean Continental Block (platform) and Qilian Fold System. This sub-domain includes the West Jiuquan, East Jiuquan and Minle basins. A preliminary study shows that Tertiary tectonism is relatively intense but heterogeneously developed (milder in the East Jiuquan and Minle basins, especially at their northern slopes). Of them, the East Jiuquan shows certain perspective for U exploration in the Hongyaogou depression at its northern margin where $K_1$ sandstone is distributed within an incised valley. The Central Qilian Sub-domain includes a series of medium/small intermountain basins that were formed during the Tertiary. No systematic reconnaissance has been done in this sub-domain. The Qaidam Basin, the only basin in the Qaidam Sub-domain, is oil-bearing, but not favourable for uranium exploration due to a thickness of more than 10,000m in response to a marked subsidence during the Tertiary and Quaternary. The Eren-Ordos Domain was developed on different pre-Mesozoic tectonic elements, the Eren-Hailar Sub-domain on Hercynian fold-belts of the Kazakhstan Plate, the Yingshan Sub-domain on the marginal Hercynian fold-belt (Inner Mongolian Axis) of the Sino-Korean Plate, and the Ordos Sub-domain on the Sino-Korean Continental Block of the Sino-Korean Plate. The Mesozoic sedimentary history is similar for the Eren and Yingshan sub-domains; it is characterized by folded $J_{1-2}$ coal-bearing clastic rock series, appearance of volcano-clastic rocks in $J_3$, and well-developed $K_1$ coal-bearing clastic rock series. The evolution is different, however, during the Tertiary since the Yingshan basins are a group of intermountain basins essentially formed during the Tertiary. Some sandstone-type U deposits are known in Cretaceous sediments of the Eren Basin, such as Nuheting and Subeng ($K_2$, tabular), and Bayantala ($K_1$, basal-channel), while the Yingshan basins contain uranium occurrences and showings mainly in Tertiary channel-filling sandstones. Therefore, the productive host sandstones are different in ages in the above-mentioned two sub-domains. The Ordos Sub-domain includes the Ordos Basin covering about 250,000 km$^2$ and a series of "satellite" basins around it. Continental sedimentation started in the Ordos Basin at the end of the Permian. The Ordos Basin was an intracratonic basin, and became a foreland basin during $T_3$ with foredeep at the west margin. During $J_{1-2}$, tectonic activity weakened and the basin was turned into successive subsidence with development of incised valleys between $T_3$ and $J_1^1$, $J_1^1$ and $J_1^2$, $J_1^2$ and $J_2^1$. The Early Yanshanian orogeny caused a large-scale uplift by the end of Middle Jurassic. Afterwards, extension occurred in Early Cretaceous associated with widespread alluvial fan, fluvial and lacustrine, and locally eolian deposits. At the end of Cretaceous, the basin was completely uplifted as a plateau followed by the formation of several Miocene grabens on its north, west and south edges. Obviously, the Mesozoic-Cenozoic evolution of the Ordos Plateau in many respects is similar to the Colorado Plateau. A few productive strata were identified, including Triassic ($T_1$ and $T_3$), Middle Jurassic (Zhiluo Fm.) and Lower Cretaceous strata. It is reported that the Dongsheng U-mineralised area was discovered at its northern margin in 1999. The host rocks are channel-filling sandstones of Zhiluo Fm. that forms a large-scale alluvial fan. A certain perspective is also indicated in the north-western Ordos Basin where Lower Cretaceous alternating sandstone-mudstone beds occur in an optimal ratio and contain radioactive anomalies.

## 4. Simplified description of selected ore deposits [15]

### *4.1. Kuji'ertai Deposit: roll sub-type, hosted in tabular sandbodies of $J_{1-2}$ coal-bearing clastic sediments* [5]

The deposit lies in the territory of Yining City, Xinjiang Autonomous Region. It occurs at the southern margin of the Yili Mesozoic- Cenozoic Basin that was developed on a Carboniferous-Permian folded basement. The deposit covers about 60km$^2$, 12km in length and 5 km in width, and consists of a north, middle, and south ore (U-mineralized) zone (Fig. 6). The basin fill comprises Middle-Upper Triassic, Lower-Middle Jurassic (Shuixigou Group), Cretaceous, Tertiary, and Quaternary sediments. Host sediments are attributed to the Shuixigou Group that forms a northward inclined monocline with dip angles of 5°-7° and contains 8 depositional cycles. Roll ore bodies are discovered in the 5th cycle of a braided delta system characterized by reverse graded bedding. The cycle obtains a sand-mud ratio of about 1-2 and has an organic carbon content of 1.12%. Host sand bodies are 20km long, more than 2km wide and 10-25m thick. Roll head of ore bodies is about 50-150m wide and 5-10m thick, and averages 0.05% U. Two wings of the roll are 200-400m wide from the south to north and 1-2m thick and grade 0.05-0.1% U in average. A few tabular-shaped ore-bodies occur in the 1st-3rd cycles of an alluvial fan-braided fluvial system with sand-mud ratios of 2-3 and an organic carbon content of 0.29%. Tabular ore bodies have a thickness of about 1-2m and a uranium content of 0.05%-0.1% U. Ore-hosting rocks are quartzose sandstone, feldspar (kaolin) sandstone with some volcanic debris, sandy conglomerate, etc. Alteration is well developed and shows a down dip zoning from intensely altered sandstone, brown yellow-colored, with high hydro-goethite content; to weakly altered sandstone, yellow/light yellow-colored with hydro-goethite content of about 6.5%; to the redox front where ore bodies are located, gray colored, with the association of hydro-goethite and pyrite; and to dark gray-colored unaltered sandstone. Uranium occurs as uranium minerals as well as adsorption in the cement of sandstone and sandy conglomerate. Uranium minerals include pitchblende (about 80%) and coffinite (about 20%), seldom brannerite, and U-Ti-bearing magnetite. Pitchblende is associated with pyrite. Adsorbed uranium is associated with coal debris and pyrite. There are a series of associated elements, such as Se, Ga, Sc, Re, V, etc., in ore bodies. Se is mainly distributed in weakly altered sandstone while the others are concentrated together with uranium in the redox front.

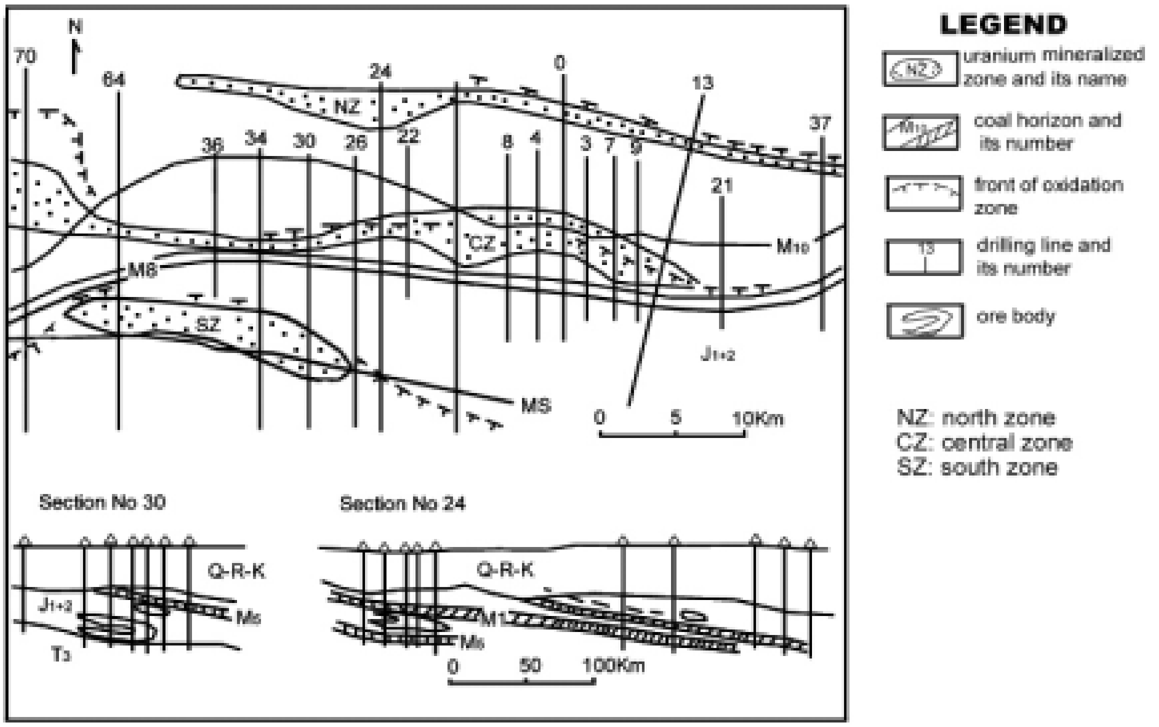


*FIG. 6. Sketch geological plane and sections showing the distribution of uranium mineralized zones and ore bodies in Kujie'ertai Deposit (After Gu Kengheng, et al., 1996).*

### 4.2. Shihongtan Deposit: roll sub-type, hosted in wide ribbon-shaped sandbodies of $J_{2x}$ coal-bearing fragmental sediments

The deposit is situated in the territory of Turpan City, Xinjiang Autonomous Region, and occurs at the SW margin of the Turfan-Hami Basin. This is an EW-striking intermontane basin in a lowland with the elevation of -154.5m at Aiding Lake. It is the second lowest lowland in the world. The basin, developed on Late Carboniferous-Early Permian transitional structural layer, started as a foreland basin during $P_2$-T time. Shuixigou Gr. ($J_{1-2}$) was deposited under a post-compression relax regime. The deposit is located in the west section of Aiding Slope, and covers about 120km$^2$, 20km in length and 6km in width (Fig. 7). The strata form a shallow -dipping monocline with a dip angle of 4º-10º, locally with a NNE-NE-trending nose-shaped swell where the Shuixigou Gr. is exposed on the surface (Fig. 8). The Shuixigou Gr. is divided into 3 formations, from the bottom to the top: the Badaowan Fm. ($J_{1b}$), the Sangonghe Fm.($J_{1s}$), and the Xishanyao Fm.($J_{2x}$). Host sediments are mainly attributed to $J_{2x}$ that is further subdivided into three members from the bottom to the top: the lower ($J_{2x}^1$) of braided fluvial system, the intermediate ($J_{2x}^2$) of meandering fluvial-delta system, and the upper ($J_{2x}^3$) of rejuvenated braided fluvial system. Firstly discovered ore bodies are hosted in a $J_{2x}^1$ proximal braided fluvial zone, that trends northwards perpendicular to the long axis of the basin. U-mineralized holes are mostly distributed along the east flank of the Shihongtan nose-formed swell. Ore bodies are of roll shape with a NE-ward-directed convex margin. Roll head is about 4-8m thick and 50-150m in length. Tabular ore bodies have a thickness of about 2-6m and a length of 100-500m.

Host rocks are mostly arkose, minor lithic sandstone. Similar to Kuji'ertai Deposit, hydrogoethitization alteration zoning is also down dip well developed as:

(a) Brown-yellowish–colored, intensely altered sandstone with $Fe^{3+}/Fe^{2+}$ >3.0 and $C_{org.}$ = 0.08%;
(b) Light yellow and variegated red-colored, weakly altered sandstone with $Fe^{3+}/Fe^{2+}$ = 1.5-3.0 and $C_{org.}$ = 0.08%-0.72%;
(c) Deeply gray/gray/grayish white-colored mineralized sandstone at redox front with $Fe^{3+}/Fe^{2+} \cong 0.50$ and $C_{org.} \cong 57\%$;
(d) Gray/light gray-colored unaltered sandstone with $Fe^{3+}/Fe \cong 0.34$ and $C_{org.} \cong 0.26\%$. Uranium is present in both uranium minerals (about 50%) and adsorption (about 50%).

Uranium minerals include mainly pitchblende, and minor coffinite and uraniferous Ti-Fe oxide. Pitchblende is usually associated with pyrite while coffinite occurs either on the surface of pyrite or in association with pitchblende and quartz. Uraniferous Ti-Fe oxide seems to be an alteration product of leucoxene or ilmenite. Absorbed uranium is closely related to clay minerals, powdery pyrite and carbon debris. Ore grade is 0.035%U in average. Associated elements include Mo, Se, Re, Ga, and Se. Based on whole rock Pb-isotopic analysis of 14 ore and rock samples, U-Pb isochron ages have been obtained as 104Ma, 24Ma and 7Ma, corresponding to late Early Cretaceous, the end of Oligocene and late Miocene respectively.

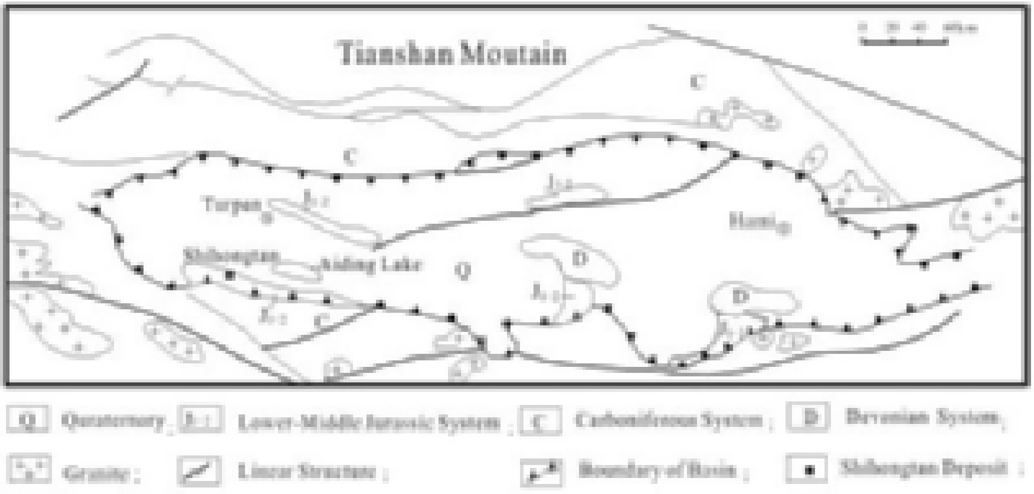


FIG. 7. Schematic geological map of Turfan-Hami Basin (After Wang Jinping, et al., 2002).

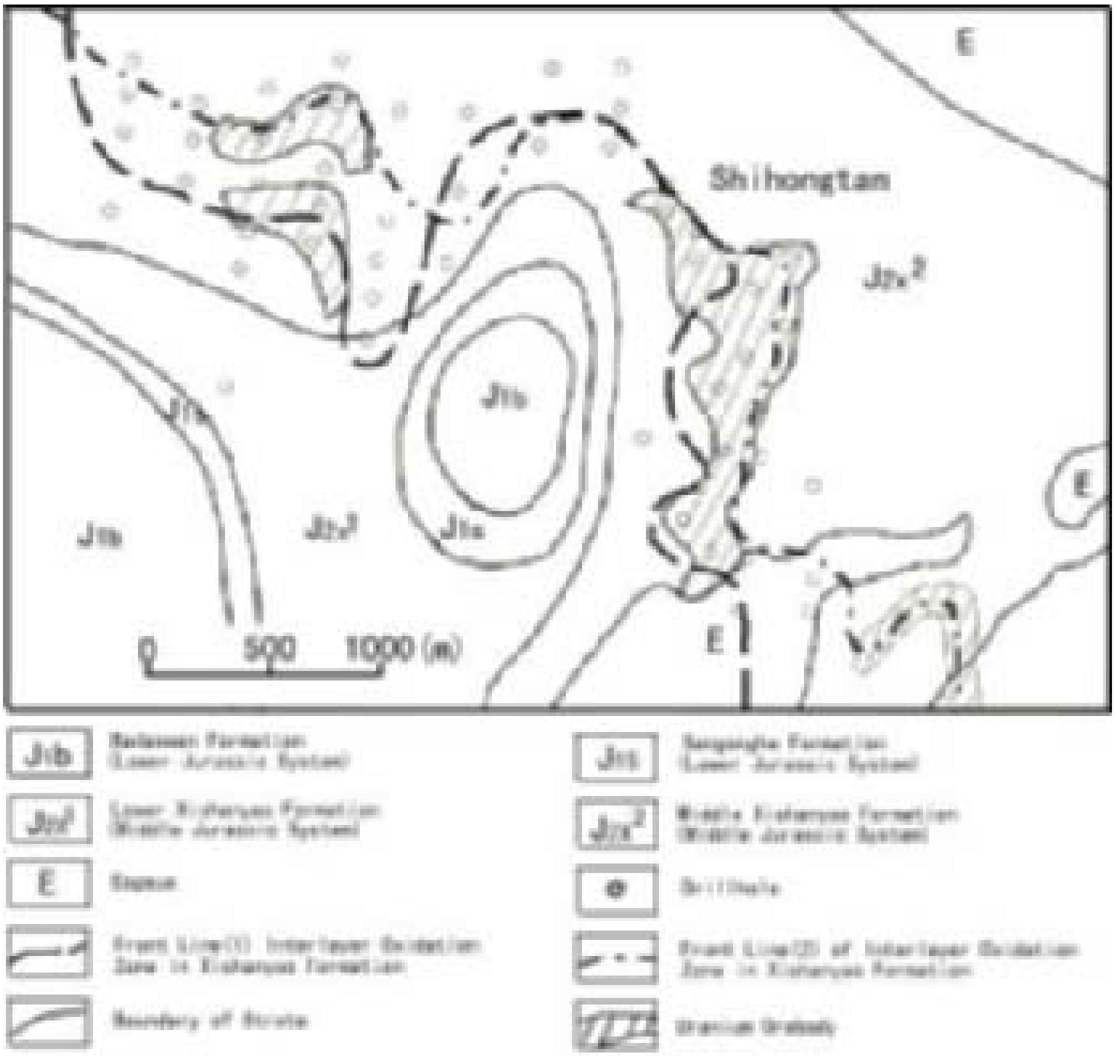


FIG. 8. Schematic map of Shihongtan uranium deposit (After Wang Jinping, et al., 2002).

### *4.3. Dongsheng uranium–mineralized Area: tabular sub-type, locally with re-distribution of uranium, hosted in ribbon-shaped sand bodies of $J_{2z}$ gray fragmental sediments*

This area is situated at the northern margin of Ordos Basin, in the territory of Ordos City, Inner Mongolian Autonomous Region. The U-mineralized area covers an area of more than 200km$^2$. Mesozoic-Cenozoic Erathem includes Upper Triassic Yanchang Fm. ($T_{3y}$), Lower Jurassic Fuxian Fm. ($J_{1f}$) and Yan'an Fm. ($J_{1y}$), Middle Jurassic Zhiluo Fm. ($J_{2z}$), Lower Cretaceous Dongsheng Fm. ($K_{1d}$), Pleistocene ($N_2$) and Quaternary (Q). The Zhiluo Fm. ($J_{2z}$) is further subdivided into 3 members, the lower ($J_{2z}^1$) of braided fluvial system, the intermediate ($J_{2z}^2$) of low sinuosity meandering fluvial system and the upper ($J_{2z}^3$) of high sinuosity meandering fluvial system. $J_{2z}^1$ is the host member that was formed in NNW-striking proximal braided fluvial zones, possibly within a large-scale humid alluvial fan when the northern part of the basin underwent regional uplifting. The zones were eroded into underlying coal-bearing fragmental rocks, filling a group of incised valleys. During $J_{2z}^2$ and $J_{2z}^3$, the uplifting of the northern part weakened and subsidence–sedimentation predominated. Meanwhile, NNW-ward valleys were turned into NE-ward sags due to compression from SE direction. It is indicated that waters of $J_{2z}^1$ sandbodies remained in hydrological connection with surface waters after covering of $J_{2z}^2$ and $J_{2z}^3$ because intercalated impermeable mudstone layers are discontinuous. As a result, the waters of $J_{2z}^1$ sandbodies were locally oxidizing and locally reducing, depending upon the distribution and influence of indigenous organic debris, and the fluctuation of water table. In such environment, first-stage uranium mineralization widely occurred with formation of tabular ore bodies at the bottom of sandbodies (Fig.9). At the end of Early Cretaceous, the area was uplifted again, even more intensely. The $J_{2z}^1$ sand bodies were denudated and exposed on the surface. In this time, a EW-striking redox front was formed with a length of 40km and pre-existing tabular ore bodies were locally reworked and turned into roll shape at a few sags (Fig.10). The ore-forming process ceased in late Early Cretaceous when $K_{1d}$ was deposited and the hydrological connection between waters of $J_{2z}^1$ sandbodies and surface waters was cut. This inference is proved by a mineralization age of 107.14Ma.

Three U-mineralized sections have been discovered discontinuously along the EW-striking redox front by reconnaissance drilling so far. They are 15km long in total. Ore bodies are several tens to one hundred m long, 1-20m thick and have ore grades of 0.033%U in average. Host rocks consist mainly of altered, gray/light gray colored coarse/medium-grained feldspar-quartz sandstone, and minor fine-grained sandstone. Color of altered sandstone is quite variable. Yellow-colored rocks are widespread on the surface, being product of oxidation. However, only blue/dark green-colored altered sandstone occurs on the up-gradient sides of U-mineralized sandstone as observed in drill cores. The detailed investigation shows that blue/dark green–colored altered sandstone contains relic debris of red-colored altered sandstone indicating early-stage oxidation, and the green-coloration is possibly caused by the presence of Ni-bearing chlorite and/or clinochlore. Therefore, it is assumed that the blue/dark green–colored altered sandstone might reflect secondary reduction of red colored, early-stage oxidized sandstone due to introduction of hydrocarbon gas from underlying gas reservoir; the red colored, oxidized sandstone, located primarily on the up-sides of regional redox fronts, may be related to the ore-forming process. Of course, the absence of red-colored and/or yellow-colored sandstones in the drill cores may raise doubts about the reality of regional redox front and roll-shaped ore bodies. Much about mineralogy and geochemistry of alteration remains unknown and needs to be clarified in the future, nevertheless.

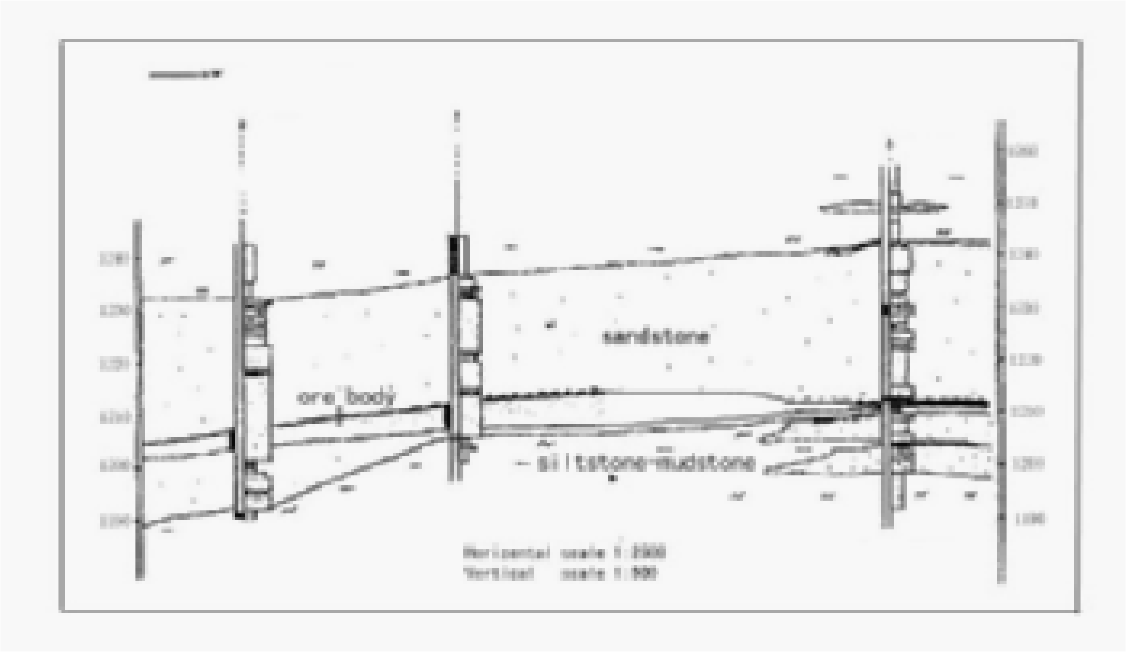


*FIG. 9. Schematic profile showing tabular-shaped ore body in Zhiluo Fm. ($J_{2z}$) at Shashagetai Section, Dongsheng U-mineralized Area (Collected from Geological Team No. 208, 2001).*

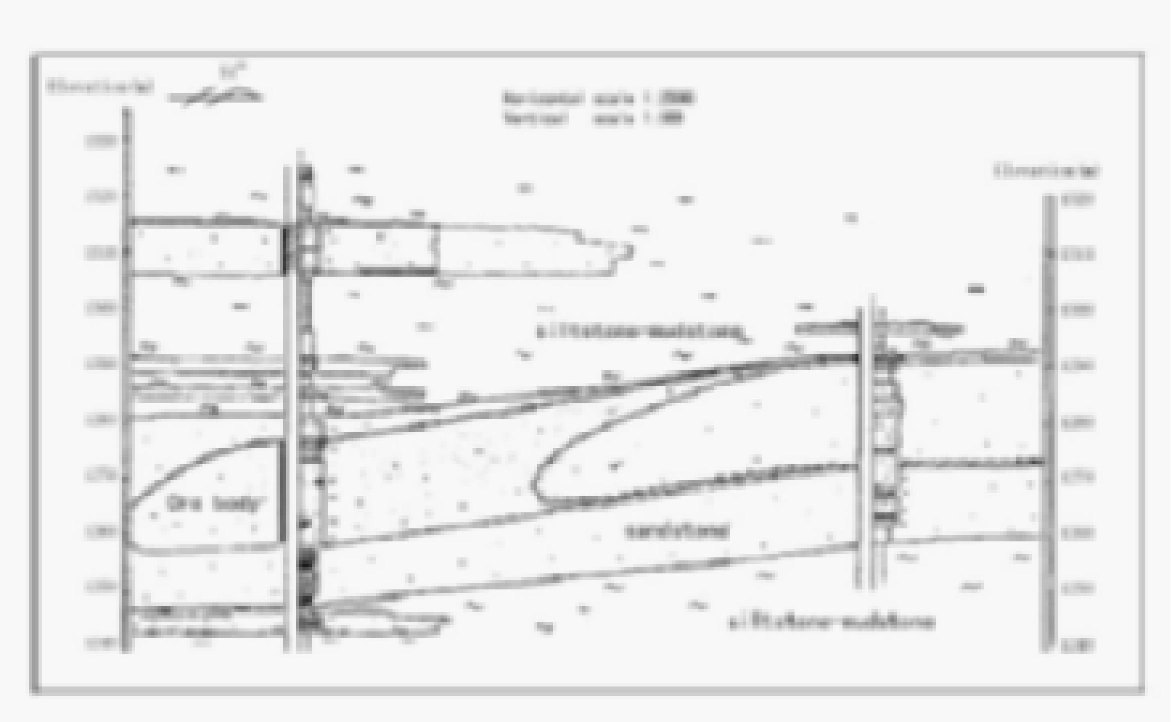


*FIG. 10. Schematic profile showing roll-shaped ore body in Zhiluo Fm. ($J_{2z}$) at Sunjianliang Section, Dongsheng U-mineralized Area (Collected from Geological Team No. 208; 2001).*

### 4.4. Nuheting Deposit: tabular sub-type, hosted in tabular-shaped sandbodies of $K_{2e}^{1}$ gypsum-bearing fragmental sediments

This deposit is located in the territory of Erenhot City, Inner Mongolian Autonomous Region and occurs in the Erennaoer depression at the northern margin of the Eren basin. The depression contains oil-source bed and reservoir in Lower Cretaceous sediments and uranium in the Upper Cretaceous Erendabusu Fm. ($K_{2e}$). At the deposit, the lower member of the upper Cretaceous is named sandstone member ($K_{2e}^{1}$), formed by a meandering fluvial system; and the Upper member is named mudstone member ($K_{2e}^{2}$), formed by a lacustrine system. Ore bodies are of lens and tabular shape. Ore grades range from 0.03%U to 0.1%U. The main ore body covers an area of 1.59-5.20km$^2$, and accounts for more than 90% of the total reserves. It is tabular-shaped and located at the topmost position of the deposit, 5-12m below the ground surface and 0.5-7m below the bottom of the mudstone member (Fig.11). The thickness of this ore body varies within the range of 0.7-1.3m. Below the main ore body there are more than 10 sporadically distributed small ore bodies. Host rocks consist of mudstone and siltstone that account for 80% and fine-grained sandstone for 20%. The ore, gray and grayish black-colored, contains considerable amount of pyrite, goethite, gypsum, carbonate minerals and carbonized plant debris. Uranium is mostly adsorbed in clay minerals.

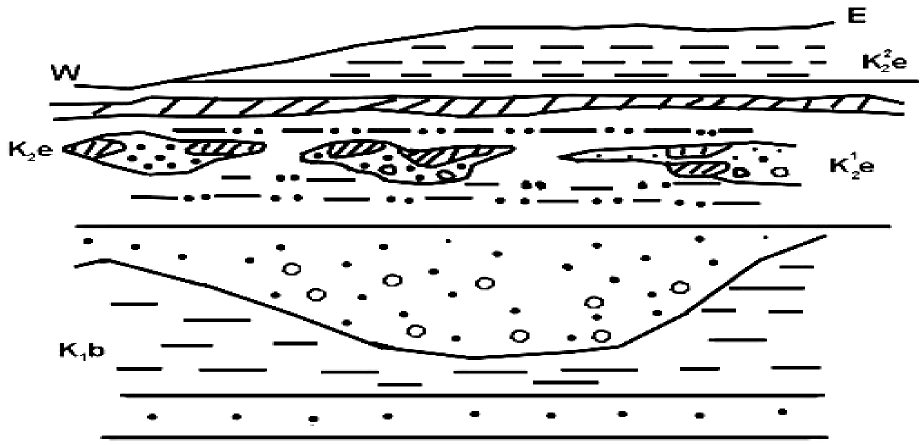
### 4.5. Bayantala Deposit: basal-channel sub-type, hosted in belt-shaped sandbodies of $K_{1bs}^{1}$ variegated fragmental sediments

The deposit lies in the territory Xianghuangqi County, Inner Mongolian Autonomous Region, and occurs at the eastern edge of the Bayantala sag, Tengge'er Depression, Eren Basin. The sag is 64 km long in NS-direction, and 7-15Km wide, developed on a Hercynian Fold-Zone and Mesozoic granite. At the sag, the Lower Cretaceous Banyanhua Gr. ($K_{1b}$) is wide spread. It includes the A'ershan Fm. ($K_{1ba}$) of an alluvial fan system, the Tengge'er Fm. ($K_{1bt}$) of a fan delta system and the Saihantala Fm. ($K_{1bs}$) of a fluvial system. The $K_{1bs}$ is further subdivided into 2 members: the lower ($K_{1bs}^{1}$) of a braided fluvial system, filling incised valleys; and the upper ($K_{1bs}^{2}$) of a meandering fluvial system. Host sediments are mostly attributed to the $K_{1bs}^{1}$ braided fluvial system (Fig.12). At Huhe Mineralized Section, lens-shaped ore bodies occur in $K_{1bs}^{1}$bluish gray or greenish gray pebbly sandstone, coarse- and medium-grained sandstone with intense smectitization and kaolinization. Ore bodies are 100-150m long and 6-12m thick (Fig.13). Ore grade is about 0.02%U in average. Besides, it is reported that uranium mineralization is discovered in sandbodies of the Tengge'er Fm. ($K_{1bt}$).

### 4.6. Chengzishan Deposit: basal-channel sub-type, hosted in ribbon-shaped sandbodies of Pliocene coal-bearing fragmental sediments

The deposit lies in the territory of Tengchong County, Yunnan Province, and occurs at the western edge of the Longchuanjiang Basin, close to the eroded outcrop of granitic basement. The basin covers an area of about 50km$^2$. The Middle Pliocene Mangbang Fm. ($N_2m$) includes 3 members, the lower ($N_2m_1$), middle ($N_2m_2$) and upper member ($N_2m_3$) (Fig.14). Host sediments are attributed to the middle member ($N_2m_2$) of an alluvial fan-braided fluvial–braided delta system. The member is sub-longitudinal- trending and dips eastwards with 5º-15º. Individual ore bodies are of tabular, lens and stacked shape (Fig.15). The lens-shaped ore bodies are hosted in deeply buried thin-bedded silty argillaceous beds enriched in organic matter and pyrite. The tabular and stacked-shaped ore bodies are 10m-160m long and 1- 8m thick and occur at shallow depth. Ore grade is 0.03%-0.1% U. Most ore bodies are hosted in sandstone, and uranium is mainly adsorbed on organic matter, pyrite and clay minerals, minor in form of pitchblende and secondary U minerals associated with pyrite, siderite and anatase. Isotopic determination of two pitchblende samples gave the ages of 4.4 Ma and 2.2 Ma.

11-A :Profile



11-B:colum

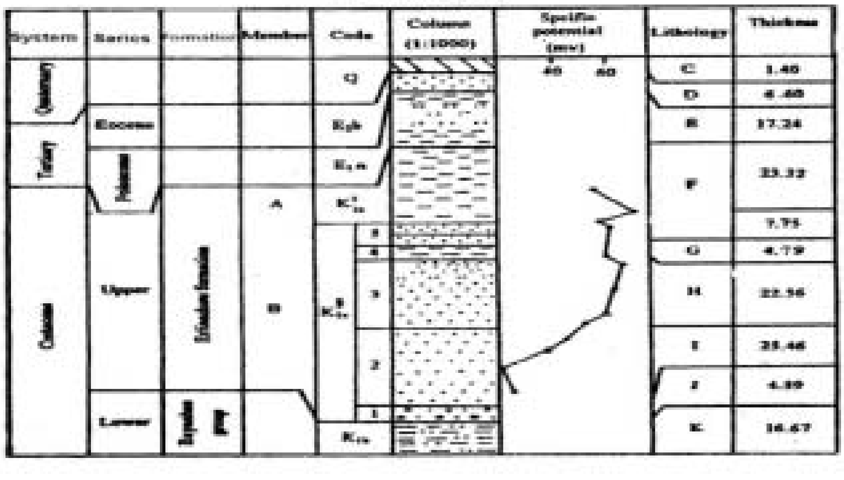


*FIG. 11. Schematic geological section and stratigraphic column of Nuheting deposit.*

*A) Mudstone Member, B) Sandstone Member, C) Clay, D) Mottled sandstone, red sandstone, E) Brown mudstone, siltstone, F) Grey mudstone, calcareous mudstone, gray black sandstone, siltstone, G) Grey black mudstone, H) Grey fine-grained sandstone with intercalations of siltstone, I) Grey-yellow gravel-containing coarse-grained sandstone, grayish yellow gravel-containing medium-grained sandstone, J) Variegated sandy conglomerate, K) Brick-red sandy and silty mudstone, variegated sandy conglomerate.*

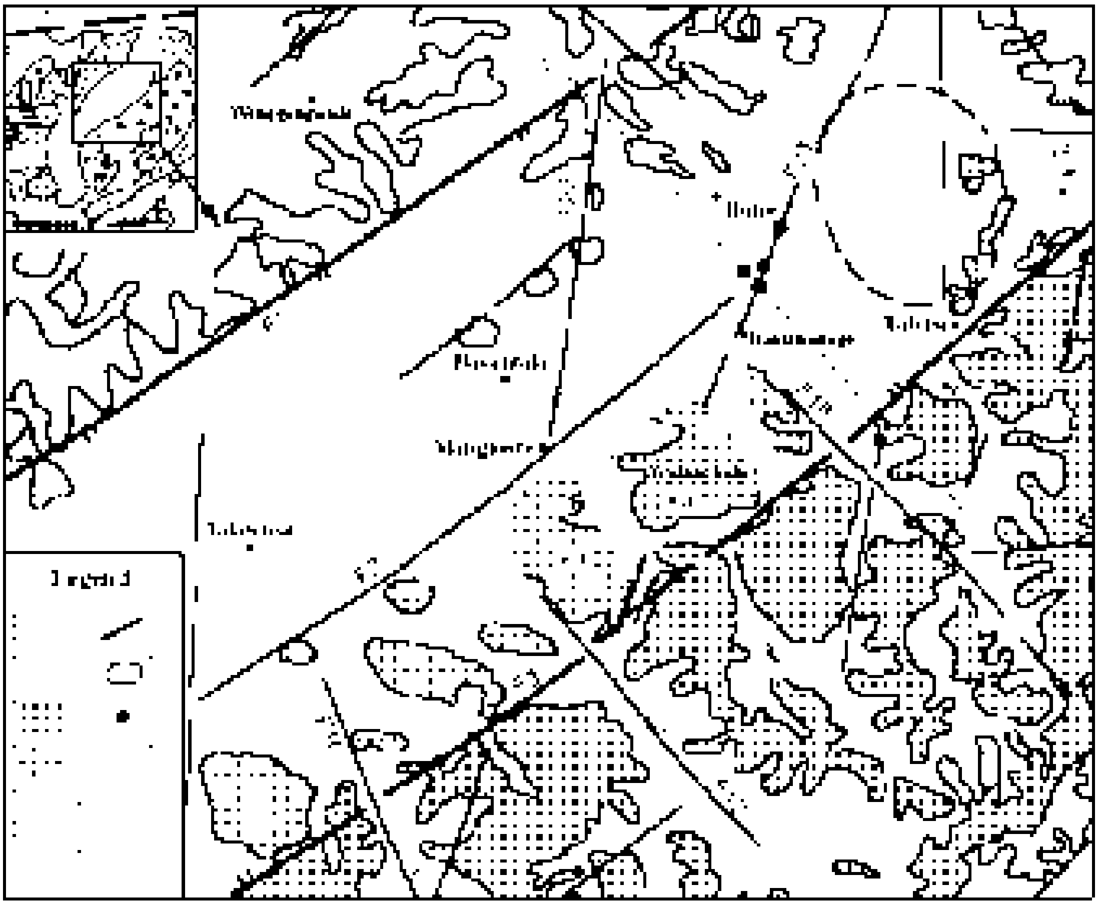


*FIG. 12. Schematic map showing distribution of braided system in Saihantala, Fm., north-eastern Bayantala Sag (Collected from Geological Team No. 208; 2001).*

*1) Lower Permian, 2) Upper Jurassic, 3) Mesozoic granite, 4) Bayanhau Group ($K_1b$), 5) Baogedewula Fm. ($N_2b$), 6) Pleistocene, 7) Faults interpreted by TM imaging, 8) Ring structure, 9) Mineralized hole, 10) Braided fluvial sediments.*

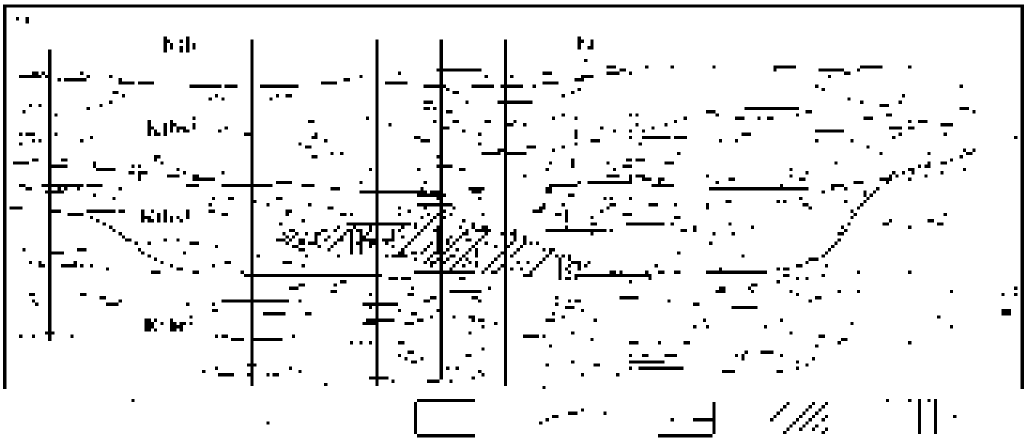


*FIG. 13. Schematic profile showing lens-shaped ore body at Huhe Section, Bayantala Deposit (Collected from Geological Team No. 208; 2001).*

*1) Sandy conglomerate, 2) Sandstone, 3) Siltstone, 4) Mudstone, 5) Stratum boundary, 6) Boundary of redox front, 7) Blue-colored alteration, 8) Uranium ore body.*

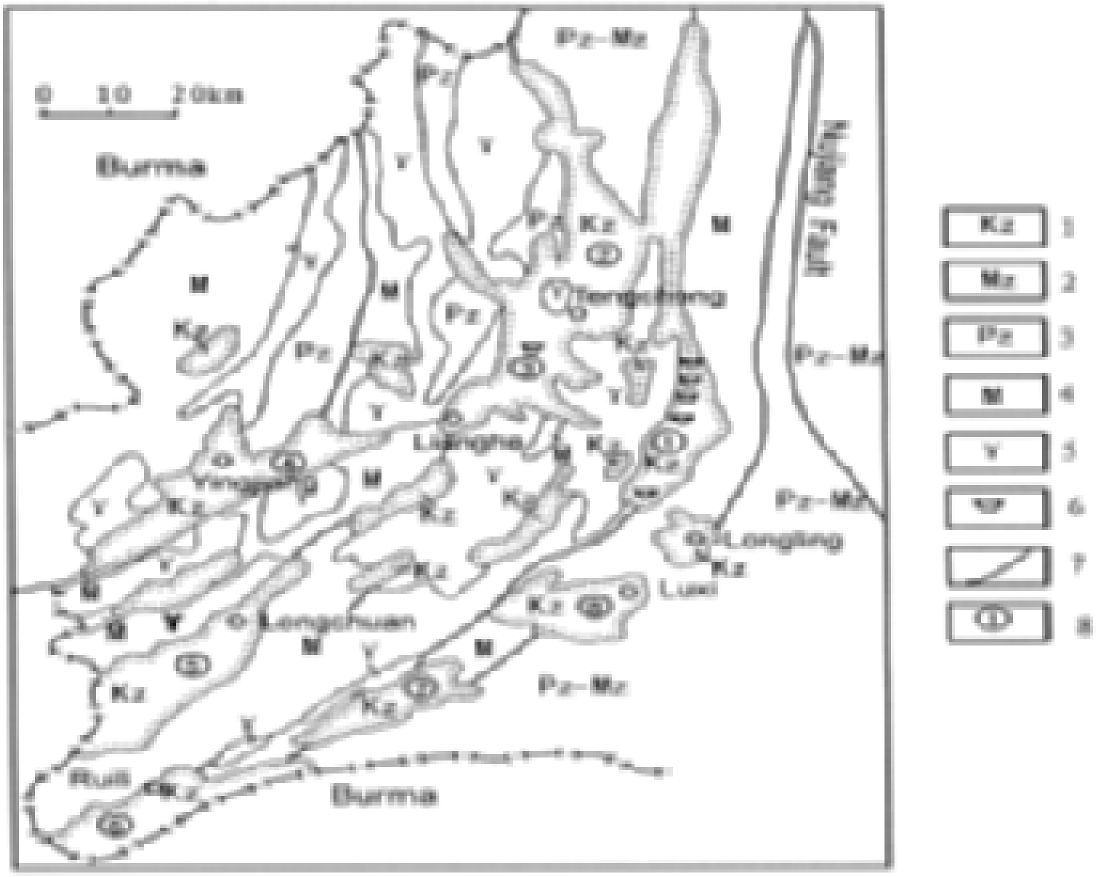


FIG. 14. Neogene basins and sandstone-type U deposits, Western Yunnan (After Chen Youliang et al., 2002).
1) Cenozoic Era, 2) Mesozoic Era, 3) Palacozolc Era, 4) Mid-proterozoic Era, 5) Granite,
6) Sandstone-type uranium deposit, 7) Fault,
8) Main basin and number: (1) Longchuanji-ang basin, (2) Tengchong basin, (3) Lianghe basin, (4) Yingjiang basin, (5) Longchuan basin, (6) Ruili basin, (7) Zhefang basin, (8) Nuxi Basin.

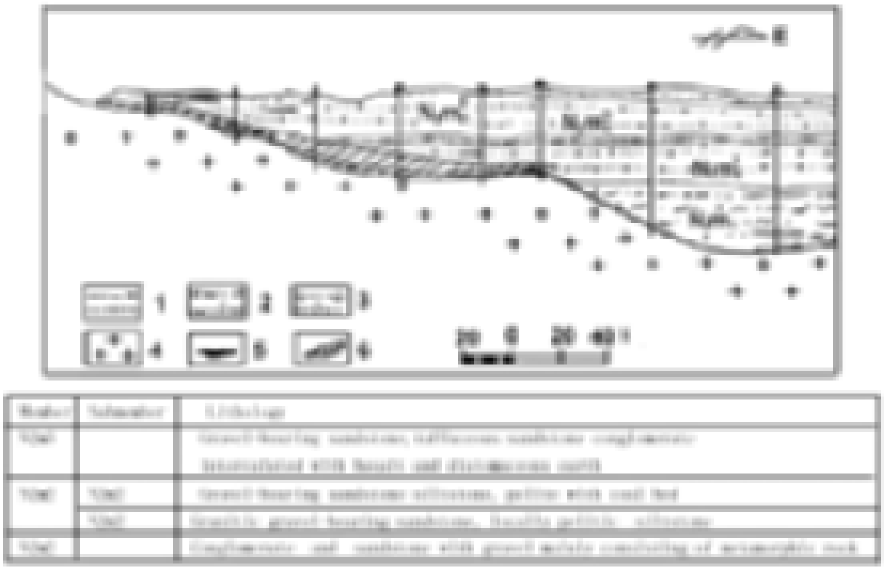


FIG. 15. Schematic Litho-stratigraphical section of Chengzishan Deposit, Western Yunnan (After Geological Team No. 209, 1985).

## 5. Conclusion and acknowledgments

ISL-amenable sandstone-type uranium deposits are actually an economic-technical type, established after successful mining by ISL technology in a series of countries rich in sandstone-type uranium resources. A considerable part of sandstone-type uranium deposits in southern Kazakhstan are known to contain “large tonnage-low grade ore reserves hosted in soft and water-saturated rocks” that are difficult and/or economically unavailable to mine by traditional underground extraction methods. In this field, ISL technology shows its particular vitality. The question is, how to recognize best deposits amenable to ISL mining in order to promote exploration and mining of sandstone-type U deposits. A logical approach would be to formulate an improved and comprehensive classification especially for sandstone type uranium deposits amenable to ISL mining. As known, most ISL-amenable deposits are of roll sub-type and as pointed out by Russian geologists, some of basal-channel (or valley) sub-type deposits might be amenable to ISL mining as well. Besides, the Crownpoint and Churchrock U deposits, New Mexico, which are considered for ISL mining indicate that a few of tabular sub-type deposits may also be feasible for ISL mining. On the other hand, there are some distinct differences between deposits of the same sub-type. For example, roll-sub-type deposits in Wyoming are obviously different from those in the Chu Sarysu-Syr Darya, Central Kyzylkum, and Yili basins in tectonic settings, scale and shape of host sandbodies and their depositional environment, as well as in the occurrence of ore bodies, including the direction of the convex margin of rolls and the relation to basin strike. A similar situation is valid for the basal-channel sub-type: deposits of Trans-Ural and West Siberia occur at the margin of a large-scale cratonic basin where the tectonic regime has been relatively stable with low-amplitude regional uplift since the deposition of host sediments. The host sediments are of Late Jurassic and younger age. In comparison, deposits of Vitimsk and western Yunnan are distributed in Cenozoic valley basins on a continuously uplifting plateau/highland where the tectonic regime is relatively mobile and host rocks are overlain by basalt or a similar competent cover. These host sediments are not older than Neogene as pre-Neogene sediments must have been denudated. So, it seems reasonable to establish ore deposit models and model series, providing guidelines for exploration.

As shown above, a series of ISL amenable sandstone type deposits have been discovered in China, especially in the Northwest Territory of China. This territory, which has seen only minor exploration in the past, remains highly perspective for the discovery of U deposits.

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# Characteristics of uranium mineralization and depositional system of host sediments, Bayantala Basin, Inner Mongolia Autonomous Region

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**Abstract.** Based upon the research of basin fills at the Bayantala basin, the genetic facies of host sediments have been ascertained and the target beds and their range are delineated. The sand bodies of the Upper Member of Tengge'er Fm deposited in fan delta front is favorable to the formation of uranium mineralization of phreatic-interlayer oxidation. The Saihantala Fm deposited in fluvial system can be divided into Lower Member and Upper Member based on depositional microfacies and paleoclimate. The Lower Member of braided system is the most important target bed enriched in organic matter where basal-channel-type uranium mineralization occurs. Features of alteration and mineralization suggest that the early-stage and the late-stage uranium mineralization are related to phreatic oxidation and interlayer oxidation (roll-type) respectively. Meanwhile, the secondary reduction has superimposed over the earlier mineralization in the area caused by hydrocarbons raising along faults.

**Key words**: Bayantala basin; Braided fluvial system; Fan delta system; sandstone uranium mineralization.

## 1. Introduction

Bayantala basin, located on Wenduermiao uplift, is tectonically one of sub-units of southern margin of the Eren Basin Group. A series of explorations for in-situ leach (ISL) sandstone uranium deposit has been carried out (Geological Party No. 208, 1998-2001; Chen, 1998; Chen, 1997, Chen et al., 1999) [1,2,3]. So far, some prospective reserves have been explored in this area. Basal-channel sub-type of sandstone-hosted U mineralization [5], as explored in the area, represents a promising sub-type amenable to ISL mining in China. The initial achievement in the area proves that the southern margin of the Tenggeer depression, Eren Basin Group is a region potential to sandstone uranium deposit. However, it is still under controversy about depositional facies of the host sediments, type of uranium mineralization and ore-controlling factors. Therefore, it is imperative to investigate the depositional system and characteristics of ore-hosted sand bodies for the future exploration [9].

## 2. Regional geological setting [7,8,10,12]

The Bayantala basin, located at Wenduermiao-Xilamulun Caledonian epicontinental accretionary foldbelt in northern margin of Inner Mongolia Epicontinental Shield of Sino-Korean Platform (Zhang and Zhou, 1994) [18], is tectonically one of sub-units of southern margin of the Eren Basin Group, which was developed on the basement of Yanshanian inter-continental thrust-overlap belt during the Mesozoic-Cenozoic (Fig. 1) (Ren and Li, 1998, Ren and Chen, 1990) [14,15].

The Basin is primarily NE trending and turns southward in southwestern part. A number of faults control the basin at its periphery. The Bayantala basin, “L” shaped, is 64 km long in SN direction and 7km~15km wide in EW direction with an area of about 600km$^2$. The basin is asymmetrical and controlled by basin marginal faults $F_1$ and $F_3$; the depositional center occurs at the north with a thickness of more than 2800m.

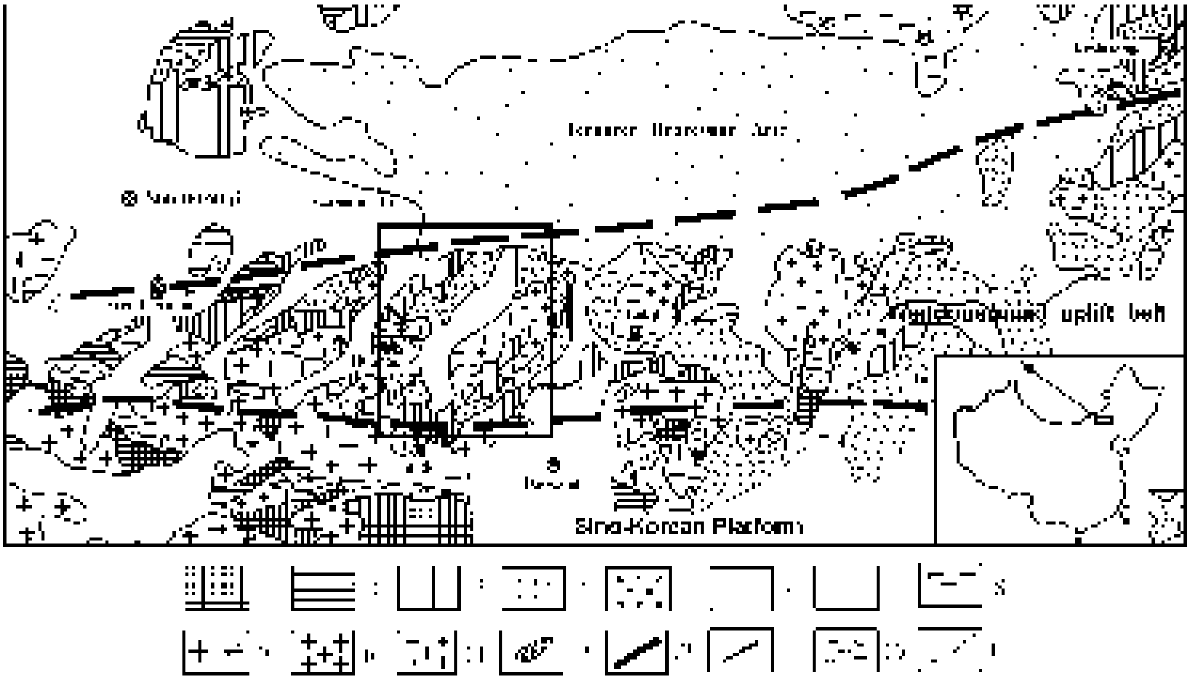

*FIG.1. Sketch map showing location and geology of the Bayantala basin, Wendouermiao uplift belt.*

*1) Precambrian, 2) Lower Paleozoic, 3) Upper Paleozoic, 4) Upper Jurassic, 5) Cretaceous, 6) Tertiary, 7) Quaternary, 8) Cenozoic basalt, 9) Jinningnian plutonic rocks, 10) Hercynian plutonic rocks, 11) Yanshannian Plutonic rocks, 12) Ophiolitic mélange, 13) Deep-seated faults: (1) Baiyunebo-Huade-Chifeng deep-seated fault, (2) Wenduermiao-Xilamulun deep-seated fault, (3) Suolunshan-Xilamulun deep-seated fault, 14) Fault, 15) Ductile-shear zone, 16) Boundary of tectonic provinces.*

The early Yanshanian granite and Early Permian submarine volcanic rocks of the Elitu Fm ($P_{1e}$) are outcropped in the southeast of the basin. The granite is present as batholiths and stocks, which are parallel to the axis of basin in the area. Lithogically, they are biotite granite and quartz diorite, in which uranium content is high ($2.7\times10^{-6}$-$6.3\times10^{-6}$) and Th/U ratio is 5.6-11.1. The leachability for uranium is 20%-40% (Chen, 1998). The submarine volcanic rocks of Elitu Fm are distributed to the southeast of granitic batholiths and stocks. The intermediate-acidic volcanic clastic rocks and lava of the Sandaogou Fm ($J_3s$) and submarine meta-sandstones of the Sanmianjin Fm ($P_{1s}$) are widely outcropped over northwest and southwest of basin. Veins of granite porphyry intruded the strata at late Yanshanian stage.

The basin is mainly filled with the Bayanhua Group ($K_1b$) of Lower Cretaceous [20]. The upper Cretaceous and Paleogene strata are missed and the basin is partly covered by the Baogedewula Fm ($N_2b$) of Pliocene and Quaternary strata. The Bayanhua Group consists mainly of sediments deposited in down-faulted background under warm climate and contrast enhanced topography. The group includes the Aershan Fm. ($K_1ba$), the Tenggeer Fm. ($K_1bt$) and the Saihantala Fm.

($K_1bs$) from bottom to top. The Upper member of Tenggeer Fm and Saihantala Fm are recognized as the target sandstone for exploration.

## 3. Geologic characteristics of uranium mineralization

### *3.1. Depositional system of host sediments* [4,6,11,13,16]

#### *3.1.1. Upper member of the Tenggeer Fm*

Basin marginal fault F3 was the most active at late Tenggeer stage (Zhu Minqiang, Yu Dagan, 2002) [19]. Because of abundant provenance, deposition of fan delta was widespread along the southeastern margin of the basin (Figs. 2 and 3). An entire fan delta (including fan delta plain, fan delta front and pro-fan delta) was well developed. Sand bodies deposited in fan delta front are host sandstones of roll-type uranium deposits.

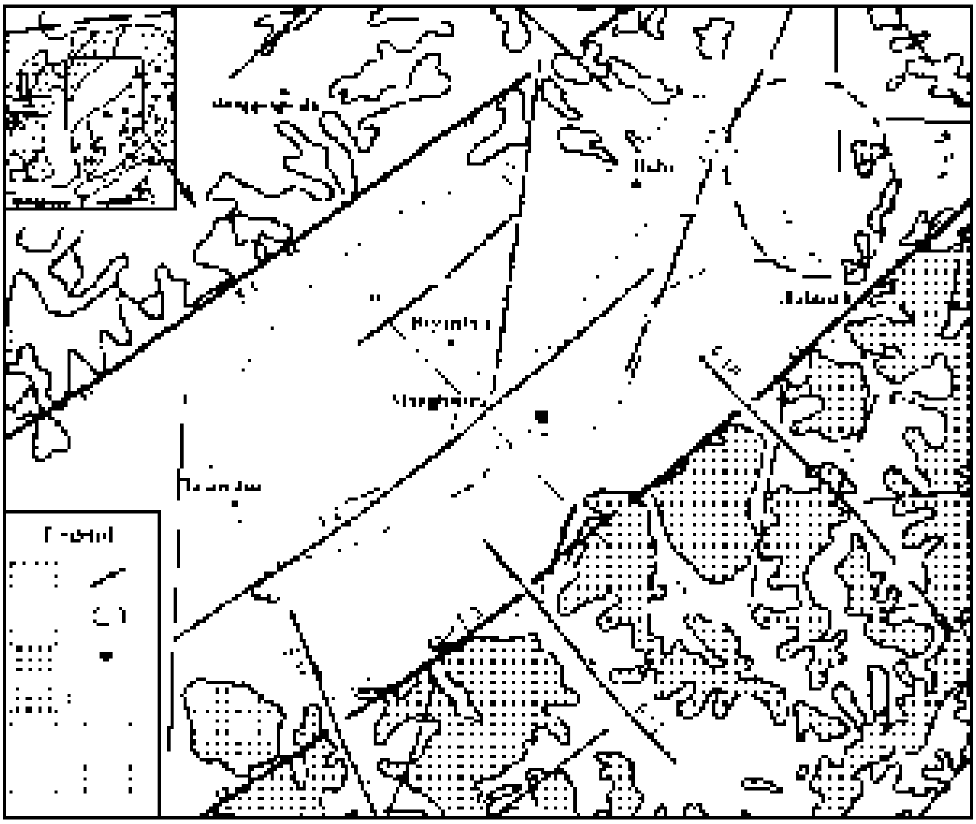

*FIG. 2. Diagram showing distribution of fan delta in the upper Tenggeer Fm, northeastern Bayantala basin. (1. Lower Permian, 2. Upper Jurassic, 3. Yanshannian granite, 4. Bayanhau Group ($K_1b$), 5. Baogedewula Fm ($N_2b$), 6. Pleistocene, 7. Interpreted faults by TM imaging, 8. Ring structure, 9. Mineralized holes, 10. Fan delta plain, 11. Fan delta front, 12. Pro-fan delta).*

The deposits of fan delta plain facies are distributed between faults $F_3$ and $F_2$. They are 3 to 5 km wide, controlled by $F_3$ and NW-trending faults. It includes sediments deposited in gravity flows, braided channel and sheetflood flow. Lithologically, they are massive conglomerate, coarse-grained sandstone and boulderstone.

The fan delta front deposits were basin-wards developed, deposited in subaqueous distributary channel, inter-distributary channel, crevasse splay, mouth bar and pebbly gravity flow. The subaqueous distributary channel sand bodies adjacent to fan delta plain are 2-10m thicker than those adjacent to pro-fan delta in which sandstones interfinger with lacustrine mudstones (Fig. 3). Sediments of subaqueous distributary channel are gray conglomeratic sand, medium-grained feldspathic and quartz sand, occasionally carbonized plant fragments. Sediments above basal scour surface are massive/graded and fining-upward. Sediments in interdistributary channel consist of carbonized fragment-bearing muddy silts, silty mud and fine-grained overbank sand/mud. Usually, less than 1m crevasse splay deposit is present in the sediments of inter-distributary channel facies. Sheetlike distant sand bodies of outer stream mouth bar (<1m) are poorly developed. During late Tenggeer stage, water was slightly deepened, indicated by gray and dark gray lamellar, massive mudstone intercalated with grayish white sandstone and conglomerate. This mudstone is poorly compacted, called as “mud neck”, and is a mark bed for correlation in south margin of the Tenggeer depression (Zhao and Zhu, 1996) [17].

The pro-fan delta facies consist of dark gray and gray mudstone intercalated with thin laminated marls and turbidites, having a great thickness in total.

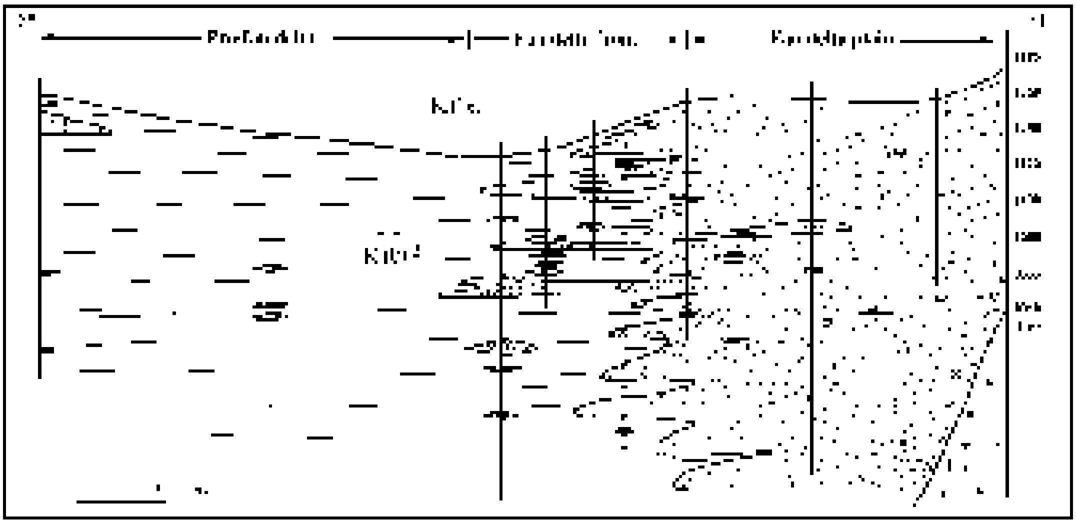

*FIG. 3. Profile diagram showing the constituents of fan delta in the upper Tenggeer Fm ($K_1bt^2$).*

Table I. Characteristics of lower and upper member of Saihantala formation

| Saihantala Fm | Depositional system | Lithological assemblage | Climate | Primary color | Organic matter |
|---|---|---|---|---|---|
| Upper member ($K_1bs^2$) | Transition into Meandering | Mudstone intercalated with sandstone, “mud encompassing sand” | Arid | Variegated red | Deficient |
| Lower member ($K_1bs^1$) | Braided | Overlap of braided channel sand bodies, “sand encompassing mud” | Warm and humid | Gray | Abundant |

### *3.1.2. Depositional system for the Saihantala Fm*

Because the regional tectonic stress was inversed at the end of late Tenggeer, the basin failed to develop and water of lake withdrew. Hence, the top of the upper Tenggeer was eroded to some extent. Afterwards, with the rejuvenation of basin, sediments of fluvial system were deposited in intermontane valley, i.e., the Sahantala Fm ($K_1bs$), which is mainly distributed around southeast of northeast basin (Fig. 4). It thins out northwestward. It is 0-60m thick and absent in the southern part of basin. Based on the documentation of cores, the Sahantala Fm can be divided into upper member deposited in braided stream, and lower member deposited in meandering stream (see Fig. 5 and Table I).

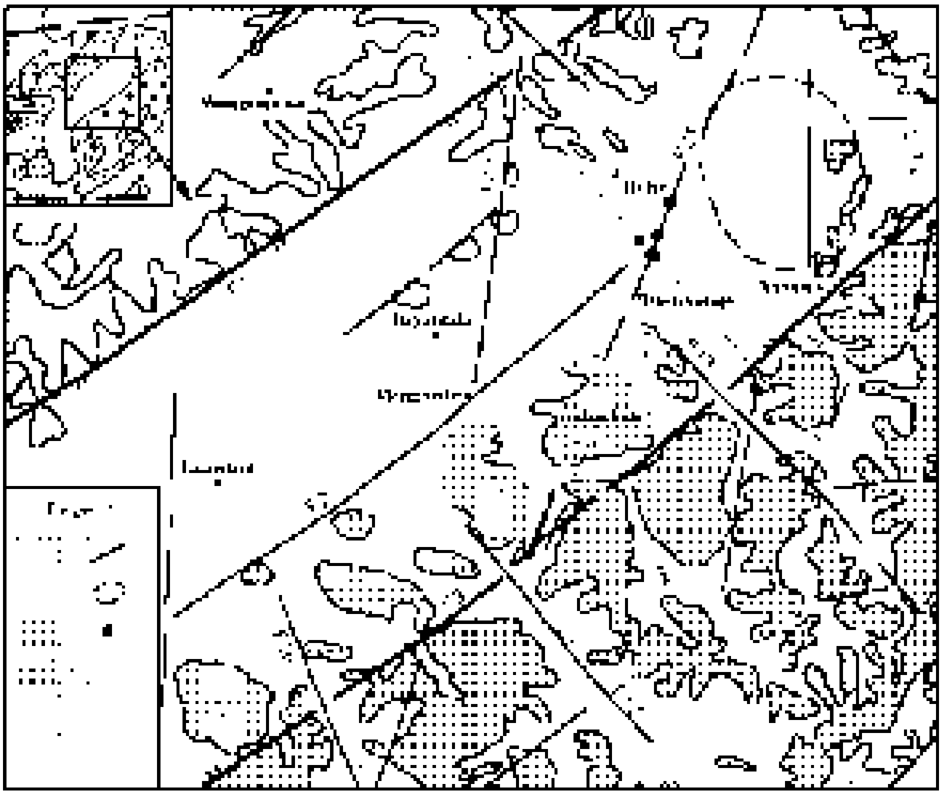

*FIG. 4. Diagram showing distribution of braided system in the Saihantla Fm, northeast basin.*
*1. Lower Permian, 2. Upper Jurassic, 3. Yanshannian granite, 4. Bayanhau group ($K_1b$), 5. Baogedewula Fm ($N_2b$), 6. Pleistocene, 7. Interpreted faults by TM imaging, 8. Ring structure, 9. Mineralized holes, 10. Braided stream deposits.*

### 3.1.2.1. Genetic facies association of lower member of the Saihantala Fm

Due to the strong tectonic activity at early Saihantala stage, the contrast of topography was enhanced and the down cutting process of stream became intense. As a result, the incised valley of a braided stream is well developed (Fig. 5). To the west of Mangheite is deposition of pebbly braided stream, while to the east is deposition of sandy braided stream. The braided channel was primarily NE-trending, basically parallel to fault $F_2$ which controls the development of stream channel. The braided stream is about 2 km wide. Generally, the pebbly braided channel deposits intercalated with the sandy braided channel deposits at the convergence of major channel with the distributaries. The lower member lithologically consists of light gray, white, yellowish green and bluish gray massive medium-to-coarse-grained feldspathic quartz sandstone, conglomeratic sandstone and sandy conglomerate, intercalated with yellowish green lenticular mudstone and siltstone, occasionally with remnant of the oxidized laminated carbonaceous mudstone. The carbonized plant fragments are usually oxidized into whitish fragment. Two segments of cumulative curves, 70% of jump population and moderate sorting from grain-size analysis suggest rapid accumulation of sediments. *(1) Braided channel (BCH) facies:* the lower channel-filling sequence, poorly sorted with obvious basal scour surfaces and lags, consists mainly of massive/graded bedding sandy conglomerate, hybrid conglomerate, imbricated conglomerate and trough cross-bedding sandy conglomerate. The upper sequence consists of parallel bedding and cross-bedding sandstones. Vertically, braided channel sand bodies are overlapped each other. *(2) Channel bar*: the floodplain deposition above channel bar deposits is commonly lenticular, so called “sand encompassing mud”. From lower to upper, sequence is lithologically composed of massive conglomerate (or sandy conglomerate) and imbricated conglomerate, parallel bedding/cross bedding coarse- to fine-grained sandstones, horizontal bedding siltstone, and massive mudstone. *(3) Swamp facies:* it is distributed in lower area between channels. The facies include dark gray silty mudstone and muddy siltstone, abundant in carbonized fragments and occasionally containing coal seams. The individual bed is about n cm thick.

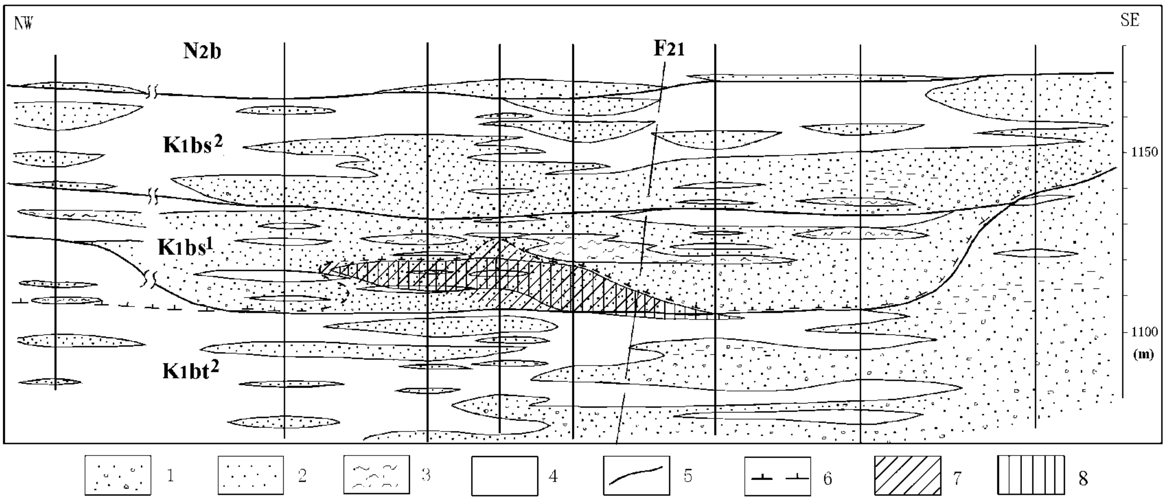

*FIG. 5. Profile diagram, showing the lithology and uranium mineralization along exploration line No. A. 1. Sandy conglomerate, 2. Sandstone, 3. Siltstone, 4. Mudstone, 5. Boundary of strata, 6. Redox interface, 7. Scope of blue alteration, 8. U orebody.*

### 3.1.2.2. Genetic facies association of upper member

As the area gradually became more stable at the late Saihantala stage, hydrodynamic regime waned and the down cutting capacity of stream lessened. Hence, the upper member is characterized by the frequent alternation of channel sand and mud, forming a “binary structure” typical to meandering fluvial deposits. The floodplain deposits are composed of yellowish green, brownish red and dark red massive sandy mudstones with some exposure marks, such as roots. The channel deposits are composed of light gray, white and yellow massive conglomerate and cross-bedding medium- to coarse-grained sandstones. The dark red or brownish red mudstone at the bottom can be viewed as a mark bed to discern the upper and lower Saihantala Fm or an indicator for the climate change from humid to arid.

The Baogedewula Fm ($N_2b$) is more than165m thick and widely distributed, overlapping the underlying strata in the basin. It is composed of dark red, brownish red, light green and yellow massive mudstone and siltstone, locally intercalated with thin-bedded sandstone and muddy conglomerate. The mudstones are sandy/conglomeratic, rich in calcareous/manganese concretions and lack of plant fossils. The massive structure was formed due to fast accumulation. The calcareous/manganese concretion-bearing mudstone of the Baogedewula Fm is obviously distinguished from that of the upper Saihantala Fm.

### ***3.2. Characteristics of uranium mineralization***

#### *3.2.1. Host sediments*

Two types of host sediments in the Bayantala basin have been identified: braided channel sand bodies of the lower Saihantala Fm in Huhe site that were deposited in incised valley; and sand bodies of the upper Tenggeer Fm in Mangheite that were deposited in fan delta front.

The braided channel sand bodies of lower member of the Saihantala Fm consist of coarse-grained conglomeratic sandstone, medium- to coarse-grained sandstone and thin-bedded fine-grained sandstone. It is inferred that the sediments were originally gray and dark gray because there are abundant oxidized gray white carbonized fragments and remnants of laminated carbonaceous mudstone from the oxidation. Feldspars and quartz mainly constitute the frame grains of sandstones. Clay minerals in sandstones include smectite (64%-80%), kaolinite (8%-28%) and illite (3%-13%). The sandstones are loose, moderately sorted and permeable with a thickness of 20m-25m thick in total. The mineralized sandstones are mainly bluish gray, medium- to coarse-grained and subordinately dark gray fine-grained. Dark gray siltstone and carbonaceous mudstone are locally mineralized. Because of hydrolysis and argillization of feldspars, the sandstones have turned blue and loose.

Sand bodies of the upper Tenggeer Fm in Mengheite site were deposited in subaqueous distributary channel of fan delta front, inter-distributary channel and outer stream mouth bar. These sand bodies are lithologically composed of gray, light gray and grayish white medium- to coarse-grained conglomeratic sandstone, dark gray fine-grained sandstone and muddy siltstone. Sands deposited in subaqueous distributary channel and outer stream mouth bar are coarser than those in subaqueous inter-distributary channel. Some beds are often enriched in carbonized fragments and mud intercalated with laminated fine-grained sandstone. Sandstones consist mainly of feldspar, quartz and some volcanic clasts and lithic fragments of siliceous rock and are intensively kaolinized, rich in organic matter. The blue alteration has not been found in such sandstones. The host rocks of uranium mineralization are gray, medium- to coarse-grained conglomeratic sandstone intercalated with dark gray muddy siltstone and mudstone.

The total organic carbon (TOC) of gray primary rocks amounts to 0.09% to 1.85%, 0.5% in average. TOC of bluish gray mineralized sandstone is 0.04% to 0.48%, 0.3% in average, almost as much as that in oxidized zone. But TOC of dark gray mineralized mudstone and siltstone is 0.34% to 12.86%, which shows abundance of TOC in original host rocks.

### *3.2.2. Epigeneic alteration of host sediments*

The braided channel deposits of lower member of the Saihantala Fm have undergone paleo-phreatic oxidation and secondary reduction. The interlayer oxidation took place later than the phreatic.

The paleo-phreatic oxidation had lasted for about 70Ma, i.e., from Later Cretaceous up to the end of Paleogene. The paleo-phreatic oxidation surface is near the bottom of incised valley (Fig. 5). Sandstones and siltstones above the paleo- water table are commonly yellow, yellowish green and white. The loose sandstones show the oxidized spots of pyrite, intense hydration of cements, weak diagenesis and high permeability. Mudstones are yellowish green and green. A bright yellowish oxidized bed (1-2m) is commonly present above the paleo- water table).

The secondary reduction, related to gleization and de-oxidation caused by hydrocarbons, $H_2S$ and $CO_2$ rising along the fault, took place after covering of red mudstone of the Baogedewula Fm. The gleization turns sandstone and mudstone into yellowish green. This alteration has a pervasive impact on the lower and upper Saihantala Fm and part of the Baogedewula Fm mudstone. However, hydrocarbons play a limited role in de-oxidation (Fig. 5) which turns the massive medium- / coarse-grained sandstone and conglomeratic sandstone into bluish or greenish within the mineralized area or around its periphery, associated with intense smectitization and kaolinization of feldspars. According to analysis of samples, the content of FeO in bluish green clay minerals amounts to 5.8%-6.2%. The host rocks are bluish gray medium- / course-grained conglomeratic sandstone and fine-grained sandstone intercalated with siltstone or coal seams. There often exist oxidized and carbonized fragments, micro-stellar/colloidal pyrite and marcasite. Sulfur in bluish gray sand bodies is commonly 0.01% to 0.12%, and 0.06% to 0.69% for mineralized area, with the maximum of 7.73%. So, allothogenic sulfur may add into the mineralization along with the hydrocarbons up faults.

The interlayer oxidation is developed near the “roof window” which is outcrop of the Bayanhua Group. The outcrop of “roof window” is mainly controlled by $F_3$ and $F_2$ (Fig. 4). Because “roof window” favors the seepage of U- and oxygen-bearing meteoric water into strata of the upper Tenggeer Fm, the fan delta front sand bodies of the Tenggeer Fm have been oxidized into light yellow in Mangheite site.

The content of Re, Se, Mo, Sc and V increases obviously in blue mineralized sandstone and dark gray fine-grained sandstone compared with others. These trace elements are positively proportional to uranium. Th and V in yellow fine-grained sandstone and dark gray sandstone are higher than in other rocks (Fig. 6).

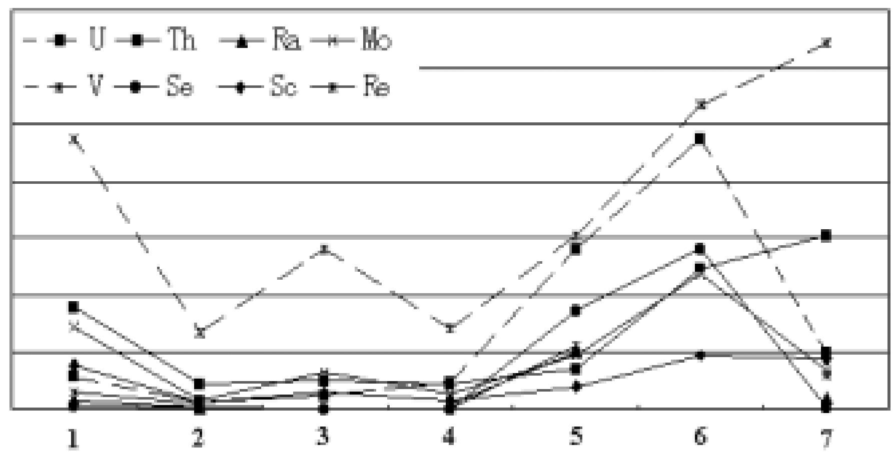

*FIG. 6. Diagram showing the variation of contents of trace elements in alteration rocks.*

*1. Yellow fine-grained sandstone, 2. White coarse-grained sandstone, 3. Yellowish green sandstone, 4. Blue coarse-grained sandstone, 5. Blue mineralized sandstone, 6. Dark gray fine-grained mineralized sandstone, 7. Dark gray sandstone.*

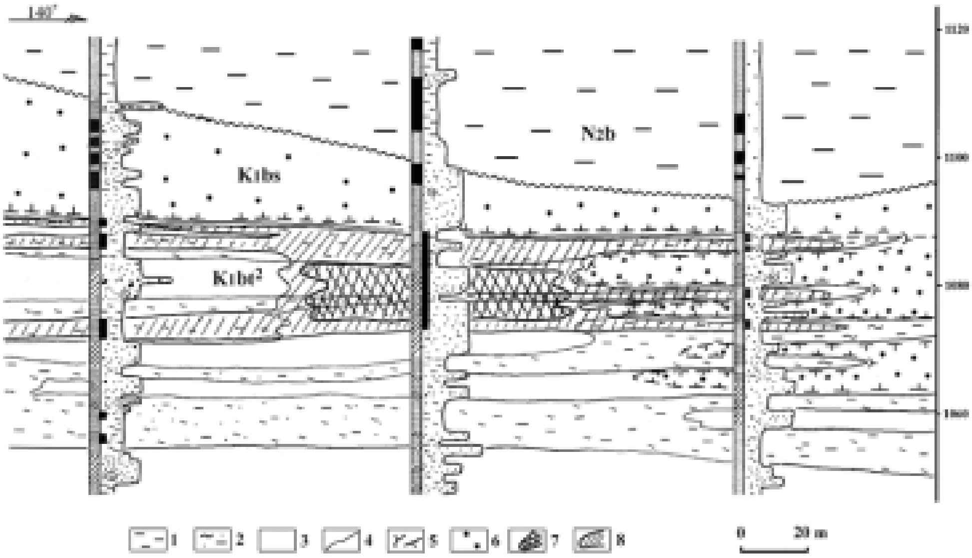

*FIG. 7. Schematic profile, showing the lithology and U mineralization along 48# line, Mengheite site.*

*1. Red massive mudstone, 2. Silty mudstone, 3. Sandstone, 4. Boundary of lithofacies, 5. Boundary of redox interface, 6. Oxidation zone, 7. Orebody, 8. Anomaly content of uranium.*

### *3.2.3. Characteristics of orebodies*

The uranium mineralization in Huhe site is hosted in braided channel sand bodies of the lower Saihantala Fm. An orebody stretches through exploration lines No.320, 336, 352 and 384 (Fig. 5), is 200 to 300 m wide, 1,600m long, buried at depths of 115 to 127m. The orebody is tabular or lenticular in shape and 2.4 to 14m in thickness, measured by gamma logging. Uranium per square meter is 1.27 kg/m$^2$-3.2 kg/m$^2$. The grade of uranium is 0.01%~0.039% measured by logging and 0.01%~0.074% with 0.109% of maximum determined by chemical analysis. The equilibrium coefficient of radium to uranium (Kp=Ra/U) in boreholes ZK320-95 and ZK320-87 is 1.50 and 1.45, respectively. But Kp in Zk320-91, ZK336-79 and ZK384-55 hole is 0.92, 0.95 and 0.87 respectively. Hence, the latter three uranium-prone boreholes penetrate the center of orebody and the former radium-prone boreholes only penetrate its margin. It seems reasonable that the oxidation is developed from both margins center-wards within a braided fluvial system.

The uranium mineralization in Mengheite site is hosted in the fan delta front sand bodies of the upper Tenggeer Fm (Fig. 7). Mineralization of uranium is buried at depths of 90 to 105m. Commercial orebody, which is quasi-roll type, 8.12m thick and 100m wide, has been found only in ZK48-129. The mean grade is 0.014%. Uranium per square meter is 2.22 kg/m$^2$. Kp is 0.84 and equilibrium is uranium-prone. This shows that mineralization of uranium continues up to now. The fine-grained pyrite and carbonized fragments occasionally occur in mineralized sandstones. The maximum permeability coefficient of mineralized sandstone is 0.44 m/d.

## 4. Depositional system and mineralization

### *4.1. Braided channel sand body and basal channel type mineralization*

The uranium mineralization in braided channel sand bodies of the lower Saihantala Fm is basal-channel-type. Firstly, the thick and universally connected sand bodies are deposited in braided stream deposits. The whole sand body overlapped by 3 to 5 fining-upward channel sand bodies is 7 to 30m thick (commonly 20 to 25m). Sandstones are loose, moderately sorted and permeable. Secondly, the original deposits of the lower Saihantala Fm are rich in organic matter, being a reductant for precipitation of uranium. Thirdly, the lacustrine mudstone of the upper Tenggeer Fm underlying the mineralized sandstones is rich in organic matter and acts as a confining bed at the bottom for migration of mineralizing groundwater. The upper Saihantala Fm overlying the mudstone consists of variegated/red meandering fluvial deposits formed under arid climate, which is favorable to phreatic oxidation. Fourthly, the braided fluvial system was developed in incised valley in Huhe site. The slope gradient along the channel is 10 to 20m/km: 20m/km in NW margin and 55m/km in SE margin. Such landform provides a good setting for migration of mineralizing groundwater. The orebody occurs at the center of channel. It is tabular or lenticular in shape adjoining the unconformity. Fifthly, the early-stage mineralization is of phreatic oxdization. The late-stage mineralization is related to interlayer alteration caused by interaction of U-bearing groundwater with hydrocarbon and $H_2S$ migrating upwards along faults.

### *4.2. Fan delta front sand bodies and roll-type mineralization*

Fan delta front sand bodies of the upper Tenggeer Fm were favorable to the formation of roll-type uranium orebodies. In the Mangheite and Huhe site, the distributary channel and mouth bar sand bodies are 4 to 30m thick. They are distributed within the scope of 1~2km far from $F_2$ (Fig. 2). These sand bodies are confined by lacustrine mudstones both above and below. In profile, the fan delta front sand bodies are inter-fingered with lacustrine mudstone toward center of basin and connected to coarse-grained sandy conglomerates toward margin of basin. Due to the differential movement of basement and uplift of fault block in the SE margin of basin, the fan delta plain sandstone and conglomerate are exposed partly in a way of “roof window” and become recharge area for uranium-mineralizing groundwater. At the same time, $F_2$ plays a role in discharging of groundwater and transporting hydrocarbons upward. Consequently, a system of recharge-runoff-discharge system is formed in such a way, favorable to the formation of roll-type orebodies. Mineralization in ZK48-129 in Mangheite site is attributed to this type, no more than 1km far from the "roof window".

## 5. Conclusions

The upper Tenggeer Fm consists of fan delta deposits. A whole fan delta system has been developed in the area. However, only the sand bodies deposited in fan delta front are favorable to the formation of roll-type uranium deposit. Because they are distributed within the scope of 1~2km of $F_2$ (Fig. 2), the scope of exploration for the target bed narrows. The Saihantala Fm deposited in a fluvial system can be divided into lower and upper members based on depositional microfacies and paleoclimate. The lower deposited in braided fluvial system and rich in organic matter, is the major exploration target bed of basal-channel type sandstone uranium deposit in this basin. The upper deposited in meander system under arid climate is lack of organic matter, and therefore is unfavorable to uranium mineralization. The range of braided fluvial system is showed in Figure 4. According to size and preservation of sand bodies, the target bed is well preserved in Huhe site where the exploration is promising. On the contrary, most of the Saihantala Fm has been eroded off or poorly preserved (only several meters to ten and several meters remained), so the Saihantala Fm is unfavorable to mineralization in Manghete. However, due to the differential uplift of fault blocks, the water recharged from "roof window" may cause interlayer oxidation in the fan delta front sand. In addition, there exit several sits with anomalous uranium content in fan delta front sand bodies. So, the basal-channel and roll type uranium mineralization is worth further investigating in both Huhe site and Mangheite site.

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# Geological and geochemical characteristics of Shihongtan uranium deposit, SW Turpan-hami Basin, Xinjiang Autonomous Region

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**Abstract.** Shihongtan Deposit, as a roll sandstone-type uranium deposit, was discovered at the end of last century on the basis of previously known U-coal deposit. At the deposit, $J_{1-2}$ ore-hosting Shuixigou Group. is widely distributed. Ore bodies are presented in tabular and lens-like forms. Roll head is about 4-8m thick and 50-150m long. Tabular ore bodies have thickness of only about 2-6m and length of 100-500m. Both lens-like and tabular ore bodies are hosted in $J_{1-2}$ loose and permeable coarse/medium-grained arkoses attributed to braided fluvial system. Alteration is well developed, including hematitization and limonitization, originated from interlayer oxidation while ore bodies are usually located at the pinch out site of interlayer oxidized zone (redox front). An obvious zonation is observed down dips as: 1) brown-yellowish-colored, intensely altered sandstone with $Fe^{3+}/Fe^{2+} > 3.0$ and $C_{org.} = 0.08\%$; 2) light yellow and variegated red--colored, weakly altered sandstone with $Fe^{3+}/Fe^{2+} = 1.5\text{-}3.0$ and $C_{org.} = 0.08\%\text{-}0.72\%$; 3) dark gray/grayish white-colored mineralized sandstone at redox front with $Fe^{3+}/Fe^{2+} \cong 0.50$ and $C_{org.} \approxeq 0.57\%$; 4) gray /light gray-colored unaltered sandstone with $Fe^{3+}/Fe^{2+} \cong 0.34$ and $C_{org.} \cong 0.26\%$. Uranium occurs in both uranium minerals (about 50%) and adsorption (about 50%). Uranium mineral is mainly pitchblende, minor coffinite and uraniferous Ti-Fe oxides. Pitchblende is usually associated with pyrite while coffinite occurs either on the grain surface of pyrite or in association with pitchblende and quartz. Uraniferous Ti-Fe oxides seem possible to be alteration products of leucoxene or ilmenite. Adsorbed uranium is closely related associated with clay minerals, powdery pyrite and carbon debris. Ore grade is 0.035%U in average. Associated elements include Mo, Se, Re, Ga, Sc. Based on whole rock Pb-isotopic analysis of 14 ore samples, U-Ph isochron dating yields as 104Ma, 24Ma and 7Ma, corresponding to late stage of Early Cretaceous, the end of Oligocene and Late Miocene respectively.

## 1. Introduction

Shihongtan uranium deposit is located in Turpan-Hami basin, Northwest China. Turpan-Hami basin is surrounded with mountains or hills, Bogda mountains in the north, Jueluotage mountains in the south, Harlike mountains in the east, and Kalawucheng mountains in the west. The basin, one of the big continental Meso-Cenozoic sedimentary basins in North China, shows irregularly narrow shape, having a length of 658 km from east to west, and a width of 60-132 km from south to north. The total area of the basin is 5 3500 $km^2$.

The topography of the basin is basically low in north and east, and high in south and west. The altitudes of Jueluotage Mountains, the provenance area of Shihongtan deposit, are 500-2000m. The topography of the ore district is flat and its altitudes are 213.93-230.62m. The ground surface of the district is covered by Quaternary gravel and sand. The Aiding lake, located to the north of Shihongtan deposit (Fig. 1), has the lowest altitude of –154.5m in China, which also is the discharge area of the deposit.

## 2. Tectonic setting

Turpan-Hami basin is located at the Turpan-Hami micromassif of the southeastern part of Kazakhstan plate. The basement of the basin is composed of both Precambrian crystalline rocks in the deep and Devonian and Carboniferous epimetamorphic rocks, intermediate-acidic and intermediate-basic volcanoclastics rocks in the shallow subsurface.

The structural features of the basin are mainly controlled by the sub latitudinal Bogeda arcuate structural belts in the north and the Aqikuduke-Kangguertage structural belts in the south, and also are affected by the Kalameili-Haerlike NW-trending structural belts in the northeast and the Aerjin NE-trending structural belts in the southeast. A large amount of sub latitudinal, NE-trending and NW-trending linear concealed faults occurs in the basin and forms arcuate, and lozengy sub latitudinal structural patterns. Tectonically, Turpan-Hami basin can be divided three tectonic units: Turfan depression in the west, Hami depression in the east and Liaodun uplifting domain in the middle.

## 3. Geology of the ore district [1]

### *3.1. Structural characteristics*

Shihongtan deposit is located at the western part of Aiding Lake slope of the Turfan depression, and Aiding Lake slope belt (Fig.1). The ore district is 20km in length from the western Baxiankou (Exploration line No.96) to the eastern Baishitan (Exploration Line No.95) and has a width of 6km. The host rocks occur as monoclinal strata gently dipping toward the north in general with the dip angle of 4~10º. A nose-shape uplift with NNE-trending axis was formed as the result of geotectonism in Shihongtan ore district. The Xishanyao Group ($J_{2x}$), Middle Jurassic outcrops and is eroded at the axis. Faults are limitedly developed and only broad and gently dipping folds are formed in Meso-Cenozoic strata in Shihongtan ore district.

### *3.2. Lithology and lithofacies of host rocks*

The ore-host rocks, Shuixigou Group, Lower and Middle Jurassic, are a set of continental coal-bearing classic rocks broadly distributed in Xinjiang Autonomous Region. Shuixigou Group can be divided into 3 formations: Badaowan Formation ($J_{1b}$), Lower Jurassic, Sangonghe Formation ($J_2s$), Middle Jurassic, and Xishanyao Formation ($J_2x$) Middle Jurassic.

#### *3.2.1. Badaowan formation ($J_1b$), Lower Jurassic series*

The Badaowan Formation encountered in drill holes has the thickness of 23~123m and is overlying the Carboniferous with angular unconformity. The bottom of the formation is thin-bedded basal conglomerates and conglomerates cemented by tuffaceous matter. The middle part is an intercalation of gray sandstone and gray-green mudstone. The upper part consists of gray, gray-green mudstone and siltstone with 8~11m stable coal seams. The coal seams are considered as the marked beds of stratigraphic correlation in Shihongtan district. The sediments of Badaowan Formation by Sangonghe Formation ($J_1s$) are overlaid on the coal layers.

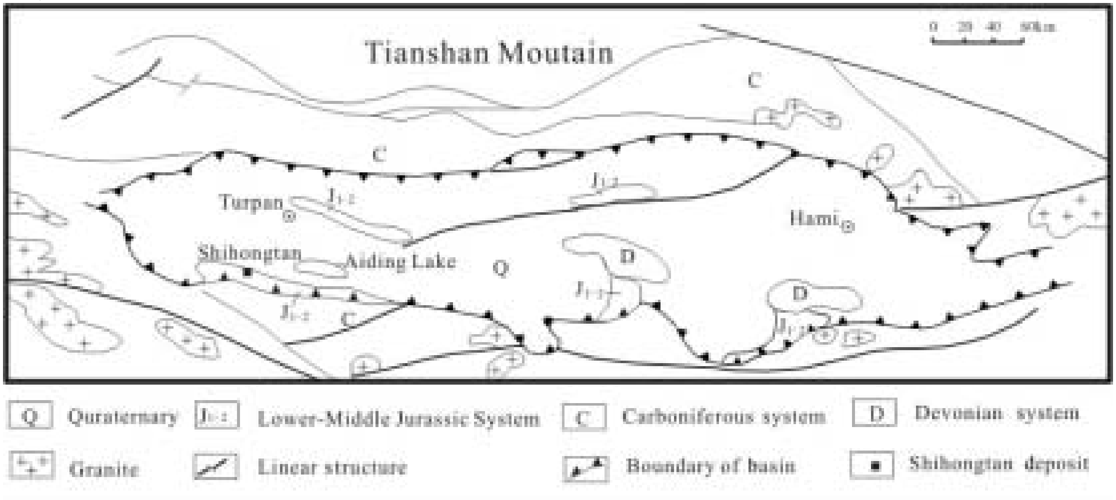

*FIG. 1. Schematic geological map of Turpan-Hami basin.*

### *3.2.2. Sangonghe Formation ($J_1s$), Lower Jurassic*

The Sangonghe Formation conformably overlies the Badaowan Formation and is 11~15m thick. It consists mainly of gray, gray-green, dark-gray mudstone and siltstone, locally intercalated with gray, light gray fine-grained sandstone, medium-grained sandstone, gravel-bearing coarse-grained sandstone and conglomerates belonging lacustrine-swampy sedimentary systems.

### *3.2.3. Xishanyao Formation ($J_2x$), Middle Jurassic*

Xishanyao Formation is formed in the expansion stage of lake basin, and attributed to delta depositional systems. The thickness of the Xishanyao Formation ranges from 35m to 691m. According to sedimentary characteristics, it can be divided into 3 lithologic members: the lower member ($J_2x^1$), the middle member ($J_2x^2$) and the upper member ($J_2x^3$). The lower member is composed of gritstone, gravel-bearing gritstone and sandy conglomerates, attributed to braided stream system with the thickness of about 35~85m. It contains three sandstone layers and each one is 2-18m thick. The top of the lower member is a stable coal seam. The middle member consists mainly of mudstone and siltstone, and is attributed to fluvial-delta depositional system. The lower part of $J_2x^2$ belongs to delta front deposits of braided stream, and the upper part-delta and delta plain facies with several sandstone units. The top of the middle member is characterized by the occurrence of several thin coal seams. The total thickness of $J_2x^2$ is 130-140m. The upper member of Xishanyao Formation is basically composed of medium-fine grained sandstone, and 0-315m thick. A three-coal bed (12-14m thick) occurs in the middle of the upper member. The member contains 3 sandstone units with the thickness of greater than 10m for each.

## 4. Geochemical characteristics of interlayer oxidation zones and Shihongtan uranium deposit

### *4.1. Interlayer oxidation zones*

Shihongtan deposit, as a roll sandstone-type uranium deposit, is hosted in Shuixigou Group ($J_{1\text{-}2}$). Alterations are well developed in the host sandstones, including hematitization and limonitization. Alterations are originated from oxygen-bearing groundwater developed along sandstone sandwiched in between impermeable mudstone beds. So, oxidized sandstone zones are also called interlayer oxidation zones at uranium deposits. Interlayer oxidation zones are distributed as an arcuate or embayed front on the plane (Fig. 2), and occur as oxidized sandstone tongues in the section. Uranium ore bodies are usually located at the pinch-out sites (roll front) of interlayer oxidation zone (Fig. 3).

Recent prospecting results show that 7-10 interlayer oxidation zones occur in the host sandstones of Shuixigou Group. An individual oxidized tongue generally is 5-30m thick, and reaches the maximum of 37m. Oxidized sandstone tongues can extend 200-2000m to subsurface along the dip and usually are 90-380m long. Uranium ore bodies are usually located at the front and two limbs (upper and lower) of interlayer oxidation zones.

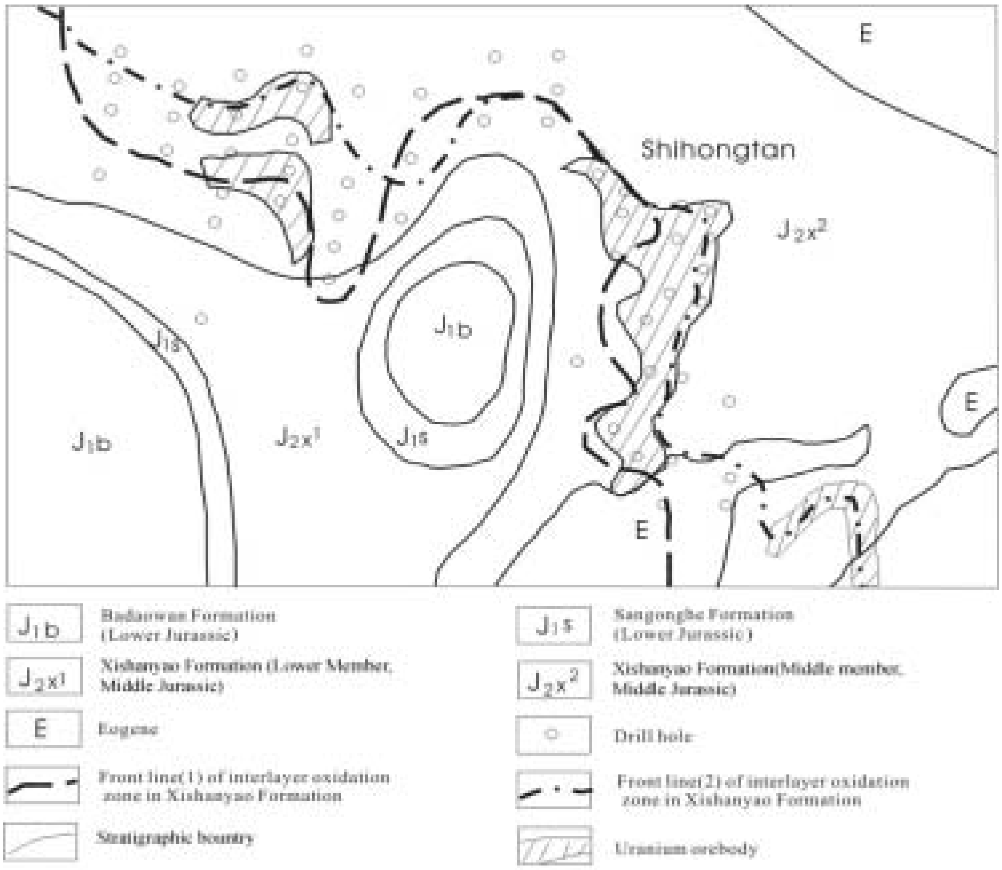

*FIG. 2. Schematic map of Shihongtan uranium deposit.*

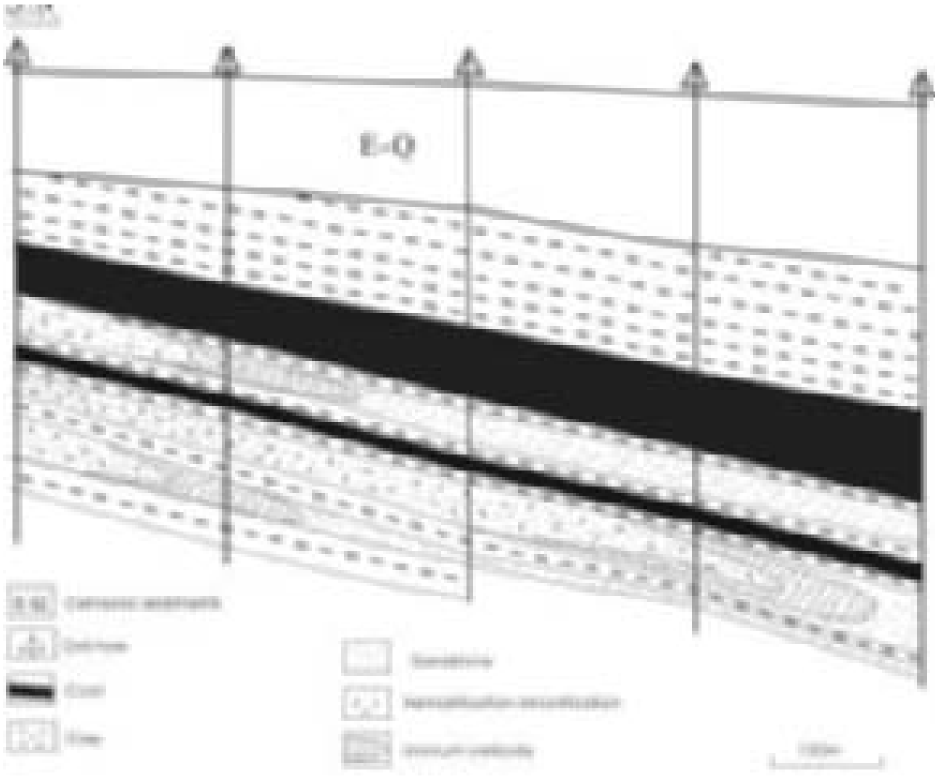

*FIG. 3. Schematic cross section showing the interlayer oxidation zone.*

### *4.2. The mineralogical-geochemical zonation of interlayer oxidation zone*

The zonation characteristics of interlayer oxidation zone are obvious. According to geochemical parameters, such as the color of rocks, the mineralogical composition and its changes, the transformation of low-valence iron minerals, the content of organic carbon ($C_{org.}$), $\Delta Eh$, $\Sigma S$ and $Fe^{3+}/Fe^{2+}$, the interlayer oxidation zone is further subdivided into: intensely oxidized subzone, weakly oxidized subzone, redox (uranium ore) subzone and subzone of unaltered rocks (Table I).

Table I. Geochemical parameters of interlayer oxidation zone

| Parameters | Oxidation zone | | Uranium ore subzone | Subzone of unaltered rocks |
|---|---|---|---|---|
| | Intensely oxidized subzone | Weakly oxidized subzone | | |
| $C_{org.}$(%) | 0.08 | 0.08-0.72 | 0.57 | 0.26 |
| $\Sigma S$(%) | 0.047 | 0.05 | 0.07 | 0.15 |
| $Fe^{3+}/Fe^{2+}$ | >3.0 | 1.25-3.0 | 0.53 | 0.34 |
| $\Delta Eh$(mv) | 20 | | 52 | 29.5 |

a) Intensely oxidized subzone: It shows brown-yellow and yellow-brown color with various dark and light tone, intercalated with light rose-red color. It is mainly composed of limonite disseminated in rock debris and cement, developed along fissure and cleavage of minerals. The low-valence iron minerals in rocks, such as pyrite, siderite were almost oxidized completely. The isomorphism of above-mentioned minerals did not occur. Biotite shows light yellow and complex red. Debris of organic carbon disappeared totally. The mean values of relative parameters in the subzone are:

$C_{org.} = 0.08\%$, $\Sigma S = 0.047\%$, $Fe^{3+}/Fe^{2+} = >3.0$, $\Delta Eh = 20mv$.

b) Weakly oxidized subzone: The rocks in this subzone show bright yellow and complex red color. The subzone is often situated near uranium orebody. The bright yellow color is originated from hydrogeothite, and complex red color is caused by the pigmentation of disseminated hematite or hydrohematite. Tiny particles of hematite and hydrohematite might be originated from the complete oxidization of pyrite or siderite and their pseudomorphous crystals remain. Minor biotite is also observed in rocks, but its margin has turned into light brown-yellow color. Meanwhile, quite a few oxidized coarse-grained carbon debris still exists. The mean values of relative parameters in the subzone are:

$C_{org.} = 0.08\text{-}0.72\%$, $\Sigma S = 0.05\%$, $Fe^{3+}/Fe^{2+} = 1.5\text{-}3.0$.

c) Uranium ore subzone: It is also named as redox subzone, which often shows dark-grey, grey and white-grey color. Sometimes, it appears as light-yellow, grey ore with yellow stain and halo. Argillitization is well developed and expressed mainly as kaolinitization and minor illitization. Powdery and tiny-grained pyritization is frequent. Meanwhile, a little amount of chalcedony-like quartz and powdery carbon materials can be seen. In addition, corrosion replacement, corrosion of clay minerals, replaced rock debris, feldspar and even quartz are widely distributed. A large amount of adsorbed uranium, pitchblende and coffinite exists in ores. The mean values of relative parameters in the sub zone are:

$C_{org.} = 0.57\%$, $\Sigma S = 0.07\%$, $Fe^{3+}/Fe^{2+} = 0.53\%$, $\Delta Eh = 52mv$.

As compared with other geochemical zones, this sub zone is characterized by high content of organic carbon, high ΔEh value and low $Fe^{3+}/Fe^{2+}$ ratio.

d) Sub zone of unaltered rocks: It consists of organic matter-enriched grey, light grey and grey-white sandstone, pebbly sandstone, sandy conglomerate etc. (the mean content of organic carbon is 0.26%) with high background value of uranium being $4.84\times10^{-6}$. In the rocks, pyrite, siderite, carbon debris and biotite have not been altered obviously. Only hydrolysis of feldspar or biotite in certain extent can be seen. Of them, carbon debris shows light brown-yellow indicating the low maturity of organic matter.

### *4.3. Characteristics of uranium orebody*

Uranium ore-bodies show both roll and tabular forms. In uranium orebodies with cut-off grade of 0.01%U, the thickness of roll-head in roll-type orebody is 4-8m in general, with the extending length of 50-150m. The thickness of tabular ore-bodies ranges from 2 to 6m with the length of 100-500m. Uranium orebody may be distributed in sandstones with different grain size. Of them, conglomerate accounts for 23%, sandstone –77%. The ore grade ranges from 0.0124% to 0.1176%, with the average value of 0.035%, and the variation coefficient of 0.65. In general, the ore grade is relatively low and changes significantly.

### *4.4. Composition of ores and wall rocks*

#### *4.4.1. Structures, textures and physical properties of rocks*

Most ores are composed of loose, relatively loose arkose sandstone and minor greywack and show grey and dark grey color. The average density of dry ores is 1.93g/cm$^3$. According to the grain-size, uranium-hosting rocks can be divided into conglomerate, sandy conglomerate, coarse-grained, medium-grained and fine-grained sandstone. Of them, coarse- and medium-grained sandstones are predominant. The uranium-hosting rocks are mainly of contact cementation, and corrosion porosity cementation can be seen as well. The content of rock debris can reach up to 90%, and filling materials consist mainly of clays, which account for less than 10%.

#### *4.4.2. The composition of ores*

a) The mineral composition of ores

Sandstone is composed of mineral and rock debris and each of which accounts for about 50% respectively. Monomineral debris is mainly composed of quartz (aggregate-crystalline quartz, polycrystalline quartz) with the content of 30-40% and 32.1% in average. The content of feldspar (potassium feldspar, albite and plagioclase) is 20-25% and 22% in average. Most debris of feldspar has been argillitized. Mica encountered in sandstone debris consists mainly of biotite and minor muscovite with the content of 1-7% and 2.8% in average respectively. Expansion, curving and tiny fissure deformation and hydrolysis are frequent. Rock debris includes: argillite, siltstone, slate and acidic-intermediate volcanics and granite. The content of the above rock debris accounts for 37-46%, and 42.6% in average.

Clay minerals, including intergranular authigenic clay and clay originated from hydrolysis alteration of feldspar debris. X-ray diffraction analysis and scanning electron microscope study show that clay minerals are mostly composed of kaolinite (accounting for 45.7% of the total clay minerals) and minor illite, illite-montmorillonite mixed-layer mineral, montmorillonite and small amount of pyrite (about 0.9%), carbonate (about 0.3%, these are calcite, siderite and dolomite). Hematite and limonite occur occasionally.

b) Chemical composition of ores

The analytical result of silicate bulk analysis of rock samples, (traditional humid method), is shown in Table 3. The mean chemical composition of ores is: $SiO_2$-74.80%, $Al_2O_3$-11.48%, $Fe_2O_3$-3.31%, CaO-0.80%, MgO-0.89%, MnO-0.02%, $TiO_2$-0.36%, $P_2O_5$-0.08%, $K_2O$-2.77%, $Na_2O$-0.95%.

Table II. Types and content of clay minerals in ores (%)

| Sample No. | Lithology* | Kaolinite | Illite | Mixed-layer Illite-Montmorillonite | Montmorillonite | Chlorite |
|---|---|---|---|---|---|---|
| T90 | FS | 44.4 | 13.9 | 27.8 | | 13.9 |
| T91 | FS | 33.3 | 13.9 | 41.7 | | 11.1 |
| T92 | CG | 65.7 | 7.4 | 22.4 | | 4.5 |
| T93 | CG | 66.2 | 6.7 | 20.2 | | 6.9 |
| T94 | MS | 56.7 | 7.5 | 29.8 | | 6.0 |
| T95 | MS | 58.1 | 23.3 | 11.6 | | 7.0 |
| T96 | CS | 48.2 | 25.9 | | 17.2 | 8.7 |
| T97 | CS | 66.6 | 17.5 | | 8.8 | 7.0 |
| T98 | CS | 60.8 | 21.8 | | 10.8 | 6.6 |
| T99 | CS | 48.2 | 26.8 | | 17.8 | 7.2 |
| T100 | CS | 64.0 | 20.0 | | 10.0 | 6.0 |
| T101 | MS | 44.0 | 30.0 | | 20.0 | 6.0 |
| T102 | MS | 60.0 | 20.0 | | 13.4 | 6.6 |
| Average | | 45.7 | 14.9 | 21.4 | 11.8 | 6.2 |

* CG- Sandy conglomerate, CS- Coarse-grained sandstone,
MS- Medium-grained sandstone, FS- Fine-grained sandstone,
(Analysed by The Xi'an Geological and Mineral Institute).

Table III. Results of silicate bulk analysis of ores (%)

| Sample No.* | U | $SiO_2$ | $Al_2O_3$ | $Fe_2O_3$ | CaO | MgO | MnO | $TiO_2$ | $P_2O_5$ | $K_2O$ | $Na_2O$ | n.n.n. | Total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| T72 | 0.0121 | 75.97 | 12.15 | 2.85 | 0.25 | 0.77 | 0.03 | 0.47 | 0.05 | 2.53 | 0.74 | 3.42 | 99.23 |
| T73 | 0.0350 | 72.14 | 12.66 | 4.25 | 0.21 | 0.92 | 0.02 | 0.40 | 0.06 | 2.29 | 0.71 | 5.72 | 99.38 |
| T152 | 0.6080 | 70.56 | 10.74 | 6.48 | 0.99 | 0.98 | 0.02 | 0.38 | 0.12 | 2.67 | 0.93 | 5.82 | 99.69 |
| T237 | 0.0112 | 74.92 | 12.11 | 3.26 | 0.51 | 0.94 | 0.02 | 0.35 | 0.09 | 2.68 | 1.07 | 3.05 | 99.00 |
| T241 | 0.0360 | 77.07 | 10.97 | 2.62 | 0.64 | 0.88 | 0.02 | 0.35 | 0.10 | 2.78 | 1.00 | 2.98 | 99.41 |
| T295 | 0.0420 | 79.72 | 10.03 | 2.03 | 0.39 | 0.78 | 0.02 | 0.20 | 0.06 | 2.98 | 1.12 | 2.24 | 99.57 |
| T296 | 0.0340 | 75.29 | 10.30 | 1.90 | 2.76 | 0.74 | 0.03 | 0.20 | 0.08 | 3.19 | 1.01 | 3.93 | 99.43 |
| T511 | 0.0940 | 72.77 | 12.94 | 3.14 | 0.64 | 1.11 | 0.02 | 0.50 | 0.07 | 3.04 | 1.02 | 4.41 | 99.66 |
| Average value | 0.1090 | 74.80 | 11.48 | 3.31 | 0.80 | 0.89 | 0.02 | 0.36 | 0.08 | 2.77 | 0.95 | 3.95 | 99.42 |

* T72, T73, R241, T295, T296- Coarse-grained sandstone,
T152, T237- Medium-grained sandstone,
T511- Fine-grained sandstone,
(Analysed by the North-West Analytical and Measurement Center, Nuclear Industry).

### *4.4.3. Existence form uranium*

Data of radiography, electron-probe analysis and chemical leaching analysis of ores show two kinds of existence form of uranium in ores i.e.: adsorption and mineral. Both of them account for nearly 50% respectively. Adsorption form of uranium is closely associated with clay minerals in ores (intergranular authigenic one, and clay originated from the alteration of feldspar debris), powdery pyrite, and carbon debris. Uranium mineral is mainly composed of pitchblende, minor coffinite and U-bearing Ti-Fe oxides. Pitchblende mostly exits as super-micro-grained particle, which are often closely associated with powdery pyrite forming spongeous texture. Coffinite occurs on the grain surface of coarse-grained pyrite, or is associated with pitchblende and chalcedony-like quartz. U-bearing Ti-Fe oxides might come from leucoxene or ilmenite. At the edge, pyrite replaces Ti-Fe oxides and often contains uranium (0.n-n%), sometimes the content of uranium may reach up to 28.95% as shown by electron-probe analysis.

### *4.4.4. Associated elements in sandstone ores*

The contents of Mo, V, Se, Ge, Re, Ga and Sc in uranium ores are tested by polarographic quantitative analysis (Table IV). Analytic results suggest that Mo, Se, Re, Ga, Sc are also concentrated in uranium ores and are of potential economic significance. The average grade of Re is $0.56\times10^{-6}$ with the highest value of up to $2.76\times10^{-6}$.

Table IV. Contents of U, Th and associated elements in ores ($\times10^{-6}$)

| Sample No.* | U | Th | Mo | V | Se | Ge | Re | Ga | Sc |
|---|---|---|---|---|---|---|---|---|---|
| T42 | 190.3 | 12.9 | 1.61 | 94.9 | <0.01 | 1.43 | 0.39 | 18.1 | 13.2 |
| T72 | 121.0 | 8.6 | 1.98 | 60.9 | 0.3 | 0.81 | 0.13 | 13.0 | 11.3 |
| T73 | 350.0 | 13.2 | 2.70 | 89.0 | 0.16 | 1.50 | 0.59 | 14.6 | 17.2 |
| T135 | 170.0 | 6.8 | 1.59 | 34.5 | 0.94 | 1.09 | 0.21 | 13.1 | 7.68 |
| T167 | 117.9 | 10.2 | 1.38 | 91.6 | 0.58 | 1.33 | 0.67 | 17.5 | 13.6 |
| T152 | 6080.0 | 9.8 | 6.95 | 76.3 | 3.01 | 2.43 | 1.95 | 14.3 | 35.2 |
| H370 | 270.0 | 8.2 | 5.99 | 62.1 | 9.65 | 2.87 | 0.22 | 14.3 | 4.92 |
| H451 | 141.9 | 7.2 | 1.50 | 114.0 | 73.5 | 4.56 | 0.29 | 12.2 | 12.1 |
| H439 | 320.0 | 8.5 | 4.58 | 39.9 | 20.5 | 1.22 | 0.34 | 12.2 | 15.2 |
| H412 | 250.0 | 6.1 | 2.34 | 36.2 | 0.58 | 0.77 | 0.13 | 11.8 | 13.6 |
| H415 | 600.0 | 8.6 | 5.72 | 34.9 | 0.62 | 0.84 | 0.46 | 11.6 | 42.6 |
| H287 | 131.0 | 10.8 | 1.21 | 78.7 | 0.31 | 1.07 | 0.18 | 18.4 | 9.78 |

* T42, H287- Fine-grained sandstone,
T152- Medium-grained sandstone,
T72, T73, T135, T167, H412- Coarse-grained sandstone,
H370, H451, H439- sandy conglomerate,
(Analysed by the North-West Analytical and Measurement Center, Nuclear Industry).

### *4.4.5. Ages of Shihongtan uranium deposit*

Based on whole rock Pb-isotopic analysis of 14 ore and rock samples (Table V), U-Pb isochron dating yields 104Ma, 24Ma and 7Ma (Xiang Weidong, 1999) [2], corresponding respectively to late stage of Early Cretaceous, the end of Oligocene and Late Miocene (Fig. 4). The data of ages show that the ore formation is a long term and multistage process.

Table V. Analytical results of U and Pb isotopes in ore and rock samples, (after Xiang Weidong, 1999)

| Sample No. | Lithology* | U ($\times10^{-6}$) | Pb ($\times10^{-6}$) | $^{204}$Pb (%) | $^{206}$Pb (%) | $^{207}$Pb (%) | $^{208}$Pb (%) |
|---|---|---|---|---|---|---|---|
| T145 | CL | 1702.32 | 15.51 | 1.188 | 33.348 | 19.251 | 46.215 |
| T151 | MS | 1285.85 | 13.16 | 0.956 | 44.994 | 16.922 | 37.130 |
| T152 | MS | 6584.41 | 43.84 | 0.532 | 58.428 | 11.068 | 29.974 |
| T153 | CG. | 66.93 | 30.02 | 1.266 | 29.401 | 19.956 | 49.379 |
| T164 | CS | 4.85 | 9.41 | 1.364 | 25.284 | 21.015 | 52.339 |
| T168 | FS | 273.84 | 13.37 | 0.971 | 43.913 | 16.846 | 38.272 |
| T169 | MS | 91.72 | 13.41 | 1.267 | 29.289 | 19.997 | 49.450 |
| Y101 | CG | 80.38 | 33.30 | 1.399 | 25.330 | 21.523 | 51.750 |
| Y102 | CG | 350.73 | 58.97 | 1.392 | 25.710 | 21.567 | 51.333 |
| Y202 | CS | 771.97 | 26.87 | 1.327 | 28.268 | 20.875 | 49.531 |
| Y203 | MS | 329.35 | 42.30 | 1.358 | 26.925 | 21.121 | 50.598 |
| Y303 | CG | 244.31 | 24.18 | 1.349 | 26.913 | 21.015 | 50.726 |
| Y205 | CG | 93.11 | 16.06 | 1.346 | 26.961 | 20.948 | 50.746 |
| Y207 | CL | 755.50 | 46.36 | 1.323 | 29.040 | 20.627 | 49.012 |

CL- Mudstone; Others see Table II.

(Analyzed by the Beijing Research Institute of Uranium Geology).

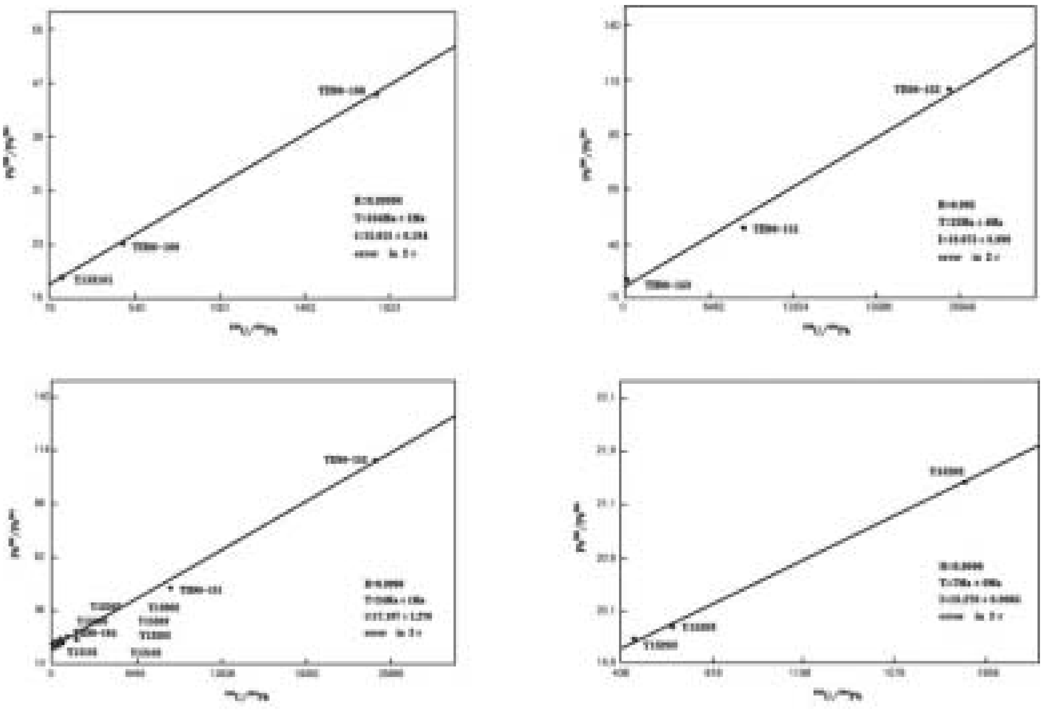

*FIG. 4. U-Pb isochron ages of Shihongtan uranium deposit.*

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# Mineralization characteristics of Dongsheng uranium mineralized area in Ordos Basin, China

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**Abstract.** The Mesozoic fluvio-lacustrine sedimentary rocks in the Ordos Basin include the Fuxian Fm. of Lower Jurassic, the Yan'an, Zhiluo and Anding Fm. of Mid-Jurassic, and the Zhidan group or Liupanshan Group of Lower Cretaceous from the bottom to the top. Of them, sandstones predominate, occasionally intercalated with coal seams, mudstone or siltstone. Interlayer oxidation zones with greenish and bluish colors are well developed in Yan'an and Zhiluo Fm. The Zhiluo Fm. mainly includes the sediments of braided fluvial depositional facies within the incised valleys. So far, the Zhiluo Fm. is much more important than the Yan'an Fm. as host sediments. The existence of purplish red and yellow residual clots in the greenish and bluish sandstones indicates that early-stage oxidized sand bodies was reworked or superimposed by afterward reduction. Commercial uranium mineralization is mostly discovered in greenish and bluish green pan-tied sand bodies of Zhiluo Fm., stretching more than 20 km long and hundreds of meters wide as a regional redox front. Mineralogical analysis shows that uranium in the mineralized sandstones is mostly in form of adsorption and pitchblende, and secondary uranium minerals such as autunite and torbernite are visible on surface. The U-Pb isotopic dating gave a mineralization age of 107±14 Ma, corresponding to so-called Mesozoic sub-orogeny .On the other hand, Paleo-hydraulic analysis demonstrated that the Ordos Basin was a closed endorheic basin prior to early Cretaceous, with the depositional center at the central part of the basin, geographically in Yan'an area. However, since early Cretaceous, the basin shrank sharply due to intensified orogeny and uplift respectively to the south, north and northeast of the basin, which resulted in the groundwater flowing from south, east and north to northwest, west and southwest respectively, associated with the depositional center moving westward. Such flow pattern maintained through Paleocene.

**Key Word:** Mesozoic basin, Sandstone-type uranium deposit, Oxidation zones.

## 1. Introduction

The Ordos Basin covers geographically Shaanxi, Shanxi and Gansu provinces and Inner Mongolia with an area of 250 000km$^2$. This is a well-known "basin of energy resources" for its large reserves of coal, petroleum and natural gas [2]. The explored natural gas reserve inside the basin reaches 500 to 700 billion cubic meters. The Changqin Oil Field and the Shenfu-Dongsheng Coal Field, most important oil and coal producers in China respectively, are also located within the basin. For sandstone type uranium resources, systematic prospecting and exploration works have been conducted in the basin since the year of 2000. Consequently, some uranium mineralization areas have been found in the strata with ages ranging from late Permian to early Cretaceous. So far, commercial uranium has been discovered in Dongsheng area, related to the interlayer oxidation zones occurring in mid-Jurassic Zhiluo Fm. and Yan'an Fm.

## 2. Geological setting

### *2.1. General picture of Ordos Basin*

The Luliang Tectonic Movement transformed the area of Ordos Basin into a part of a platform (Sun Zhaocai, et al, 1990), which kept in stable from Meso-Proterozoic to Triassic. A succession of marine dominated sediments was deposited during this period. However, since late Triassic, this area was transferred from a platform to an intracratonic basin, then foreland basin and subsequently a superimposed down-warped basin (Li Sitian et al., 1992) [1]. In response to the tectonic evolution, the sedimentation in the basin was also transited from marine dominated sediments in Triassic to continent dominated sediments in Jurassic. The late Triassic-Jurassic fluvio-lacustrine sediments in the Ordos Basin include the Yanchang Fm ($T_3$), Fuxian Fm.($J_1$),Yan'an Fm.($J_2$),Zhiluo Fm.($J_2$) and Anding Fm.($J_2$) from the bottom to the top. Lithologically, they are mainly composed of grayish medium-grained detritus at the lower part and red argillaceous material in the upper part of the sedimentation succession. In contrast, the lower Cretaceous sediments, namely Zhidan Group or Liupanshan Group in Tianhuan area and Yijinhuoluo Fm. and Dongsheng Fm. in Dongsheng area, are dominantly fluvial and partly eolian.

### *2.2. Tectonic evolution* [3]

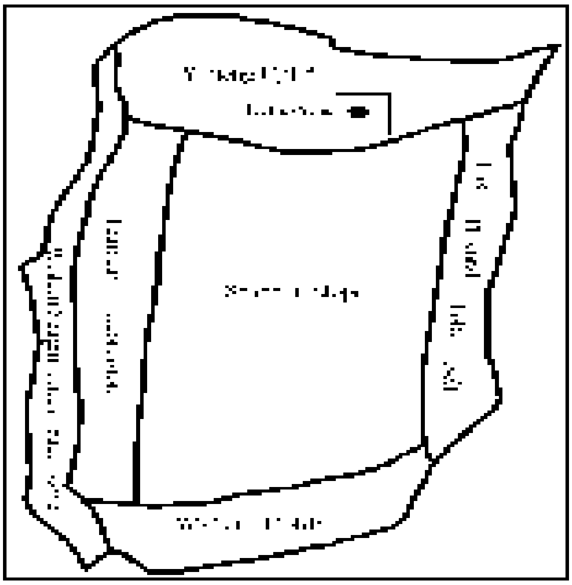

*FIG. 1. The diagram illustrating the tectonic pattern of Ordos Basin and the location of Dongsheng mineralized area.*

The Ordos basin is located at the transitional area between Tethys Tectonic System (in the west) and the Circum-Pacific Tectonic System (in the east). So its tectonic stress field and tectonic evolutions are controlled by the two mentioned tectonic systems, and its boundary is also delimitated by different intracontinental orogenic belts formed at different geological time. During the period of late Triassic to middle Jurassic, intensively influenced by the Qinling Orogenic Belt and the Alashan Compressive Massif respectively, the western and southern parts of the Ordos Basin were tectonically active (Sun Guofan et al., 1985; Li Sitian et al., 1990, Wang Fengzhen et al., 1990). In contrast, the northern part of the basin remained relatively stable and Yimeng Uplift and the Shaanbei Slope were formed (Fig. 1). The Dongsheng area is just placed at the connection site of the Uplift and Slope, indicating that the area was under a continental depositional environment nearby the denudation area.

The Yan'an Fm. and the Zhiluo Fm. in the area are present in monocline with a gradient of 10m/km, no folds and faults exist, and the groundwater flowed in the period of early Jurassic to early Cretaceous from north to south.

The grayish coal-bearing sedimentary formation at the lower part of sedimentation succession indicates a humid and hot climate, whereas the red sedimentary formation in the upper part suggests an arid and hot climate. Both different climates and sediments played important roles for uranium enrichment: the former acted as the geochemical barriers for uranium migration, and the latter supplied oxygen-bearing groundwater and uranium sources. In addition, in late Yan'an stage, uplifting of Yimeng area led to large scale of denudation, and finally resulted in the forming of connected sand bodies of incised valley genesis. The denudation area acted as the sources of uranium and the pan-tied sand bodies should have been the host for uranium migration and enrichment. Therefore, the climate change and tectonic shift might have been the two most important controlling factors for uranium mineralization in this basin.

### *2.3. Hydraulic characteristics*

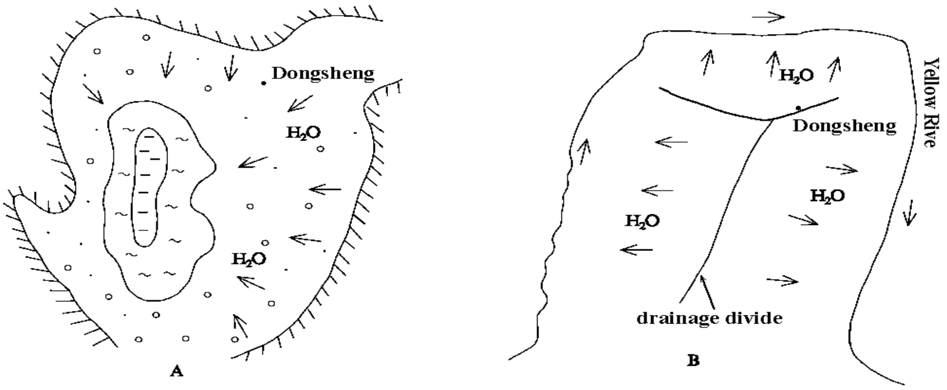

**Fig. 2 Hydraulic Pattern**

**A: Hydraulic pattern of early Cretaceous**

**B: Hydraulic pattern of moden current surface drainage**

The Ordos Basin had been a closed endorheic basin prior to Eocene, since then, it has shifted to an open external basin. In middle Jurassic, affected by the Yanshan Tectonic Movement, the northern and eastern part of the basin began to uplift, and the depositional center of the basin was shifting to the center of the basin, nearby Yan'an city, where the Yan'an Fm. and the Zhiluo Fm. have their maximum thickness. In the southern area of the basin, because of the influence of intensified Qinling orogeny, fluvial sediments were deposited in a very large scale. The surface and ground water at that time flowed from the north, east and south to the center. In early Cretaceous, the area of the endorheic basin shrank sharply, the deposition area and the depositional center moved westward to Huachi-Huanhe, and the flow directions were from south, east and north to northwest, west and southwest respectively (Fig. 2A). This flow patterns remained stable through Paleocene. The uranium mineralized area in Dongsheng is just located at the southwestern area of the basin, suggesting the northern and northeastern margins of the basin acted as the provenance of uranium and the flows from northeast to southwest was the most important hydraulic factor for uranium migration from the provenance.

## 3. Geological characteristics of mineralized area

### *3.1. Structural characteristics*

The basin fill inclines smoothly and gently toward the southwest with a dip angle of 1°~3° without intense tectonic deformation inside the basin. Structures are mainly of block movement constrained by regional deep faults and basement faults. According to remote sensing data, the Ordos Basin is a fault block constrained by two EW trend structural zones located respectively in the north and south of the basin. The northern structural zone passes through the Dongsheng area as a crest of uplift, while the southern one goes through the Zhaohuohao and Sunjialiang sites. Besides, there exists a series of second-order structures with NS, NE and NW trends inside the basin/block. However, these second-order structures could not be directly identified on the surface because no obvious misplaced outcrop is observed in the field.

### 3.2. Depositional characteristics of Yan’an Fm

The Yan’an Fm. is composed of the sediments of fluvial-lacustrine depositional system under humid climate. According to Li Sitian (1996), this set of fluvial-lacustrine sediments includes five genetic stratigraphical units, Unit I, Unit II, Unit III, Unit IV and Unit V from the bottom to the top. The Unit I consists of the sediments of fluvial depositional system coarse to medium-grained sandstone or gravelly coarse-grained sandstone intercalated with siltstone and mudstone in grayish or dark grayish color. The Unit II, III and IV consist of sediments of lacustrine delta depositional system, with a thickness of each unit of about 40 to 76 m. They are dominated by dark-grayish or black mudstone and siltstone with intercalation of grayish sandstone and black shale. The Unit V is of the fluvial depositional system: its lower part is dominated by grayish medium- and fine-grained sandstone intercalated with grayish or black mudstone, whereas the upper part is mainly composed of grayish white medium-or fine-grained sandstone, and close to the top of Unit V, certain amount of kaolin in the sandstone becomes very common as an indicator for the existence of weathering crust.

### *3.3. Depositional characteristics of Zhiluo Fm*

The Zhiluo Fm. in Dongsheng area is presented by a set of variegated clastic sedimentary formation which is bounded at its top by the sandy conglomerate of Yijinhuoluo Fm. of early Cretaceous and at its bottom by Yan’an Fm. Zhiluo Fm. includes two members: the lower one is a set of sediments of braided fluvial system deposited under humid climate and the upper one - meandering fluvial system under arid climate.

The difference of depositional systems between the lower member and the upper member of Zhiluo Fm. has just rightly reflected the evolution process of a stream from braided fluvial of early stage (the stage of incised valley) to low-sinuosity fluvial of intermediate stage and finally to high-sinuosity fluvial of late stage. The sand bodies deposited during braided fluvial stage, which are dominantly composed of coarse- to medium-grained detritus and rich in organic matter and other reducing material such as sulfides, are the main host sand bodies in the area. These sand bodies are spatially tied one by one, forming a series of sand body belts of 2 to 3 km wide that stretch from north to south. During meandering fluvial stage (including low-sinuosity fluvial and high-sinuosity fluvial stage), a set of grayish to red detritus sediments with flood plain argillaceous sediments, were formed. The argillaceous sediments and coarse- to medium-grained sediments deposited during meandering fluvial stage forms a “binary structure”.

Besides, the sedimentary characteristics of Zhiluo Fm. indicate a change in climate from humid at the braided fluvial stage and low-sinuosity fluvial stage to arid and hot at high-sinuosity fluvial stage.

### *3.4. Hydro-geological characteristics*

The mineralized area occurs at the artesian area of Dongsheng Slope where groundwater comprises of the pore water in Quaternary unconsolidated sediments and the fissure water in the detrital rocks of mid-Jurassic, early Cretaceous and Tertiary. The groundwater is mainly of $HCO_3$-Na type and has a mineralization degree less than 1g/l. The water table in the mineralized area is no deeper than 5m. The very low mineralization degree suggests a fast flow and quick water exchange of the groundwater, demonstrating the hydrogeochemical characteristics of an open basin. In the mineralized area, the Zhiluo Fm. contains 1 to 4 ore-bearing aquifers. Of them, the relatively stable ore-bearing aquifer lied at the lower member of the Zhiluo Fm., 30~50m thick in average with 11.94m thick aquifuge, the artesian head higher than 40~50m, the hydraulic gradient less than 2~4%, porosity of the aquifer around 27.29%. The recharge of groundwater is mostly meteoric water. The drainage divide is close to Dongsheng: to the south of the divide, groundwater flows toward the southeast, while to the north of the divide, water flows towards the north, and both waters flow finally into Yellow River.

## 4. Interlayer oxidation zone

### *4.1. Interlayer oxidation zones in Yan’an Fm*

The primary color of the host sandstone in Dongsheng area is dark gray, rich in organic matter, detrital charcoal and sulfides. Alterations in the sandstones are typically observed as oxidation and reduction. Interlayer oxidization in Yan’an Fm. includes two stages: the early stage is characterized by purplish red sandstone; the late stage is by yellowish sandstone. Besides, there exists phreatic oxidation in Yan’an Fm. The reduction occurred after the first stage of oxidation, is identified by the green and blue sandstone.

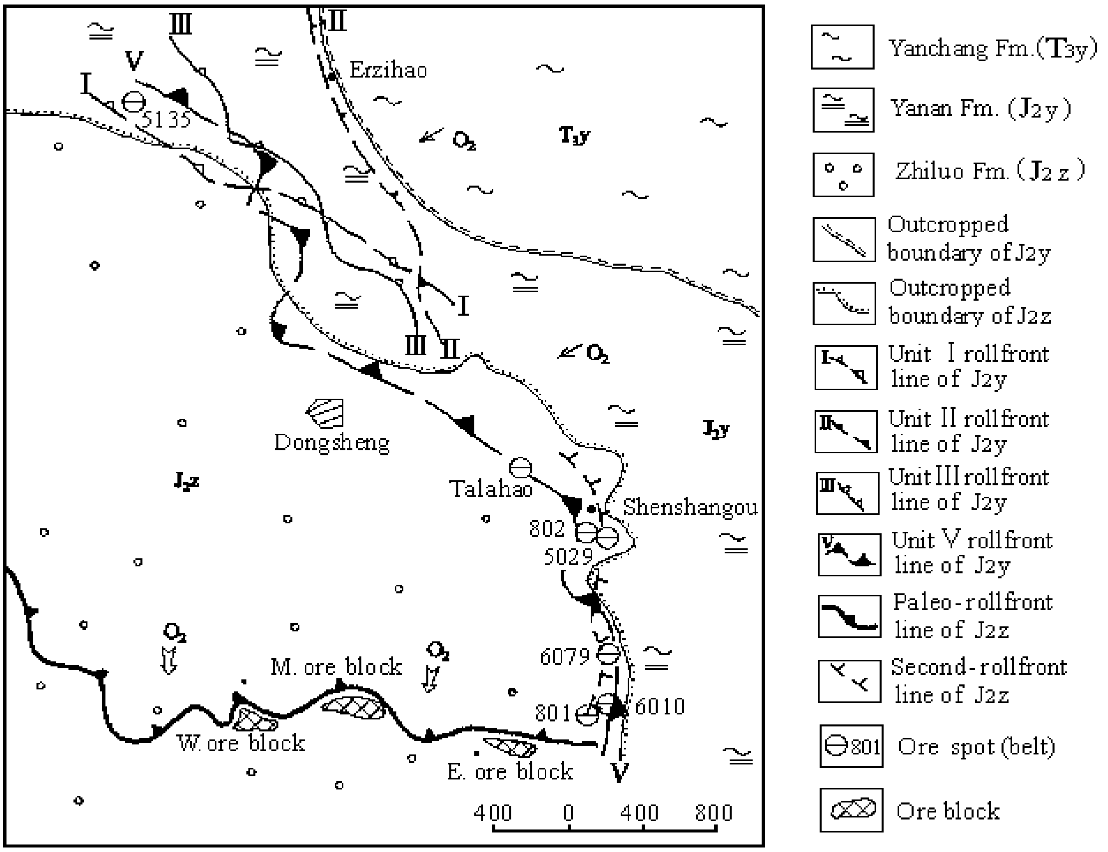

*FIG. 3. Systematic diagram illustrating the distribution pattern of uranium mineralized interlayer oxidation zones.*

On the basis of core analysis, 4 interlayer oxidation zones have been delineated respectively in genetic stratigraphic unit I, II, III and V of Yan'an Fm. as illustrated in Figure 3. They all stretch from northwest to southeast. Of the four interlayer oxidation zones, the one lied in unit V is the largest that is in arc form and with stretch length of 50 to 60 km. Usually, the oxidation zones are 10 to 20 m thick, and have a stable "mudstone-sandstone-mudstone" hydrogeological structure. The oxidization was developed from east and northeast to west and southwest. The oxidized area is mainly in yellow color, occasionally in green. In reduced area, the rocks are of grayish to dark grayish color where nodular and framboidal pyrites are common.

### *4.2. Interlayer Oxidation Zones in Zhiluo Fm*

So far, two interlayer oxidation zones have been delineated in the lower member of Zhiluo Fm. deposited in alluvial plain facies of braided fluvial system (Fig. 4). The oxidation zone distributed in Zhaohuohao area is about 40 km long in EW trend. This EW- trending oxidation zone is considered to be formed at the early stage and had experienced the later stage reduction. The color in the northern part of the EW trending oxidation zone is light blue and blue, and gradually transited to gray and grayish black in the southern part, suggesting that the oxidization should have started from north and developed southwards. The width of the green zone ranges from several km to more than 20 km.

Another interlayer oxidation zone lies under the surface, NS-trending, about 20 km long and yellow in color. It is a secondary oxidation zone formed under the surface condition.

The distribution pattern of interlayer oxidation zones in Zhiluo Fm. is shown in Figure 4.

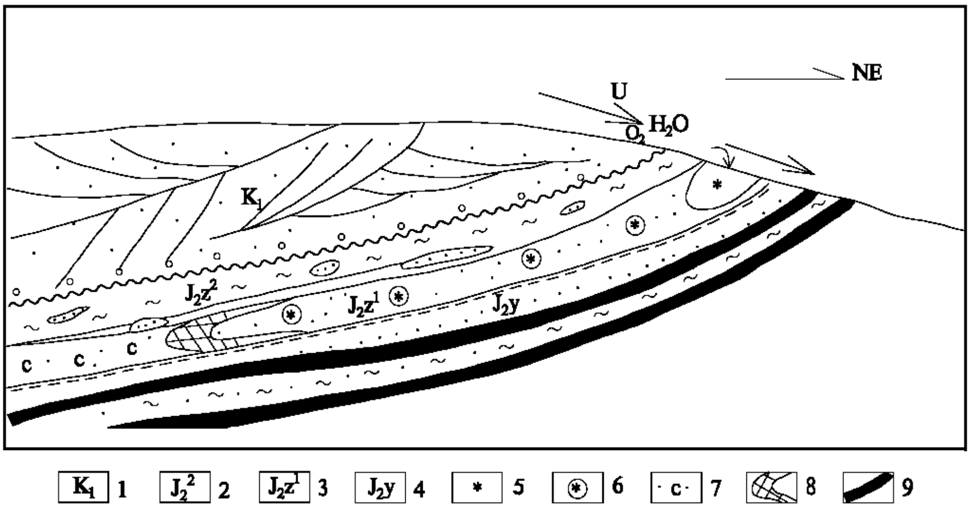

*FIG. 4. The Schematic map showing uranium mineralization and interlayer oxidation zones in Dongsheng area.*

*1. Lower Cretaceous Series, 2. Upper member of Zhiluo Fm., 3. Lower member of Zhiluo Fm., 4. Yan'an Fm., 5. Secondary oxidization zone, 6. Oxidization zone of early stage, 7.Reduction zone, 8.Orebody, 9. Coal.*

The green belt lying near the front interface of the altered rocks, is considered to be the most important indicator of uranium mineralization, and is characterized as follows: (1) the $Fe^{3+}/Fe^{2+}$ ratio in green belt is 1.29, which is lower than that of red sandstone (1.84) in oxidation zone and higher than gray sandstone (0.972) in unaltered sandstone, indicating part of the ferric iron has been reduced to ferrous iron in the transition process from red stone to green stone; (2) residual clots of red and yellow sandstone or mudstone are visible in green coarse-grained sandstone belts; (3) very high concentration of hydrocarbon matter is observed in green belt; (4) the green color resulted from the existence of nickel chloride and clinochloride that are usually formed under reducing condition; (5) the most important time for mineralization-related oxidation is late Jurassic to early Cretaceous in Dongsheng mineralized area as ore -forming process lasts about 50 Ma.

The proved orebodies are mainly in the transitional zones of green belts and gray belts. The forwarding direction of mineralized roll-front is in accordance with that of the oxidization of the strata.

## 5. Uranium mineralization

### *5.1. Mineralization on surface*

A series of uranium occurrences, such as occurrences No.801, 6010, 5029, 802, 6070 and 5135, have been found on the surface (Fig. 3). The orebodies at all these sites are considered to be the residual of the secondary oxidation, and are characterized as: (1) zonal distribution in feldspathic quartz sandstone of yellow color in Zhiluo Fm.; (2) very high ore grade ranging from 0.05% to 0.1%U, with the highest as 0.843%U and secondary uranium minerals such as autunite and torbernite occasionally visible; (3) orebody length from dozens of m to 500m and 0.2m to 11.57m for thickness of orebodies, 0.5 to 3m thick the most common.

### *5.2. Uranium mineralization in Yan'an Fm*

Only one orebody is known in Unit V of Yan'an Fm. The orebody is in tabular shape passing through several layers, with the maximum thickness in each layer of 3.3 m. Ore grade ranges from 0.01% to 0.02%U. The host rocks of orebody are mostly grayish fine sandstone, partly siltstone and mudstone.

### *5.3. Uranium mineralization in Zhiluo Fm*

Uranium orebodies are mostly distributed in the sediments of braided fluvial depositional system. The ore zone is EW trending, with a length of about 15km and total reserve of several thousand tU. The burial depth of the ore zone increases from east to west, with the smallest burial depth of 77m in the east and biggest of 185m in the west, indicating that the distribution pattern of the ore zone is closely related to that of Zhiluo Fm. There are two types of orebodies, the roll-shaped and the tabular. The roll-shaped orebodies occur in both eastern and western sections of the ore zone, while the tabular ones lie in the middle section of ore zone. The thickness of orebodies is 11.4m in the east section, 4.76m in the middle and 3-7.4m in the west.

The average ore grade is 0.02% to 0.05%U, with the maximum value of 0.235%U from core samples. The average uranium yield in the east section is 5.56 kg/m$^2$ with a maximum of 10.67 kg/m$^2$ in the east, 3.56 kg/m$^2$ in the west, and only 1.72 kg/m$^2$ in the middle section.

Host rock is mainly sandstone, occasionally with intercalated bed of calcareous sandstone. Chemical compositions of the ores are given in Table I. Besides, the $CO_2$ concentrations of ores are also analyzed, with an average value of 1.55%, and this value can reach as high as 8.77% if the intercalation of calcareous sandstone exists. Orebodies are sporadically placed in the mudstone layers both above and beneath the mineralized sandstone.

The mineralized sandstone is dominantly presented as feldspathic-quartz sandstone, loosely consolidated, moderately sorted and rounded. The cements are mainly of hydromica and calcite. The grain sizes and their percentages are shown in Table II.

Table I. The chemical composition of mineralized sandstone.

| Sample | Lithology | $Al_2O_3$ | $SiO_2$ | $P_2O_5$ | CaO | $K_2O$ | $TiO_2$ | $MnO_2$ | $Fe_2O_3$ | MgO | $Na_2O$ | Ignition loss | FeO |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ST-200-1 | Gray Coarse-grained | 12.35 | 74.96 | 0.081 | 0.58 | 3.42 | 0.425 | 0.036 | 2.31 | 0.79 | 2.04 | 2.52 | 1.90 |
| ST-200-2 | Gray Fine-Grained | 13.27 | 72.89 | 0.056 | 0.80 | 3.71 | 0.322 | 0.033 | 2.45 | 1.19 | 2.00 | 3.01 | 1.48 |
| ST-200-3 | Gray Coarse-Grained | 13.27 | 70.17 | 0.078 | 1.60 | 3.48 | 0.556 | 0.034 | 3.00 | 1.16 | 1.99 | 3.98 | 1.45 |
| ST-200-4 | Gray Fine-grained | 10.26 | 68.62 | 0.055 | 5.97 | 3.13 | 0.375 | 0.123 | 1.30 | 0.64 | 1.83 | 6.51 | 1.08 |
| Average | | 12.29 | 71.66 | 0.068 | 2.24 | 3.44 | 0.42 | 0.056 | 2.26 | 0.94 | 1.96 | 4.00 | 1.48 |

Remark: Samples are analyzed by Beijing Research Institute of Uranium Geology

Table II. The granulometric compositions of ore.

| | Number of samples | Gravel | Coarse | Medium | Fine | Very fine | Silt and mud |
|---|---|---|---|---|---|---|---|
| Eastern section | 13 | 0 | 10.51 | 58.99 | 23.51 | 7.56 | 1.25 |
| Middle section | 13 | 0.03 | 13.83 | 56.70 | 21.67 | 5.28 | 1.42 |
| Western section | 3 | 0 | 5.90 | 54.95 | 34.92 | 4.59 | 2.09 |

Remark: Analyzed by Geological Party No.208, CNNC, Baotou, China

The results of electronic microprobe analysis for ores, which is given in Table III, show that the uranium exists in two forms: adsorption and pitchblende dominated uranium mineral. The concentration of uranium in adsorption state is positively correlated with the contents of clay mineral, powdered pyrite and detrital charcoal. Whereas, the pitchblende is often associated closely with pyrite, occasionally exists in calcite cements, or as guest mineral exists in biotite and chloride. Most of pitchblende in calcite cements contains a certain amount of FeO.

U-Pb dating of 9 ore samples gave a mineralization age of 107±14Ma, about late early Cretaceous.

The calculation results of U-Ra equilibrium coefficient (Kp) show that the U and Ra in the roll-shaped orebodies inside the oxidation zone is in equilibrium (with Kp value of 0.9-1.02), and the outcrops outside the oxidation zone is in disequilibrium (Kp value of 0.7-0.8). These Kp values further indicate that the uranium ores at the front of the oxidation zone (redox front) were formed at the time of oxidization and have not been affected by later reduction. The U-Ra disequilibrium suggests that the ores had experienced secondary oxidation that led to the re-migration and re-enrichment of uranium in the pre-existing ores.

Table III. Chemical compositions of uranium minerals (Wt%)

| No. | $SiO_2$ | $Al_2O_3$ | CaO | FeO | $P_2O_5$ | $UO_2$ | Remarks |
|---|---|---|---|---|---|---|---|
| 1 | 18.7 | 1.47 | 0.65 | 1.06 | 0.43 | 73.7 | Pitchblende in calcite cements |
| 2 | 18.8 | 1.42 | 0.69 | 2.24 | 0.48 | 74.7 | |
| 3 | 15.8 | 1.23 | 2.67 | 1.23 | | 69.3 | |
| 4 | 18.5 | 1.33 | 0.89 | 1.54 | | 72.8 | |
| 5 | 17.9 | 1.27 | 1.26 | 2.05 | 0.51 | 71.1 | |
| 6 | 16.2 | 1.05 | 1.16 | | 0.42 | 74.9 | Pitchblende in the interlayer of chloride |
| 7 | 17.1 | 0.91 | 0.54 | 0.64 | 0.43 | 77.5 | |
| 8 | 18.2 | 1.33 | 1.58 | | 0.67 | 73.3 | |
| 9 | 17.4 | 1.23 | 0.60 | | 0.46 | 76.2 | |
| 10 | 16.7 | 0.97 | 0.91 | | 0.71 | 74.9 | |

Analyzed by Beijing Research Institute of Uranium Geology

## 6. Conclusion

(a) The pan-tied sand bodies at the lower member of Zhiluo Fm., deposited in incised valley, are the main host rocks in the Dongsheng mineralized area, Ordos Basin. The uranium mineralization is classified as basal channel type (or sub-type), controlled by phreatic oxidization and interlayer oxidization.

(b) The mineralization age in Ordos Basin is 107±14Ma, corresponding to so-called sub-orogeny in Mesozoic.

(c) The recognition and delineation of oxidation zone is the preliminary task for prospecting sandstone-type uranium deposit. In Ordos Basin, the purplish red residual clots existing inside the green and blue altered sandstone indicates that the oxidization of earlier stage has been transformed by later stage reduction, therefore, the altered zones of green and blue color in primarily gray colored sandstone can be taken as an criteria for oxidation zone of earlier stage. Generally, in coal-bearing basins, many cautions should be taken in delineating oxidation zones in terms of the color of rocks: not only the red and yellow can represent oxidization, but green, blue and probably others can also be the indicators of oxidization in some cases. So, it is necessary to analyze if there existed a secondary reduction in the history.

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# Characteristics of uranium mineralization and ore-controls of Kujieertai Deposit, Yili Basin, Xinjiang Autonomous Region*

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**Abstract.** Kujieertai deposit, with an area of 24 km$^2$, is the first- discovered large-scale in-situ leachable sandstone uranium deposit in China. It is hosted in loose sandstone units of coal-bearing series, Shuixigou Group (Lower to Middle Jurassic), and is strictly controlled by interlayer oxidation zones. The uranium mineralization is hosted in sandstone units of lakeshore delta facies and braided stream facies. There are 2 uranium ore-hosting horizons at the deposit. The ore-hosting sandstone units are 10-30 m thick with the permeability coefficient ranging from 0.1 m/d to 1.4 m/d. Two uranium mineralized zones have been explored, and they are 5000 m and 2500 m long respectively. Orebodies are 5m thick in average at the roll front, 2.7m thick at the upper limb, and 0.8m at the lower limb, with the grade ranging from 0.01% to 0.16%. Uranium exists in form of uranium minerals and adsorption form. Uranium minerals are mostly pitchblende (accounting for 80%) and minor coffinite (accounting for about 20%). Associated elements of uranium at the deposit include Se, Ga, Sc, Re, V, Mo etc., Se is distributed behind the roll front while other elements are located in uranium ores (roll front). Se, Sc, Re, Mo can be economically recovered as by-products. Basic geological structural features of interlayer oxidation zone, and characteristics of uranium mineralization such as the distribution of uranium mineralization, orebody shape, ore composition etc. are summarized in this paper. Authors suggest that the development of the interlayer oxidation zone and uranium ore-formation are mainly controlled by gently-dipping monocline structure resulting from sub- orogeny, K-E/J unconformity, deltaic sheet-like sandstone body and tabular sandstone body of alluvial fan to fluvial systems with abundant organic matter and other reductants, abundant uranium resources, favorable hydrodynamic regime and paleoclimatic evolution of the region.

**Key words**: Uranium deposit, interlayer oxidation zone, mineralization characteristics, ore-controls.

The Kujieertai uranium deposit in Yili basin, Xinjiang autonomous region, becomes the first large-scale roll subtype of sandstone type uranium deposit in China after several years of exploration. It is hosted in coal-bearing rock series of the Middle-Lower Jurassic. In northern China, there are lots of coal basins whose geological characteristics are similar to those of Yili basin. So the study on the geological characteristics and ore controls in Kujieertai uranium deposit can guide and help the exploration of uranium deposits in other regions, especially in northern China.

## 1. Regional geology

Yili basin is located in the west of Tianshan fold belt. It is a Mesozoic-Cenozoic intramontane continental basin formed, developed and evolved on the basis of Kongnaishi

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* The research was subsidized by the Ministry of Science and Technology of China, Project No 2001CB409808.

Carboniferous-Permian interarc taphrogenic aulacogen. The basin covers 40 000 km$^2$ area and its east part (territories of China) is about 16 600 km$^2$. The sublatitudinal fault at the southern margin of the basin and the northwest-trending fault at the northern margin (Fig. 1) control not only the borders of the basin in the south and north respectively, but also the formation and evolution of the basin. Structurally, the basin is divided into fold zone in the north, depression zone in the central, and slope zone in the south. Subsequent structural movement of the basin is characterized by the heterogeneous action, i.e., the intense movement in the north and east, the weak one in the south and west. The Mesozoic-Cenozoic strata in the southern slope zone occur as monocline with a gently dipping angle, so the slope zone is a favorable structural unit for the formation of roll subtype of uranium deposit.

*FIG. 1. Sketch geologic map of Yili Basin.*

*1) Quaternary, 2) Tertiary, 3) Jurassic, 4) Triassic, 5) Upper Paleozoic, 6) Lower Paleozoic, 7) Middle and Upper Paleozoic, 8) Hercynian granite, 9) Inverse fault, 10) Fault of unknown character, 11) Infered fault, 12) U-deposit, 13) U-occurrence.*

The basement of the basin belongs to Paleozoic fold belt and is composed of Devonian, Carboniferous and Permian intermediate-acid volcanic rocks, pyroclastic rocks, shallow-marine and continental clastic rocks, and Middle-Late Hercynian granites. The cover of the basin consists of Triassic, Jurassic, Cretaceous, Tertiary and Quaternary strata. The formation and evolution of the basin underwent the following 5 stages, namely, intensely extensional stage ($P_2$-$T_2$), weakly extensional stage ($T_3$-$J_{1-2}$, forming ore-hosting series), uplifting and erosion stage, weakly compressional stage, differential subsidence stage.

## 2. Geological features of the ore district

### *2.1. Structure and stratigraphy*

The ore district is located in the west of slope zone in the south of the basin, and is a relatively structurally stable region without big fault and fracturing. The strata dip to north gently, forming monocline with the dip angle being 5°~15°. In the slope zone, a series of sublatitudinal uplifts and depressions are formed under the neotectonism. The deposit is located at the margin of Kujieertai uplift to the west of Honghaigou sag.

The strata in the ore district include Xiaoquangou Group of Middle-Upper Triassic, Shuixigou Group of Middle-Lower Jurassic, Cretaceous, Tertiary and Quaternary. Xiaoquangou Group consists of lacustrine sediments, mainly mudstone and siltstone. Its uranium content is $3.92\times10^{-6}$, and Th content is $11.10\times10^{-6}$. Shuixigou Group is an ore-hosting series composed of alluvial fan, fluvial, delta and swamp facies sediments, i.e., as multi-rhythmic interbeds of conglomerate, sandstone, mudstone and coal. Its uranium content is $5.72\times10^{-6}$, and Th content is $9.72\times10^{-6}$. The Cretaceous is composed of fluvial-lacustrine sediments occurring as variegated calcareous conglomerate, sandstone and mudstone with the uranium content being $1.68\times10^{-6}$ and Th content being $7.90\times10^{-6}$. The Tertiary consists of piedmont alluvial fan sediments mostly containing variegated coarse clastic rocks with the uranium content being $2.38\times10^{-6}$ and Th content being $7.80\times10^{-6}$. The Quaternary is composed of piedmont alluvial facies and pluvial facies sediments.

### *2.2. Depositional characteristics of the ore-hosting horizon (Shuixigou Group)*

Shuixigou Group is also a set of coal-bearing series containing 13 coal seams. In the ore district, coal seams No.3, No.5, No.8 and No.10 are developed. Of them, coal seams No.5, No.8 and No. 10 are stably extended and can be regarded as mark beds at the southern margin. In view of characteristics of sedimentary rhythms, 8 sedimentary cycles can be distinguished from the Shuixigou Group upwards (Fig. 2).

Cycles I-IV belong to alluvial fan facies and proximal braided stream facies. They are 143m thick and contain 2~3 sandstone units that are confined by stable underlying and overlying mudstone layers. Sandstone units are composed of gray conglomerate, sandy conglomerate and pebbly medium-coarse grained sandstone with the content of organic carbon being 0.29% in average. The ratio of the thickness of sandstone units to that of mudstone layers is about 2~3. Cycles I-II are important ore-hosting horizons in the ore district.

Cycles V-VI begin from coal seam No. 5 and end at coal seam No. 10 and have 2 sandstone units, with a total thickness of 129 m. They are characterized by inverse upgrading bedding. The sandstone unit of cycle V is 15-27m thick, and extends stably. Thick impermeable mudstone and siltstone layers are developed above and beneath the sandstone unit. The sandstone unit is loose, and is mainly composed of gravel-bearing medium- to coarse-grained sandstone with abundant reductants such as organic matter and sulfides. The content of organic carbon is 1.12% in average. The sandstone unit is sheet-formed and belongs to delta facies of fan-delta depositional system. This horizon is the major ore-hosting horizon, its thickness ratio of sandstone layers to mudstone units is 1-2.

Cycles VII-VIII, with the total thickness of 51-108m, are composed of gray medium- to coarse-grained sandstone, gravel-bearing medium- to coarse-grained sandstone, siltstone, and coal seam with normal upgrading bedding. The content of organic carbon is 1.51% in average. These cycles mostly belong to lacustrine-swamp and lakeshore delta facies. Large-scale non-economic uranium mineralization is encountered in sandstone unit of cycle VII in the ore district.

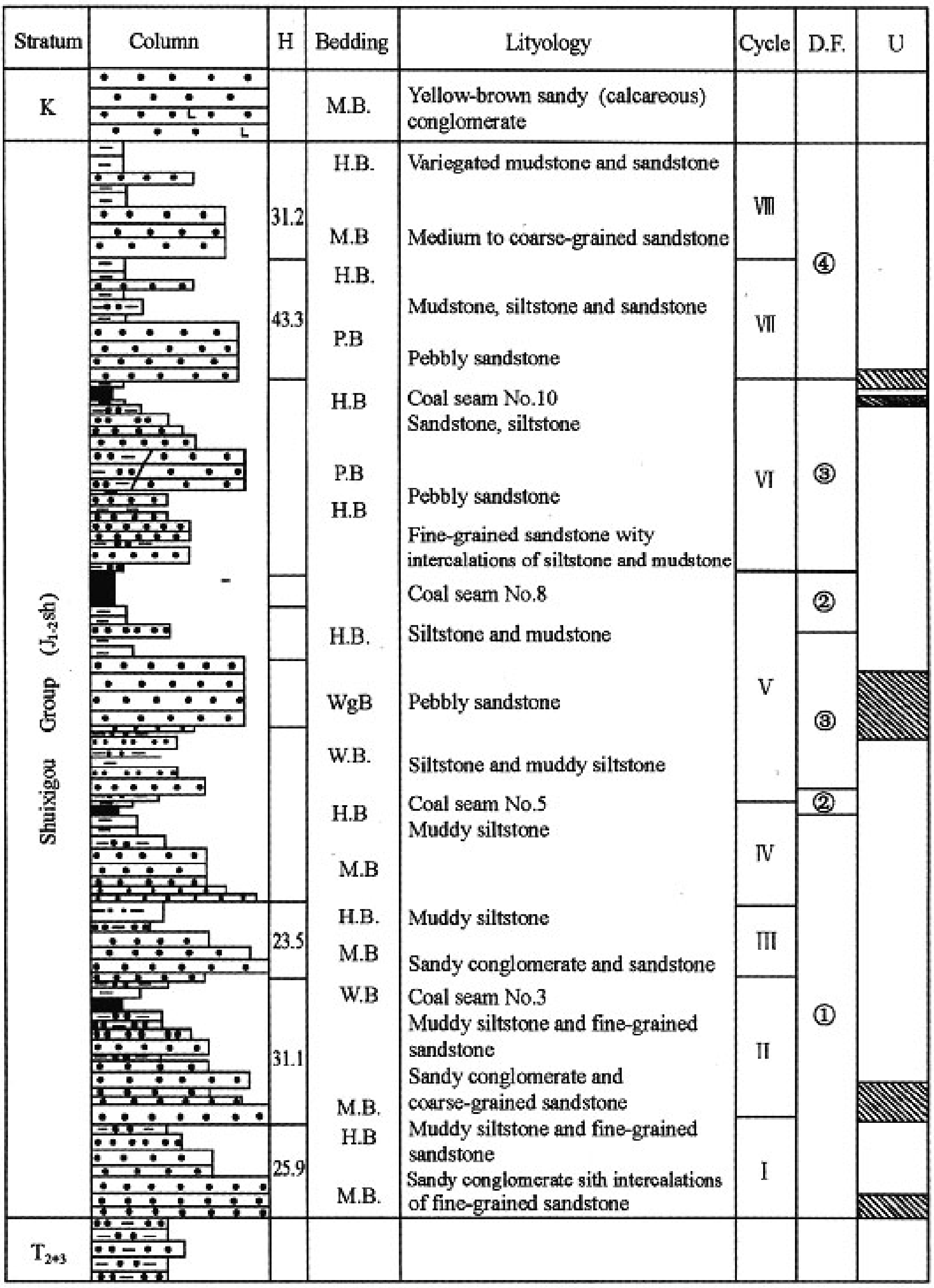

*FIG. 2. Geologic column of Shuixigou group of the ore district.*

*H) thickness, D.F.) depositional facies, U) uranium mineralization, M.B.) massive bedding, H.B.) horizontal bedding, P.B) parallel bedding, WgB.) wedged bedding, W.B.) wavy bedding, (1) alluvial fan, (2) lacustrine and swamp, (3) delta, (4) fluvial.*

## 2.3. *Hydrogeological features*

### *2.3.1. Aquifer*

There are 7 aquifers in Shuixigou Group in the ore district. Of them, aquifers of cycles I, II, V, and VII show close relationship with the interlayer oxidation type sandstone uranium mineralization.

The aquifers of cycle I and cycle II are located between the basal conglomerate and coal seam No. 3 and have two units of sandstone bodies. They are 25.9m and 23.5m thick respectively. Since the mudstone intercalation between the 2 sandstone units is unstable, sometimes they are regarded as one ore-hosting aquifer. The specific yield of the aquifers ranges from 0.0063-0.01 L/s.m, and the permeability coefficient is 0.1-0.24m/d.

The aquifer of cycle V is hosted between coal seams No.5 and No.8. It is 15-20m thick with stable extension. Its permeability coefficient is 0.7-1.4 m/d, specific yield is 0.06-0.12 L/s.m, water head is 112.26-148.18m.

The aquifer of cycle VII, located above coal seam No.10, is 15-20m thick. Its permeability coefficient is 0.73 m/d, and the specific yield is 0.059 L/s.m.

### *2.3.2. Hydrochemical characteristics of groundwater*

According to the water analysis of hydrogeologic boreholes, the ore-hosting aquifers in the ore district are characterized by high water head, shallow burial depth, and moderate specific yield and permeability coefficient. The water quality type belongs to $HCO_3$•$SO_4$a-Ca•N type with low salinity and weak alkalinity (Table I).

### *2.3.3. Recharge, runoff and discharge system of groundwater*

The groundwater of each aquifer in ore district is mainly recharged by surface water from the southern mountain area and Quaternary phreatic water. The Honghaigou groove cross the ore district cuts into the strata above Shuixigou Group, leading to the direct overlap of the alluvial sediments of present stream channels over the ore-hosting aquifers. So the groundwater of the ore district can be recharged by surface water and Quaternary phreatic water. The hydraulic gradient of the groundwater is 3%.

In the center of the basin, Shuixigou Group is mainly composed of lacustrine mudstone due to the facies change, and is buried over 1 600m below the surface. Because the geostatic pressure is much larger than the static pressure of groundwater, the groundwater moves upward and overflows to the surface, forming regional discharge area of groundwater in the southern blank of Yili River.

According to the geophysical data interpretation, a buried fault exists 1 000m to the north of the ore district. It is regarded as local discharge channel. This local discharges area is also a depressurization and gas-escaping zone, and acts as a key hydrogeologic condition controlling the development of interlayer oxidation and formation of uranium mineralization.

Table I. Hydrogeologic and hydrogeochemical indexes of main aquifers at Kujieertai uranium deposit

| Aquifer | | VII | V | | | I-II | |
|---|---|---|---|---|---|---|---|
| No.of hydrogeologic drill hole | | 2425 | 411 | 2611 | 5403 | 2402 | 3012 |
| Hydrogeologic parameter | Lithology | Medium grainded sandstone | Gritstone | Gritstone | Pebbly sandstone | Sandy conglomerate | Sandy conglomerate |
| | Thickness (m) | 19.0 | 19.2 | 21.8 | 17.8 | 17.0 | 29.0 |
| | Depth of water level (m) | 67.93 | 44.01 | 55.83 | 82.14 | 68.64 | 61.61 |
| | Water head (m) | 99.87 | 148.1 | 124.5 | 118.46 | 123.36 | 127.4 |
| | Specific yield (L/s.m) | 0.059 | 0.1 | 0.089 | 0.063 | 0.0064 | 0.0065 |
| | Permeability (m/d) | 0.73 | 1.37 | 1.02 | 0.85 | 0.15 | 0.1 |
| Hydrogeochemic Parameter | Total salinity (g/l) | 0.15 | 0.93 | 0.59 | 0.22 | 0.64 | 0.62 |
| | Water quality type | H-C | SH-NC | HS-CN | H-C | SH-NC | SH-CN |
| | Water temperature (°C) | 12.5 | -- | -- | 12.0 | -- | 14.0 |
| | Rn (Bq/L) | 12 | -- | -- | -- | 93 | 292 |
| | U ($10^{-6}$) | 1 | 30 | 60 | 30 | 1 | 1 |
| | pH | 8.3 | 8.1 | 8.3 | 8.12 | 8.4 | 8.4 |
| | Eh (mV) | 218 | -11 | -- | 2 | 168 | -163.5 |
| | Eh critical value (mV) | -80.4 | -25.5 | -42.9 | -44.6 | -112.8 | -163.5 |

The code of water quality type: H-$HCO_3$, S-$SO_4$, C-Ca, N-Na.

### 2.4. *Characteristics of interlayer oxidation zone*

#### *2.4.1. Distribution of interlayer oxidation zone*

8 layers of interlayer oxidation zones are developed in Shuixigou Group. Of them, those in cycles I-II and cycle V are closely related to sandstone type uranium mineralization. The fronts of them occur in sinuous form on plane, and in imbricated form in profile. They are 10 km long in EW direction, and several hundreds to thousands of meters wide in SN-direction. The wider the interlayer oxidation zone (indicating good development of interlayer oxidation zone) and the more obvious its protrusion to the north, the more favorable it is to the formation of uranium mineralization.

#### *2.4.2. Geochemical zonation*

According to the existence form of iron minerals and subsequent alterations, the interlayer oxidation zone can be divided into oxidized zone, redox zone and zone of unoxidized rocks (Fig. 3). The oxidized zone can be further divided into intensely oxidized subzone, moderately oxidized subzone and weakly oxidized subzone. From oxidized zone to redox zone, the content of organic carbon in rocks increases gradually with the highest reaching up to 5.6%, and Eh decreases from >300mV to –150 mV, $Fe_2O_3$ decreases gradually, FeO increases gradually, iron minerals are changed from hematite- (or limonite-) dominating to pyrite dominating. Uranium is mainly enriched in redox zone, forming uranium ore zone. Se, Mo, Re are enriched in redox zone locally, and are positively correlated to uranium (Fig. 4).

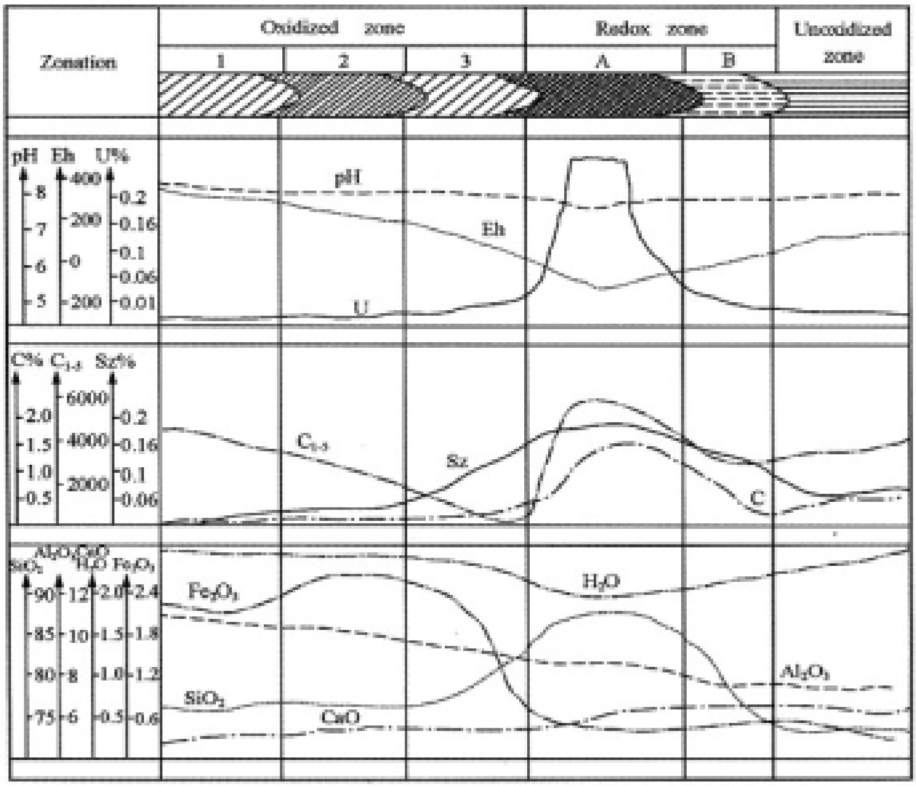

*FIG. 3. Map showing the geochemical features of interlayer oxidation zone of cycle V.*
*1) intensely oxidized subzone, 2) moderately oxidized subzone, 3) weakly oxidized subzone, C) organic matter, $C_{1-5}$) total content of hydrocarbon, Sz-sulfides.*

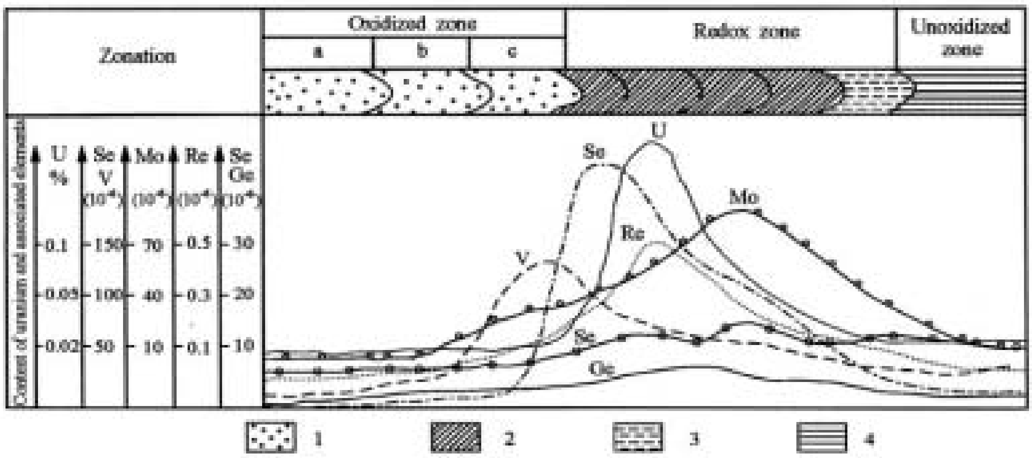

*FIG. 4. Map showing the distribution features of uranium and associated elements in interlayer oxidation zone of cycle V. 1) yellow oxidized sandstone, 2) uranium ore, 3) uranium anomaly, 4) unoxidized sandstone, (a) intensely oxidized subzone, (b) moderately oxidized subzone, (c) weakly oxidized subzone.*

## 3. Characteristics of uranium mineralization

### *3.1. Distribution of uranium mineralization*

The commercial uranium mineralization is mainly hosted in gravel-bearing gritstone in the middle-lower part of cycle V, and in coarse sandstone and sandy conglomerate of cycles I-II. The distribution of uranium mineralization is strictly controlled by interlayer oxidation zone (Fig. 5).

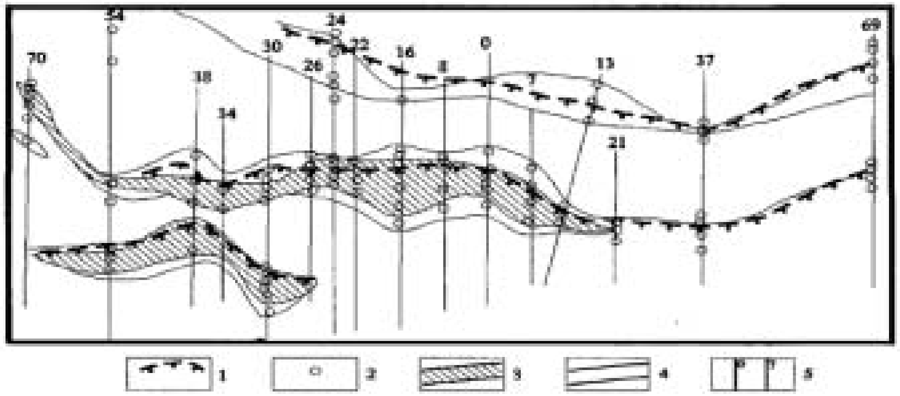

*FIG. 5. Map showing the distribution of interlayer oxidation zones and uranium mineralized zones of Kujieertai deposit. 1) redox front, 2) location of boreholes, 3) uranium mineralized zone, 4) non-economic mineralized zone, 5) exploration profile and its number.*

On plane, the uranium mineralization is located along the front of interlayer oxidation zone, constituting two sublatitudinal commercial uranium mineralized zone with the width being 200-500m and the length being 5 000m (cycle V) and 2 500m (cycle I-II) respectively.

In profile, the commercial uranium orebodies are mainly located at the front of the interlayer oxidized tongue, showing a roll shaped orebody at the contact with unoxidized gray sandstone. Minor uranium mineralization is hosted in gray sandstone at the roof and the bottom of interlayer oxidation zone, constituting the so-called limb orebody. The orebodies are buried at the depth of 140-240m. They are mainly complex roll-formed, and minor of stratiform and lens-form. (Figs.6 and 7).

### *3.2. Thickness and grade variation of the orebody*

The average thickness of the orebodies is 3.7m. In average, the orebody is 5m thick at roll head, 2.7m at upper limb and 0.8m at lower limb. The ore grade of the deposit ranges from 0.01% to 0.16%. In average, the ore grade of mineralized zone of the cycle I-II is 0.045%, and that of the cycle V is 0.03%. In general, from the limb to the roll head, the thickness and grade of the orebody increase gradually.

### *3.3. Ore composition*

The ores show dark gray, black gray and light black color, and loose texture. The detrital minerals are mainly quartz (51-79%), rock debris (8-20%) and feldspar (5-15%). Most feldspar minerals have been altered into kaolinite. Silts and clay account for 13.77%, carbonized plant fragments –1.5%, limonite less than –3%, sulfides–less than 0.37%, carbonate –0.23%, uranium minerals –0.01-1.52%. 95.3% of the ore component cannot be dissolved or are difficult to be dissolved by sulphuric acid. Only 1.5-5.5% of them might be dissolved by sulphuric acid.

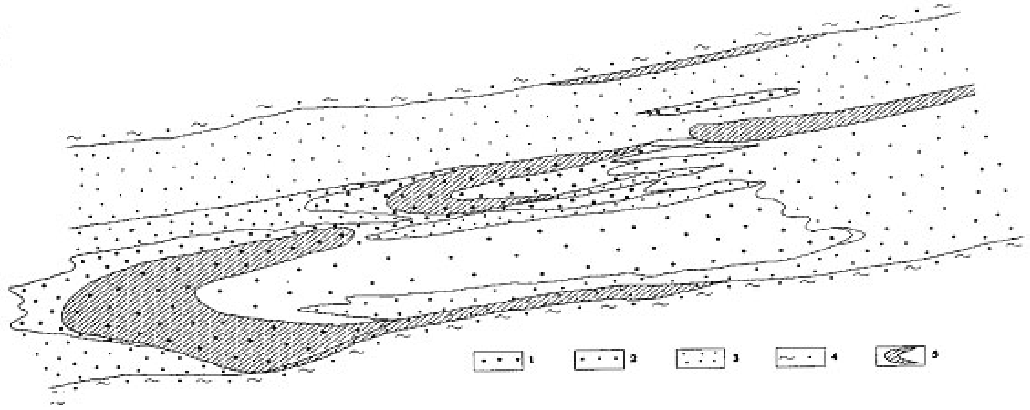

*FIG. 6. Section showing the complex roll shape of the orebody in cycle V, profile No.4.*
*1) pebbly gritstone, 2) medium grained sandstone, 3) fine grained sandstone, 4) mudstone, 5) uranium orebody.*

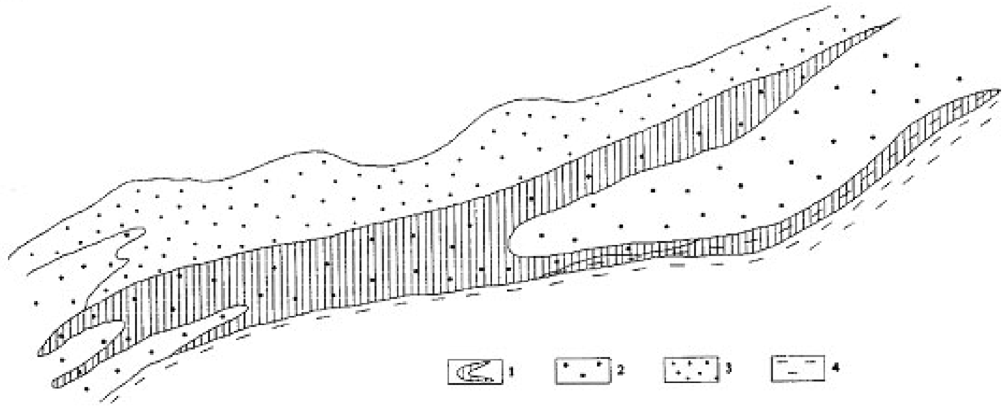

*FIG. 7. Section showing the shape of the orebody in cycle V, profile No.0.*
*1) uranium orebody, 2) pebbly gritstone, 3) medium grained sandstone, 4) mudstone.*

Uranium in ores exists in form of uranium minerals and disseminated adsorption form. The uranium minerals include pitchblende (80%) and coffinite (20%). Sometimes brannerite and uranium-bearing titano-magnetite are observed. Pitchblende occurs as microscopic or supermicroscopic crystals, mostly coating quartz and pyrite or within the cell of carbonized plants. Its lattice cell parameter is $5.41\times10^{-10}$m in average, indicating the moderate oxidation. Coffinite often occurs in microscopic form. Brannerite and uranium-bearing titano-magnetite are placer minerals from provenance areas. Disseminated adsorption uranium exists in the cement of ores, usually adsorbed by the carbonaceous, pelitic materials and pyrite.

Associated elements include Se, Ga, Sc, Re, V, Mo etc. Se is distributed immediately behind roll orebody, while other elements are located in the roll ores. Of them, Se, Sc, Re, Mo can be recovered economically as by-products.

The ore composition of the deposit indicates that it is very favorable for acid in-situ leach mining.

### *3.4. U-Ra equilibrium*

U-Ra equilibrium coefficient (Kpp) of ores in cycle V and cycles I-II are 0.89 and 0.87 in average respectively, indicating the deviation to uranium during the epigenic process. From the oxidation zone to redox zone, then to unoxidized zone, Kpp shows a gradually decreasing trend.

### *3.5. Age of uranium mineralization*

According to the study of Chen Daisheng et al, Beijing Research Institute of Uranium Geology, U-Pb isotopic age dating of ores yields 19±11Ma. Pb-Pb isotopic age dating of ores and country rocks by Gu Kangheng [1] yields 25.38Ma. These data suggest that the major ore -formation mostly took place during the period from Late Oligocene to Early Miocene.

## 4. Major ore controls

### *4.1. Structural control*

#### *4.1.1. The gentle monocline slope formed by neotectonic movement is an important ore-localization space*

The neotectonic movement results in the uplifting of the mountains to the south and north of the basin, forming monocline slope dipping toward the basin at the pediment area in the southwest part of the basin. Within the monocline slope, the differential uplifting leads to the formation of a series uplifts and sags. Kujieertai deposit is just located at the margin of a relative uplift. Shuixigou Group and its overlying strata dip towards the basin with a dipping angle of 5-10º, which provides favorable prerequisites for the infiltration of groundwater into the loose sandstone units.

#### *4.1.2. K-E/$J_{1-2}$ unconformity formed by pulse uplifting during Late Yanshanian period controls the formation of the deposit*

Affected by the multiple structural impact, two unconformities, namely, $J_{1-2}$/ $T_{2-3}$, K-E/ $J_{1-2}$ unconformities are formed during the formation and development of the basin. These two unconformities, especially the K-E/ $J_{1-2}$ unconformity, control the development of the interlayer oxidation zone type uranium mineralization. The K-E/ $J_{1-2}$ unconformity corresponds to a period of paleo-regolith. Strata above the regolith are a set of variegated sediments. Those below it have been involved in paleo-phreatic oxidation zone extensively developed at southern margin of the basin. The exposure of the ore-hosting aquifers of Shuixigou Group meets the unconformity with the meeting angle of 2-3º. Structural uplifting led to a quick circulation of groundwater, and made paleo-phreatic oxidation zone be developed deeper along the aquifers and thus interlayer oxidation zone and associated uranium mineralization were formed.

### *4.2. Lithological and lithofacies control*

Shuixigou Group is composed of sediments of alluvial fan, braided stream, delta, lacustrine and swamp depositional system. Uranium mineralization is mostly hosted in braided stream and delta facies. The ore-hosting sandstone units are distributed extensively with the thickness being 15-50m, striking extension being greater than 50km and dipping extension being greater than 2km. Lithologically ore-hosting sandstone units are composed of gravel-bearing medium- to coarse-grained sandstone and sandy conglomerate. Ore-hosting rocks are characterized by pelitic cement, loose texture, good permeability and high content of reductants such as organic matter, pyrite, as well as hydrocarbon.

### *4.3. Hydrogeologic control*

Complete hydrodynamic regime (recharge, runoff, discharge) is well developed in southwest margin region of the basin. The ore district is located in the runoff area of groundwater. Hydrogeochemically, the 7 confined aquifers in the ore district are favorable to uranium ore-formation. Especially the aquifers of the cycles I-II, V have moderate thickness, good permeability, highly confined interlayer groundwater with moderate flow speed, temperature, Eh, pH and salinity, which are very favorable to the formation of interlayer oxidation zone type uranium mineralization.

### *4.4. Uranium source control*

The uranium source for the deposit is considered to be abundant. C-P intermediate-acidic volcanics and Hercynian granite are extensively distributed in the southern provenance area of the basin, with an exposure area greater than 3000 $km^2$. Uranium content of them is $4\times10^{-6}$-$14.3\times10^{-6}$ in average. These suggest that the provenance area could provide abundant uranium for uranium ore formation in the basin. Moreover, the oxidation zone of the ore-hosting horizon can also provide some uranium for the ore formation during interlayer oxidation process.

### *4.5. Paleoclimatic evolution control*

During Early to Middle Jurassic, coal-bearing clastic rocks of Shuixigou Group were formed in the basin under warm and humid paleoclimate. Since Late Jurassic, the basin has been under semiarid to arid climate and weakly compressional structural regime. The semiarid to arid paleoclimate and gentle uplifting make the groundwater rich in free oxygen and intensely circulating. So the development of interlayer oxidation zone and the formation of sandstone type uranium mineralization must also be attributed to the change of paleoclimate from humid to arid.

## REFERENCE

[1] Kangheng, GU., Baoqun, WANG., Uranium Metallogenic Geologic Characteristics of Deposit No.512 in Interlayer Oxidation Zone, Yili Basin, Xinjiang, Northwest Uranium Geology, 1995, (in Chinese).

# Metallogenetic features and perspective evaluation of sandstone-type uranium mineralization in Hailaer Basin, NE, China

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**Abstract.** Hailaer basin is located at the Mongolia-Erguna microplate between Siberian and North-China plates. The basement of the basin is composed of Precambrian igneous and metamorphic rocks, which experienced multiple granitization, and Late Paleozoic, Mesozoic granites and acidic-intermediate volcanics constituting a uranium-enriched provenance area. The sedimentary cover of the basin consists of continental sedimentary series of Late Jurassic to Tertiary. Of them, Lower Cretaceous (Damouguaihe Formation) clastics of alluvial, fan-delta and fluvial facies rich in organic matter are the main uranium ore-hosting series. Numerous uranium occurrences have been found at the western part of the basin, and uranium mineralization mainly occurs in coarse-grained clastics of the second and third members of Damouguaihe Formation. Uranium orebodies usually are tabular, a few roll-shaped. The thickness of individual orebody ranges from 0.3m to 5m. Ore grade commonly is 0.0n% with the encountered highest grade of 0.38%. Uranium in ores is in adsorption form, heterogeneously disseminated in the cement of sandstone. No independent uranium mineral has been found. Associated elements in ores include Mo, V, Se, Sc, and Re. Discovered uranium mineralization in the basin approximately occurs at the same elevation intervals (660-680m), suggesting the paleo-phreatic origin. Uranium mineralization is mostly localized in permeable sandstone units of fluvial and fan-delta facies with high content of organic matter. Ore-formation age is supposed to be the period from $K_2$ to N when the ore-hosting sedimentary series outcropped at the surface and was eroded. High content of uranium in provenance area, existence of permeable ore-hosting sandstone units and the oxidation (phreatic and interlayer) alteration of ore-hosting sandstone after its deposition under arid climate environments are key factors determining the perspective potential of uranium ore-formation.

**Key words:** Perspective evaluation, sandstone-type uranium mineralization, Hailaer Basin.

## 1. Geological setting

### *1.1. Geotectonic feature*

The Hailaer basin is geotectonically located in the Mongolia-Erguna microplate between the western Siberia and North China Plate (Fig. 1). The microplate extends in NE direction and is mainly composed of Precambrian igneous and metamorphic rocks. These basement rocks underwent multiple granitization and were enriched in uranium. The high content of uranium in basement rocks could provide abundant source for uranium ore-formation in the basin, especially its western part. In fact, a lot of different type uranium deposits, such as volcanic and sandstone types of uranium deposits, occur in the microplate and form a NE- trending uranium metallogenic belt (Fig. 2). In addition, a number of large or super large gold, silver-lead-zinc and copper-molybdenum deposits, were discovered in the region as well.

### *1.2. Tectonics of the Basin*

The main part of Hailaer basin is located in NE China, with its southwestern part in Mongolia, and covers approximately area of 40 000 km$^2$. It is a compound basin and composed of a series of depressions and uplifted blocks (Fig. 2), which are structurally controlled by NE-striking faults. Some of the depressions, such as Xihulitu, Kelulun, Chagannor and Herhongde, have been studied for prospecting uranium resources.

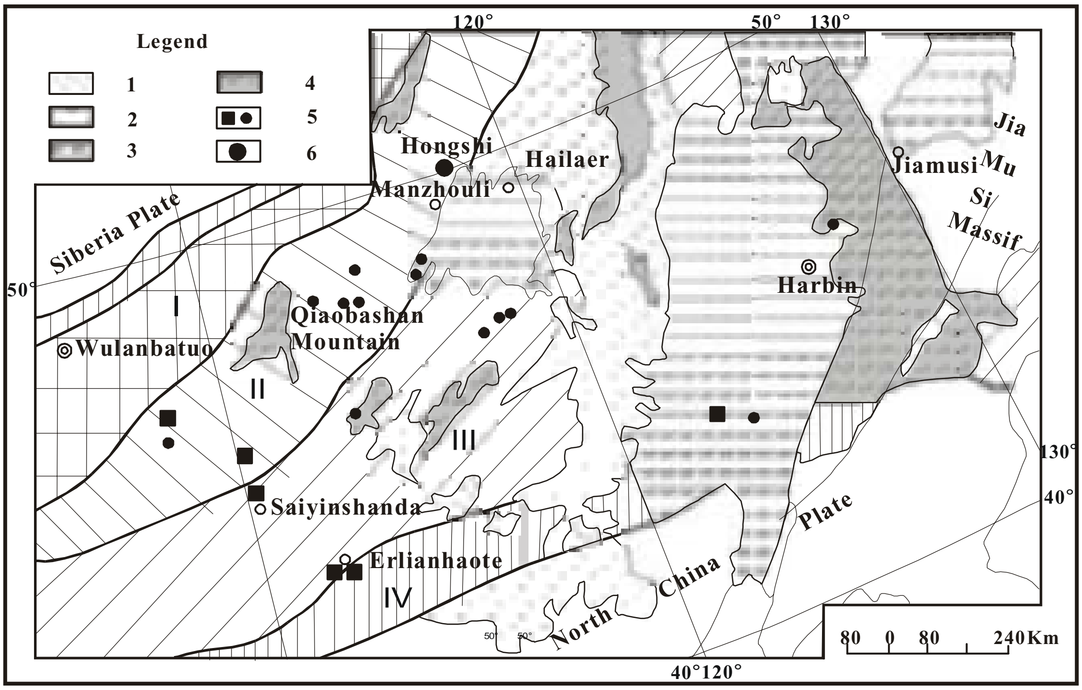

*FIG. 1. Geotectonic map showing the location of Hailaer basin.*

*1) Quaternary basalt, 2) Mesozoic volcanics, 3) Mesozoic basin, 4) Paleozoic granite, 5) Sandstone-type U-deposit and occurrence, 6) Hydrothermal U-deposit. Microplates: (I) South Siberia, (II) Mongolian-Erguna, (III) Xin'an, (IV) Songliao-Xilinhote.*

The basin has typical structural pattern consisting of basement and sedimentary cover. The basement rocks are Precambrian metamorphic rocks, Late Paleozoic and Mesozoic granites and Jurassic intermediate-acidic volcanic rocks. The sedimentary cover is composed of Meso-Cenozoic sediments.

### *1.3. Evolution of the Basin*

The evolution of the Hailaer basin can be divided into six stages according to its tectonic features and depositional succession of sediments. Characteristics of each evolution stage are discussed as follows respectively.

***1) Depression-developing stage:*** During the Late Jurassic period, after the basement underwent volcanism and metamorphism, the dynamic feature of tectonics changed from compression into extension regime due to the upwelling of the mantle. Primary extensional faulting took place and down-faulted depressions started to be formed.

***2) Strongly extensional faulting stage:*** Down-faulted depressions continued to evolve and tectonic environments for depressions and uplifts were getting more and more different due to strongly extensional tectonics. The strongly down-faulted depressions were accompanied by rapid, badly sorted and shortly transported coarse-grained sediments, which are violet-red in color, belonging to molasses formation deposited under the arid paleo-climate. The sediment sequence was mainly deposited in alluvial fan and fluvial facies and is named Tongbenmiao Formation.

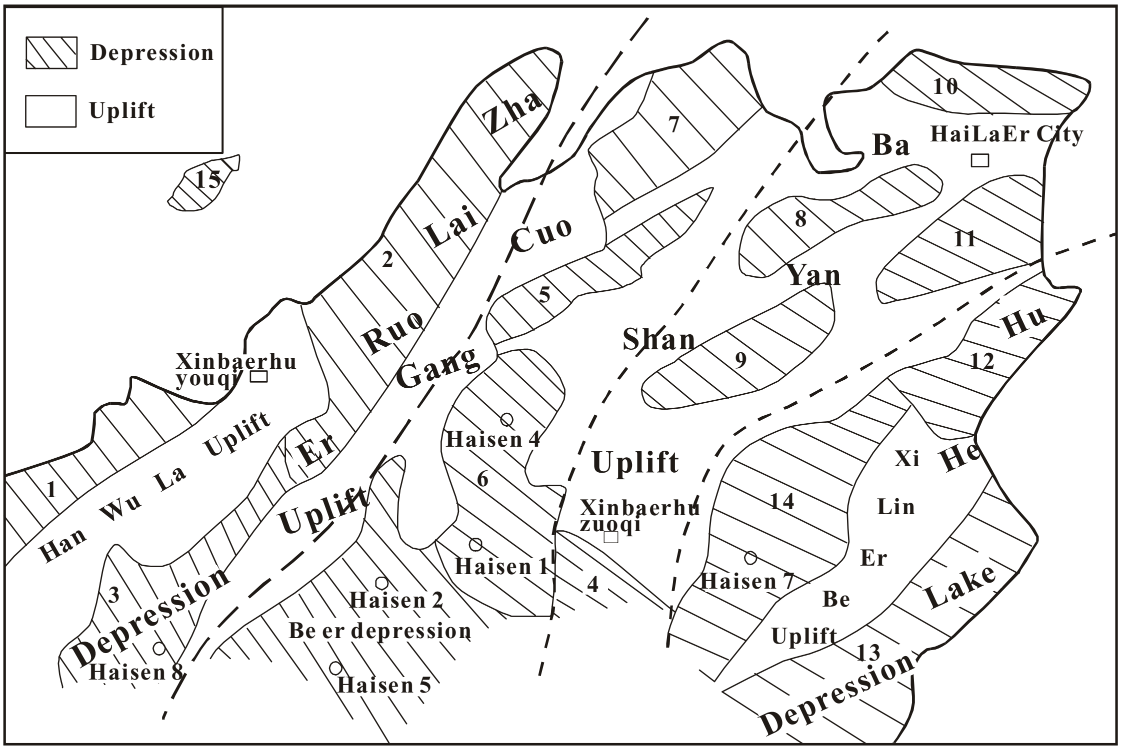

*FIG. 2. Structural division of Hailar basin.*

*1) Bayanhushu dep.; 2) Hulunhu dep.; 3) Chaganruoer dep.; 4) Muchang dep.; 5) Hongqi dep.; 6) Wuerxun dep.; 7) Heerhongde dep.; 8) Wuguruoer dep.; 9) Modamuji dep.; 10) Dongming dep.; 11) Ewenke dep.; 12) Yimin dep.; 13) Jiuqiao dep.; 14) Huhehu dep.; 15) Xihulitu dep.*

***3) Rapidly down-faulting stage:*** After strongly extensional faulting, the depressions settled rapidly and expanded. Water bodies became deeper and the paleoclimate changed from arid to intermittent arid, humid conditions. The sediment sequence is represented by the Nanten Formation, which is mostly composed of gray coarse to medium-coarse grained clastics. They have complex composition and belong to deep to semi-deep lacustrine, deep-water fan and turbidity fan facies.

***4) Stable extension stage:*** Extensional strength increased and the depressions evolved into stable extension stage. Water depth became shallow. Sediments were deposited usually in fluvial lacustrine system, being mainly composed of fine to medium grained sandstones. The sediment sequence is interbedded with coals, and usually contains organic materials, which indicate the predominant humid paleoclimate. This rock sequence is named Damoguaihe Formation, which is an important ore-hosting horizon for uranium mineralization.

***5) Erosion stage:*** During Late Cretaceous to Early Tertiary ($K_2$ to $E_1$), tectonic dynamics were changed from extension to compression character, and the crustal movement was basically characterized by vertical uplifting-subsidence. The most part of the basin was exposed and eroded. No sediments were recorded.

***6) Final filling stage:*** During Late Tertiary to Quaternary, settlement continued to be developed. The sedimentation was dominated by fluvial system. The sediments are characterized by coarse-grained sandstone and reddish color, indicating the arid climate at that time.

### *1.4. Rock sequences of sedimentary cover*

The Hailaer basin was mainly filled by Meso-cenozoic sedimentary rocks, which can be classified into Tongbenmiao and Nanten Formations, Late Jurassic, Damoguaihe and Yimen Formations, Early Cretaceous and Qingyuangan Formation, Late Cretaceous, Huchashan Formation, Late Tertiary and Quaternary series. As discussed above, these sedimentary rocks were tectonically controlled by evolutionary features of the basin. Their filling sequences and lithological descriptions are summarized in Table I.

Table I. Rock sequences and lithological features of the Hailaer Basin

| Age | Formations | Main Facies | Lithological features | Notes |
|---|---|---|---|---|
| Q | Quaternary series | Eolian alluvial and lacustrine | Soils and unsolidified deposits | |
| N | Huchashan Formation | Fluvial and lacustrine | Colorful clastic rocks | |
| $K_2$ | Qingyuangan Formation | Fluvial and lacustrine | Mainly reddish clastic rocks, partly gray rocks | Locally distributed |
| $K_1$ | Damoguaihe Formation | Alluvial fan-delta, fluvial, lacustrine and marsh | Clastic rocks, shales and coals | Ore-hosting bed |
| $J_3$ | Nanten Formation | Alluvial fans and lacustrine | Mainly gray coarse- to medium-coarse grained clastic rocks | |
| | Tongbenmiao Formation | Alluvial fans and fluvial | Mainly coarse grained sediments | |
| Pre $J_3$ | Paleozoic and Precambrian rocks | Basement | Metamorphic, volcanic and granitic rocks | |

Most of these formations are widely distributed in the basin except Qingyuangan Formation, which is locally found in some depressions. The rock sequences also show that the basin underwent multiple tectonic movements and a long-term erosion during Late Cretaceous to Early Tertiary.

To select favorable uranium-hosting units, following criteria have been used:

(a) Burial depth of orebody: less than 500 meters.
(b) Favorable sandstone to mudstone ratio of ore-hosting unit: 2:1 to 1:1.

(c) Reductants for uranium concentration: a certain amount of organic matter or sulphide minerals etc.
(d) Occurrence of ore-hosting unit: dipping angle usually less than 10 degrees.
(e) Good permeability and wide distribution of ore-hosting unit.

The Damoguaihe Formation in the region is regarded as the main target unit for uranium prospecting.

## 2. Metallogenetic features

A lot of uranium occurrences have been discovered in Damoguaihe Formation in Hailaer basin, especially in its western part. The general metallogenetic characteristics are discussed in the following sections.

### *2.1. Orebodies and lithology*

Damoguaihe Formation can be subdivided into three members from the top to the bottom based on its filling successions and lithological features:

***Member 1*** is dominantly composed of coarse grained clastic rocks, such as conglomerate, gravel-bearing sandstone, different kinds of sandstone and a little mudstone. Generally, These are badly sorted clastics, belonging to alluvial fan system, and having complex compositions.

***Member 2*** is generally composed of relatively fine-grained clastic rocks, mudstone and coals. The clastics are dominated by medium to fine grained sandstone, and usually well sorted. They belong to fluvial-delta system in facies. Mudstone usually contains abundant organic matter and sulphides such as pyrite. In some beds of member 2, the content of organic matter is so high that they can be regarded as coal beds. They are obviously formed in marsh environments.

***Member 3*** is similar to the member 1, mainly consisting of coarse grained clastics, deposited in alluvial fan system.

Three Uranium ore-hosting units have been found in the upper two members of the Damoguaihe Formation:

The first ore-hosting unit occurs in transitional site between the member 2 and member 3, but mainly at the bottom of the member 3. So, lithologies of the ores are conglomerate, gravel-bearing sandstone, coarse grained sandstone and some siltstone.

The second ore-hosting unit exists in the upper part of the member 2, usually above coal beds. Ores are mainly composed of siltstone and contain abundant organic matter.

The third ore-hosting unit occurs at the bottom of the member 2, below coal beds. Ores mainly consist of medium grained sandstone, and some fine grained sandstone and siltstone.

In general, ores are loosely cemented.

### *2.2. Depth of uranium mineralization*

The occurrence depth of uranium ore-bodies varies from place to place, generally is less than 120m, mostly ranging from 30 to 90m, and in places, orebodies outcrop at ground surface. Actually, uranium mineralization took place at the similar sea-elevation level in the same depression, because it is controlled by paleo-groundwater table.

### *2.3. Shape, grade and thickness*

Orebodies are generally tabular-shaped, and locally roll-shaped, depending on the genesis of uranium mineralization. In addition, the impermeable mudstone beds below ore-hosting units are developed, but above the ore-hosting units they exist locally.

Grades of ores vary from place to place, with the highest grade of up to 0.378% and generally are 0.0n%. Ore grades are positively correlated with the content of organic matter. Thickness of ore beds also varies from place to place. The thickness of single ore bed ranges from 0.3 to 5 meters.

In general, uranium occurs in the adsorption form and is heterogeneously distributed in ores.

### *2.4. Geochemical features*

***1) Geochemistry of major elements:*** Uranium ores are geochemically characterized by acidic compositions (Table II), namely, high content of $SiO_2$, $Al_2O_3$, $K_2O$, $Na_2O$, and lower content of MgO, CaO, $MnO_2$, $Fe_2O_3$. The chemical compositions also show that ores are arkose sandstone and originated from acidic volcanic rocks.

Table II. Chemical compositions of major elements of ore samples from the Xihulitu depression

| Samples | $Al_2O_3$ | $SiO_2$ | $P_2O_5$ | CaO | $K_2O$ | $TiO_2$ | $MnO_2$ | $Fe_2O_3$ | MgO | $Na_2O$ | L.O.S |
|---|---|---|---|---|---|---|---|---|---|---|---|
| ZK2-3-1 | 15.86 | 68.77 | 0.039 | 0.43 | 4.82 | 0.849 | 0.018 | 1.47 | 2.42 | 2.65 | 4.32 |
| ZK2-3-5 | 14.14 | 67.75 | 0.247 | 0.71 | 4.19 | 0.741 | 0.019 | 2.91 | 0.43 | 2.26 | 5.95 |
| ZK2-3-6 | 13.68 | 71.75 | 0.057 | 0.43 | 5.23 | 0.509 | 0.017 | 1.22 | 0.28 | 2.89 | 3.08 |
| ZK2-3-16 | 13.96 | 72.12 | 0.021 | 0.42 | 5.29 | 0.395 | 0.014 | 1.06 | 0.25 | 3.12 | 2.71 |
| ZK2-3-17 | 14.01 | 72.02 | 0.036 | 0.49 | 5.03 | 0.436 | 0.013 | 1.02 | 0.27 | 3.15 | 3.01 |
| ZK2-3-18 | 12.03 | 75.82 | 0.027 | 0.34 | 4.92 | 0.318 | 0.011 | 0.81 | 0.28 | 2.8 | 1.99 |
| ZK2-3-43 | 11.15 | 55.19 | 0.032 | 1.06 | 3.79 | 0.641 | 0.029 | 1.97 | 0.41 | 2.03 | 22.92 |

Table III. Chemical compositions of trace elements of ore samples from the Xihulitu Depression ($10^{-6}$)

| Element | Clark's value | Max. Value in ores | Enrichm. coefficient |
|---|---|---|---|
| Mo | 1.1 | 777 | 706 |
| V | 90 | 605 | 6.7 |
| Se | 0.05 | 18.3 | 366 |
| Sc | 10 | 13.15 | 1.3 |
| Re | 0.007 | 1.407 | 201 |

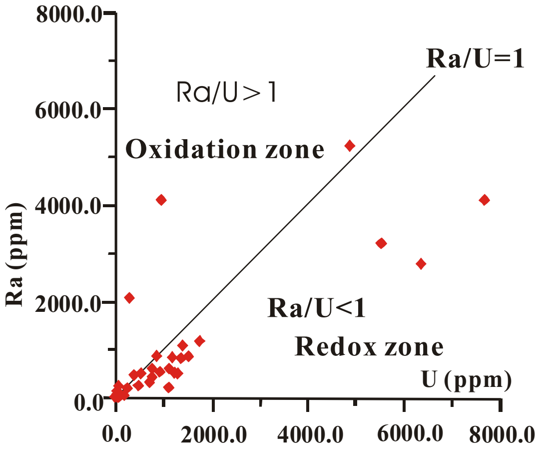

*FIG. 4. Relationship between uranium and radium in different conditions.*

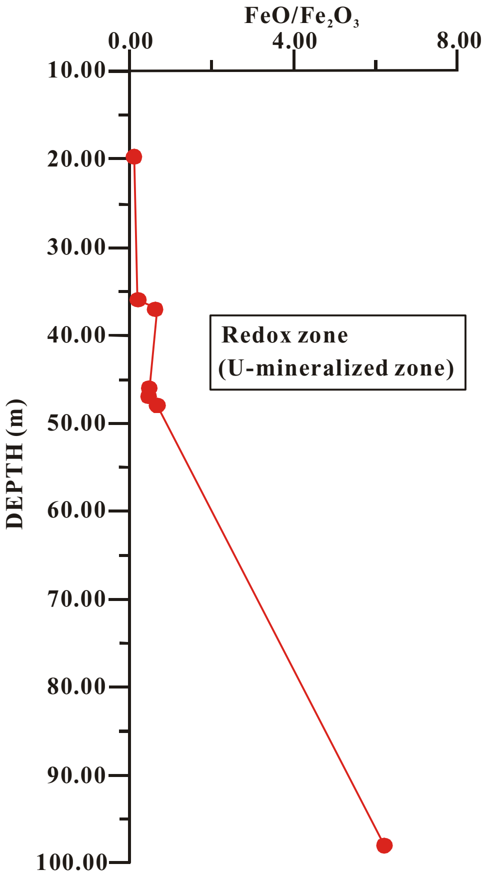

*FIG. 3. The variation of ratio $FeO/Fe_2O_3$ vs. depth showing redox environment in the ore section.*

The chemical composition data show systematic change from oxidation, redox zones to zone of unaltered rocks. The change is especially represented by the $FeO/Fe_2O_3$ ratio (Fig. 3). That is, the ratio increases with the depth from oxidation to reducing environment.

***2) Geochemistry of trace elements:*** In general, the studied area is enriched in Li, Rb, Zr, Hf, Nb and depleted in Cr, Co, Ni as compared with Clark's values of these elements. These geochemical signatures also confirm that the provenance rocks of the basin sediments are characterized by acidic composition, which usually have high content of uranium and thorium. In addition, some trace elements such as Cu, Pb, Zn, Ba and rare earth elements are enriched to a certain degree in uranium ores. The enrichment signatures of trace elements are characterized by uranium-associated elements such as Mo, V, Se, Sc, Re (Table III). The enrichment coefficients change from 1.3 to 706 (Table III), and molybdenum is enriched the most. These signatures mean that those associated elements migrated together with uranium under oxidation environment and were accumulated under reducing environment, having similar geochemical behaviors. In fact, enrichment degree of those elements is different from element to element in different zones, e.g. molybdenum is more mobile than uranium and precipitates in front of uranium, and Se just in return.

***3) Equilibrium coefficient of radium to uranium:*** The analyzed data from the samples of the study area show that the coefficient also changes systemically from oxidation, redox zones to zone of unaltered rocks (Fig. 4) The coefficient is more than 1 in oxidized zone, the maximum coefficient value of the oxidized sample from the Xihulitu depression is 7.468, that is, uranium has been removed strongly in oxidized zones. And in the redox zone, the coefficient is less than 1 with the minimum value of 0.205, and the statistically mean value of 0.6, indicating the strong enrichment of uranium. Uranium and radium is in equilibrium in the zone of unaltered rocks with the coefficient of about 1. It means that both uranium and radium have not been removed after the diagenesis. In other words, these rocks didn't undergo any post-diagenetic processes. Furthermore, the coefficient variations also indicate that uranium mineralization took place through the epigenetic or redox processes.

### *2.5. Main ore-controlling factors*

In general, the ore-controlling factors can be summarized as follows:

(a) Uranium mineralization in Hailaer Basin is mainly controlled by the paleo-phreatic oxidation and the location of tabular uranium orebodies represents the ancient ground water table. So the vertical geochemical and mineralogical zonations can be identified, and uranium mineralized intervals in boreholes often occur at the similar elevation.

(b) Lithofacies is also an important factor controlling the location of mineralization. Ores with high grades are usually found in facies of fluvial and delta-front sandstones.

(c) Uranium mineralization is associated with reductants such as organic materials and sulphides in ore-hosting sandstone. Sandstone units are barren of uranium mineralization.

(d) Fault structures play a certain role in the localization of uranium mineralization, especially in case of the local interlayer oxidation zone uranium mineralization, because faults improve hydro-geological condition (being local discharge channel).

In summary, the uranium mineralization in Hailaer basin is genetically controlled firstly by ancient phreatic oxidation surface, and secondly by interlayer redox zone.

## 3. Perspective evaluation

The comprehensive study shows that Hailaer basin, especially its western part, possesses following favorable conditions for uranium ore-formation.

(a) Abundant uranium resources: Regional airborne radiometric survey data and analytical data confirm that the basement and ore-hosting units (Damoguaihe Formation) are enriched in uranium. Acidic volcanic rocks and granitoids in the basement have uranium content generally ranging from 4 to 8 ppm, and the highest uranium content of more than 10 ppm; Sedimentary rocks of the ore-hosting units have uranium content similar to that of basement rocks. These data show that the basin must be a very perspective potential for uranium ore-formation, especially in its subsidiary depressions.

(b) Favorable target units: The target units in Damorguaihe Formation (some area, Yimen Formation) are widely distributed, shallow buried (<500m), gently dipping (dipping angle <10 degrees), having suitable sandstone to mudstone (>1) ratio and proper permeability, as well as certain amount of reductants.

(c) Favorable tectonic evolution of basin: After the deposition of the target units, the basin underwent a long term depositional break ($K_2$ to E) and the target units were exposed so that oxidation processes made uranium in the rocks mobile and the enrichment of uranium possible in the target units.

(d) Paleo-climatic evolution: Ore hosting units were formed in humid paleo-climatic conditions so that they could contain certain amount of organic matter, and afterwards, the paleo-climate changed from humid, semiarid to arid one, which was favorable for the infiltration of groundwater, and the development of oxidation processes and uranium ore-formation.

(e) Hydrological condition: This is an important prerequisite for the formation of interlayer oxidization type uranium deposit, because well developed hydrodynamic system composed of recharge, run-off and discharge is necessary for the formation of sandstone-hosted uranium deposit, and some faults which were acting as discharge zones could improve hydrodynamic regime of the basin.

(f) Reductants: The potential ore-hosting units in Damoguaihe Formation contain abundant reductants such as organic matters and sulphides. These reductants are necessary to reduce and enrich uranium in ore-hosting units.

(g) A lot of uranium occurrences and anomalies have been found, that can be regarded as indications for the enlargement of uranium resources in the future.

In fact, the above mentioned conditions can be used as evaluation criteria for regional perspective analysis at the same time, and it can be concluded that Hailaer basin is of certain potential for sandstone type uranium deposits, especially those formed by paleo-phreatic oxidation process.

## 4. Conclusions

(a) The basement rocks of Hailaer basin are highly evolved and underwent multiple granitization, resulting in the enrichment of uranium and could provide abundant uranium for ore-formation.

(b) Ore-hosting Damoguaihe Formation was deposited in a stable extension stage and belongs mainly to a fluvial and fluvial fan-delta system. The long depositional break between Late Cretaceous and Early Tertiary is, in fact, an important stage for uranium ore-formation.

(c) Paleo-climatic evolution of the region underwent a change from humid in Early Cretaceous to semiarid, arid features in Late Cretaceous and Early Tertiary. This climatic change was favorable for the migration and concentration of uranium in ore-hosting units.

(d) The uranium orebodies are of shallow burial depth, loose cementation, low content of carbonates, high content of associated elements. Orebodies usually exist in tabular form and are controlled mainly by the ancient groundwater surface. High-grade ores are found in sandstones of fluvial facies. Phreatic oxidization of uranium ore-formation has been confirmed by many features of uranium ores and orebodies.

(e) Basic criteria of perspective evaluation have been discussed. The western part of Hailaer basin is favorable for uranium ore-formation and of significant potential for sandstone type uranium deposits.

# EXPLORATION: NEW PROJECTS

# Exploration and reserve calculation of the uranium deposits amenable to the ISL method in Kazakhstan

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**Abstract.** Exploration methods, study of ores and reserve calculation of the uranium deposits hosted in the Cretaceous sediments at the Chu-Saryssu ore region in Southern Kazakhstan, are shown in the paper. The Zhalpak, Mynkuduk, Akdala, Inkay and Budyonovskoe deposits form a unique uranium Ore Belt, and have been discovered and studied for 20 years, from 1971 to 1991. In the paper a very important conclusion is made on the key role of regional bed oxidation zones in forming such large-scale uranium ores. Drilling was the main study method. Several stages of study have been described in the paper: pre-search, search, preliminary exploration and detailed exploration. At the first stage, the study was carried out by reconnaissance drilling using previously created lithologic-facial plans for the predicted sediment horizons. Lines of drilling holes were situated taking into account the underground water flows from a recharge area and the position of grey-coloured channel facies among overall mottled sediments of the region. At the next stages, drilling hole grids of various densities were used for contouring and sampling ore bodies. The important role of geological description of the drilling core, geophysical and hydro-geological data as well as the results of modelling using laboratory filtration pipes for the creation of lithologic-filtration maps and the division of the ores into lithologic-filtration types were shown. Based on these data the reserve calculation was carried out using the "geological blocks" method. Thus in the paper, the complete sequence of operations -from discovery to reserve calculation- is demonstrated. It is shown that work at different stages could be carried out simultaneously across the entire Ore Belt. In this case, the peculiarities of the ore localization received at the detailed stage were used for the search and reconnaissance stage. It is also shown that exploration work was carried out at a rapid pace, widely using drilling without a core, employing geophysical data, and with a high efficiency of work. A high level of uranium recovery was proven by the results of the field tests.

## 1. Introduction

In 1956, while studying uranium deposits hosted in Cretaceous sediments on the territory of Uzbekistan, geologists V.M. Mazin and G.A. Pechenkin established a spacial relation for uranium ore between the boundaries of the yellow oxidized sand sediments of aquifers and un-oxidized grey sand sediments. Use of this peculiarity permitted the discovery of oxidation zone development among friable water-bearing sediments. These oxidized zones were later called bed oxidation zones, (BOZ) by Soviet geologists. Under further investigation, wide expansion bed oxidation zones were revealed among friable sediments of the artesian basins of Uzbekistan and the South of Kazakhstan. A whole series of uranium deposits amenable to the In Situ Leaching (ISL) method was revealed at the area of BOZ attenuation in favourable conditions. In connection with the later established important ore-generating role of BOZ for uranium deposits, such deposits were named BOZ deposits by Soviet geologists.

The search for BOZ deposits, on the territory of the depression structure of Kazakhstan, started in the late 50s. By this time, the favourable features of BOZ development and related uranium deposits were formulated:

(a) hydrodynamic conditions of infiltration artesian basins;
(b) arid climate conditions of the ore deposition epoch;
(c) favourable lithologic-geochemical type of host rocks (grey-coloured, easily permeable sediments).

Chu-Saryssu and Syr-Darya depressions were the most perspective territories. In this region 15 large and unique uranium deposits [1] were found in Cretaceous and Palaeogene sediments. Depressions were divided by the young uplift of the Karatau Range, but taking into consideration the commonality of the geological characteristics of the ore and sediment formation, they are joined in the united Chu-Syr Darya ore region (ChSR), which forms the foundation of Kazakhstan's uranium base (Fig. 1).

Uranium ore is primarily located in the Cretaceous sediments of the Chu-Saryssu depression (ChSD), which is the eastern sector of the Chu-Syr Darya ore region. In this depression the large and unique Zhalpak, Mynkuduk, Akdala, Inkay and Budyonovskoe deposits were discovered. These deposits form the unique Zhalpak-Budyonovskoe ore belt, containing about 800 000 tonnes of uranium. In connection with regional character of BOZ and the wide expansion of large fluvial systems in the Cretaceous, favourable conditions were created for almost continuous BOZ ore in the sediments of these systems. Ore bodies form uranium deposits in this unique uranium region. This region was studied for 20 years, during the period between 1971 and 1991. In this period a very efficient method of search and exploration work was developed. This method used experience accumulated during the exploration of the uranium deposits amenable to the ISL method in Uzbekistan and Kazakhstan.

## 2. Search and exploration method

In carrying out work on the discovery and exploration of uranium BOZ deposits, three main stages can be identified: pre-search, search and exploration. Each stage is characterized by a specific set of tasks. The general effectiveness of work depends on the high-quality fulfilment of investigation at all three stages. The work of each stage must be carried out strictly in sequence. Considering the large dimensions of depression structures, work of the second and third stages can be carried out in parallel in different parts of the investigation region. I.e., if in one part of the depression exploration work is already being carrying out, in other parts search work can be only beginning. In this case, particularities of the ore localization that are determined at the exploration section can be successfully used during searches at other sections.

### *2.1. Pre-search stage*

#### *2.1.1. Search preconditions and region selection for search work*

One of main preconditions for investigation region selection is the existence of depression structures with an infiltration artesian basin. Other important preconditions are the existence of permeable grey-coloured sediments formed in humid period sedimentation, the existence of sedimentation breaks in the arid period, or the existence of overlying red-coloured and mottled sediments that also characterize arid periods. Besides, an essential condition is the existence of young intensive uplifts of mountain systems adjacent to a depression (activation of the mountain surroundings). This fact determines the possibility for active penetration deep-ward of the artesian basin oxygen-bearing water and active BOZ development. The existence of over-clay and under-clay of grey-coloured sand horizons are favourable factors for directional BOZ development. Signs of epigenetic oxidized sand sediments in the core of drilling holes indicating possible BOZ development and higher radioactivity on the logging data (radioactive anomaly) are direct preconditions for ore detection. The region of investigation is selected based on the presence of the above features.

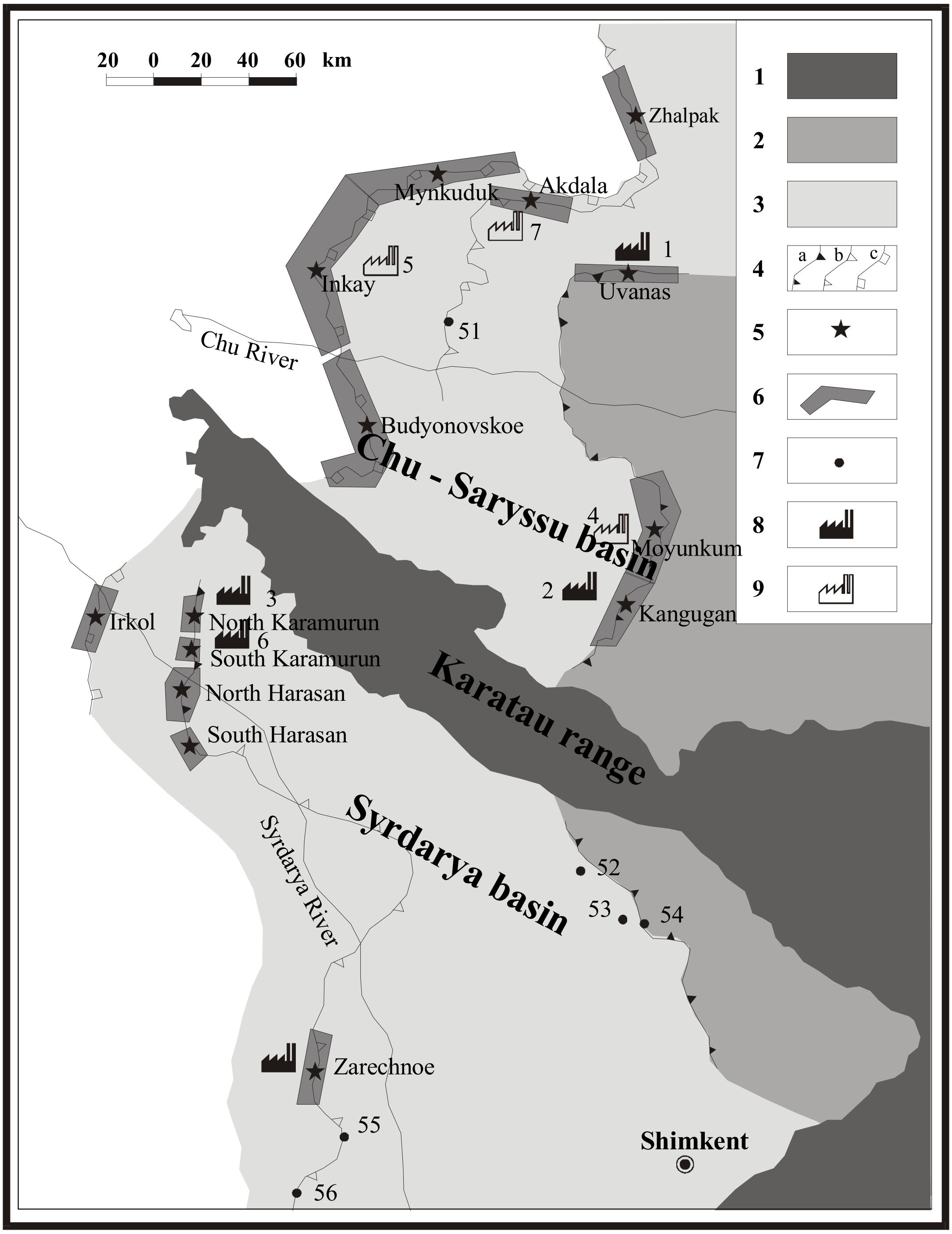

**FIG. 1 Distribution of uranium deposits in the Chu-Syrdarya ore region in Kazakstan**

1 - Outcrop of Pre-Mesozoic rocks, 2 - Area of the bed oxidation zone development on whole thickness of Cretaceous-Paleogene sediments, 3 - Area of the bed oxidation zone development in Cretaceous sediments only, 4 - Redox-front a) in Paleogene sediments, b) in Zhalpak horizon of the top upper Cretaceous, c) in Mynkuduk-Inkuduk horizon of middle part of upper Cretaceous, 5- Commercial uranium deposits amenable for ISL, 6 - Ore-fields of the commercial uranium deposits, 7 - Unprofitable uranium dePosits, 8 - Operating production centres (1-Stepnoe, 2-Tsentralnoe, 3-№6, 6-South Karamurun, 8-Zarechnoe), 9 - Planned field test production centres (4-Katko, 5-Inkay, 7-Akdala)
**Unprofitable deposits:** 51 - Sholak-Espe, 52 - Kyzylkol, 53 - Lunnoe, 54 - Chayan, 55 - Zhautkan, 56 - Asarchik

### *2.1.2. Compilation of facies-lithological horizon maps*

A very important phase of the pre-search stage is the compilation of facies-lithological maps of perspective horizons that are identified for investigation. Areas of favourable sediment formation (channel facies or other sections of grey-coloured sediments, organic material accumulation and so forth), signs of epigenetic oxidation into sand sediments are shown on these maps. When compiling these maps, all sources of geological information (state geological survey data, search drilling well data from oil, hydro-geological and other organizations) are used. As a result of the analysis of horizon map data, a possible BOZ attenuation position can be found and the character and direction of the reconnaissance drilling hole lines for the confirmation of facies-lithological map data can be determined.

### *2.1.3. Drilling of the reconnaissance borehole lines*

Reconnaissance borehole line drilling is carried out using voluntary line spacing and with a distance between wells of 12.8-6.4 km. The line spacing is determined by the features of the geological forming sediment conditions and may be as large as 30-40 km. In this case, particular emphasis must be placed on the well core quality and quantity. Permeable sand sediments of the borehole core must not be contaminated by mud fluid. Borehole core quantity of sand sediments must be 70% or more. Otherwise, the identification of the direct signs of BOZ development will be complicated and this can lead to mistaken conclusions. According to reconnaissance borehole line data, the direction of underground water flows during an ore-forming period and possible position of BOZ attenuation are determined. In this case, the details of geological condition formation of horizon sediments (paleo-valley orientation and so forth), and the position of recently activated young mountain surroundings must be considered.

An ore formation period is preliminarily determined by the mountain system activation age and the age of arid periods under the formation of the sediment series. According to the reconnaissance borehole line drilling results, perspective uranium deposit areas are segregated.

## **2.2. Search stage**

### *2.2.1. Selection of borehole line orientation*

It is very important to select an accurate drilling line orientation when search work is only just beginning so as these lines can become integrated into a future joint exploration system, including wells of the detail exploration stage. Generally BOZ area attenuation and related ore bodies have a very complex configuration of their details. This is connected with the generally alluvial character of sediments and the considerable variation in the lithologic-geochemical features of the rocks. Therefore, the first-phase search drilling lines must be orientated in the direction of paleo-flows and perpendicular to the area of the main BOZ attenuation. Under more detailed searches, the drilling lines can be perpendicular to the initial line direction. This orthogonal line system is preserved at the exploration stage, and allows to obtain the proven reserves with optimized costs using data on the boreholes of all stages under reserve calculation. The results of the ore bodies detailing under different drilling densities are shown in Figure 2.

### *2.2.2. Justification for search and exploration line grid of drilling holes*

The drilling lines of the initial search phase are situated with a spacing of 25.6 km. But often this distance is decreased to either 12.8 or 6.4 km depending on the results of reconnaissance work and the dimensions of the revealed prospect areas. Generally, the dimensions of the favourable facies expansion area and the position of the BOZ attenuation at these areas are determined by the drilling lines data of this stage. Additionally, at this stage it is already possible to reveal the direct signs of uranium ore. This can indicate the possible potential resources of the region.

Using a line spacing of either 3.2 or 1.6 km will already allow one to draw a conclusion on the possibility of commercial uranium ore discovery.

To determine the commercial character of the revealed uranium ore, preliminary exploration is carried out using a drilling grid of 800-400×200-50m revealing the EAR-1 reserves. According to the results of preliminary exploration, a decision is taken on carrying out a detailed exploration on the 200-100×50-25m grid, revealing the RAR reserves.

The grids used for each stage of the drilling work and the corresponding confidence in the revealed resources and reserves is shown in the following Table.

| Stage | Scale of work | Line spacing, m | Distance between wells on the line, m | Resource confidence, reserve category |
|---|---|---|---|---|
| Reconnaissance | 1:500 000 | 30.000-40.000 | 6.400-100 | SR ($P_3$) |
| Search stage | 1:200 000 | 25.600 | 6.400-100 | SR ($P_3$) |
|  | 1:100 000 | 12.800-6.400 | 3.200-100 | SR ($P_2$) |
|  | 1:50 000 | 3.200-1.600 | 800-(100-50) | EAR-2 ($P_1$) |
| Preliminary exploration |  | 800-400 | 200-50 | EAR-1 ($C_2$) |
| Detailed exploration |  | 200-100 | 50-25 | RAR ($B+C_1$) |

Note: Categories of resources and reserves in the classification system of the former USSR (used in Kazakhstan) are shown in brackets in the resources confidence column.

### *2.3. Exploration stage*

Exploration stage work is undertaken after a proof of the possible commercial significance of the revealed uranium ore. All work of this stage is aimed at obtaining comprehensive data for carrying out the reserve calculation and the technological description of the reserves.

The goal of the exploration stage is to segregate both the preliminary explored reserves (EAR-1) and the detailed explored reserves of the commercial category (RAR). In this case all boreholes are drilled with a core recovery of 75% or more through the ore zone. All boreholes of each stage with ore intersections are sampled for all kinds of assaying. Such boreholes are included in an exploration grid of the detail exploration stage and are used for the reserve calculation.

## 3. Reserve calculation [2]

### *3.1. Geo-technological mapping*

One of the main features of ore bodies is the geo-technological properties of the ore sediments. Technological sorts of the ore are segregated taking into consideration these properties. The task of studying the geo-technological properties of ore includes the investigation of the lithologic-filtration and engineering-geological properties of sediments, and is decided by geo-technological mapping. Various data from borehole core geological description, hydro-geological, geophysical, laboratory investigation, technological trials assaying, and modelling with laboratory leaching pipes–are used for carrying out geo-technological mapping.

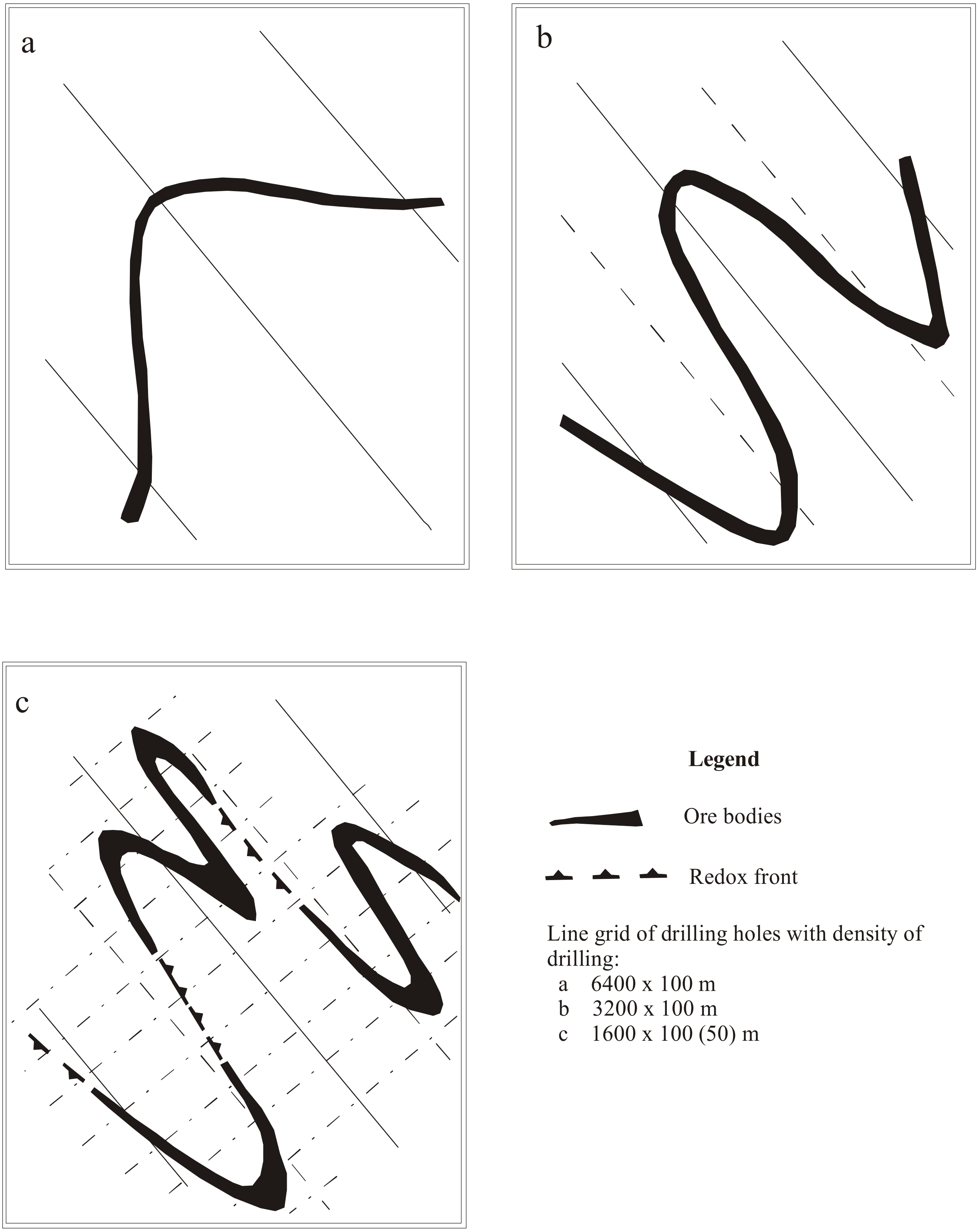

**FIG. 2 The use of the orthogonal line grids of drilling holes for the ore body contouring**

### *3.1.1. Geological borehole core description*

One of the main sources of obtaining information about lithologic-filtration ore properties is a borehole core geological description. This description is accompanied by sampling using the appropriate grid to determine the carbonate content of ore and sediments and their grain composition. Sediment colour, grain composition, and percentage of clay in sand must be denoted. Geological description data are the main primary documents for boreholes and are used to compile cross-sections, maps, and calculation plans.

### *3.1.2. Hydro-geological investigation*

The main goal of hydro-geological investigation under geo-technological mapping is the determination of the filtration coefficients of aquifer sediments using pumping tests. Use of pumping tests is the most objective method for aquifer sediment filtration coefficient determination. At the same time, some factors interfering the accurate determination of the filtration coefficient must be taken into account.

### *3.1.3. Geophysical investigation*

Using electro-logging interpretation data, cross-sections for boreholes without core selection are drawn. In addition, geophysical investigation is used for the determination of the filtration coefficients of the ores and sediments. Values of the filtration coefficient of separate beds of the ore horizon and ore intersections are determined using a re-counting coefficient and data from an electro-logging interpretation in conjunction with the results of grain analysis and data from hydrological filtration coefficients.

### *3.1.4. Laboratory investigation and modelling using laboratory-leaching pipes*

Exploration work is accompanied by wide set of laboratory investigations. The main kind of laboratory analyses is a chemical analysis for uranium in borehole core samples and radiometric analysis for radium. Data from these analyses form the basis for a radioactive disequilibrium study at different sections of the ore bodies, and for the determination of the correction factor for gamma-logging data using these factors under reserve calculation.

Other methods are also used to comprehensively describe the ore bodies. These are: mineralogic-petrographic determinations of the ore and sediments, determinations of carbonates, organic material, and associate element contents, as well as the determination of grain composition, iron valence, general iron content, and density of the ore.

Technological samples for carrying out an investigation, using laboratory-leaching pipes, are selected from the core material. Study of the technological ore parameters (filtration coefficient, velocity and recovery fullness, acid costs, etc.) are carried out using material from these samples. Selection and analysis of the technological samples at the location of the field test and whole deposit area allow one to interpolate the results of the field test for the whole deposit, characterizing the technological properties of the ore at the various sections of the deposit.

## *3.2. Compilation of the lithologic-filtration maps and segregation of the lithologic-filtration sorts of the ores.*

Lithologic-filtration maps describing the filtration heterogeneity of the ore sediments are compiled using geo-technological mapping data. On these maps, the areas of sediments with close filtration coefficients values are segregated. These maps are used to determine the calculation block boundaries. During deposit mining, the map data allow one to select the optimal line grid of drilling holes and well density for the well pattern formation.

### *3.3. Selection of the reserve calculation method*

The reserve calculation is carried out using data from the gamma-logging interpretation with using correction factors for radioactivity disequilibrium and for the conditions of carrying out gamma-logging – squeezing of radon into well side during the initial (main) logging. These corrections have different values at different deposit sections. They are determined by specific investigations. The reliability of the corrections is confirmed by the chemical analysis data and the results of the direct determination uranium logging. Corrections factors may reach 20% or more.

Carrying out of the reserve calculation using gamma-logging data allows one to drill a considerable portion of the wells without core recovery. In this connection, the speed and efficiency of exploratory work increases considerably.

The geological block method was chosen for the reserve calculation. The choice of the calculation method was determined by the complex ore body morphology and by the use of the ISL method for deposit mining. Calculation blocks in the cross-sections are formed taking into consideration the entire volume of the sediments, which is subject to acid influence. On the calculation plan, the blocks are contoured by wells with profitable ore. For the optimal selection of the mining conditions, the calculation blocks are formed taking into consideration the data of the lithologic-filtration plans. The boundaries of the blocks are drawn taking in account the field boundaries with close filtration coefficients values.

### *3.4. Analysis of conditions used for reserve calculation*

Special requirements, called conditions, are determined for the reserve calculation. These conditions are confirmed by authority bodies and contain some parameter restrictions for the well, which are attributed to profitable ones and are included into the calculation. The main restrictions are the cut-off grade (0.01%), and cut-off grade x thickness (line productivity – 0.600). In addition, conditions are determined by carbonate content restrictions (2% of $CO_2$) and ore permeability (filtration coefficient of 1m/day or more). Some other restrictions are determined by the geological blocks method calculation. Such restrictions are specially considered. Confirmed conditions at practically all deposits of the Zhalpak-Budyonovskoe ore belt are in good accordance with morphological and other ore features, and qualitative parameters of the ore bodies. This is confirmed by the fact that only a very small portion (about 2%) of the uranium ore was assessed as sub-profitable ores, as well as the fact that uranium recovery price from profitable ores at the Mynkuduk deposit are not high (USD 20.0 per kilogram of recovered uranium).

### *3.5. Carrying out of the field tests*

Uranium recovery field tests using the ISL method are carried out to prove the cost-effectiveness of calculated reserves for uranium production and to determine the project parameters of profitable production. Investigations are carried out at special test polygons using different borehole placing schemes (well patterns). The most common well patterns are polygons with 3 injection and 6 recovery wells. Pattern with 2 wells are also often used.

# 4. Geological properties of the zhalpak-budyonovskoe ore belt

## *4.1. Geological characterization of the region and conditions of uranium ore formation*

### *4.1.1. Formation history of the sediments of the Chu-Saryssy depression*

The Chu-Saryssu depression is located on the edge of the large Turan Plate and is filled with friable sediments from the Cretaceous to the Quaternary. The foundation of the depression is Palaeozoic lithified sediments lying at a depth of up to 700-800 m. The platform sediments are friable continental Cretaceous rocks of up to 320 m in thickness, marine and shallow-marine Palaeogene sediments of up to 200 m in thickness, and red-coloured sandy-clay Oligocene-Quaternary formation. The formation of the red-coloured sediments is connected with the young Alpine orogeny and mountain uplift in the East and, principally, in the Southeast of the Tian-Shan mountain system region [3]. The main stages of the regional geological history connected with uranium deposit formation are [4]:

(a) The formation of the thick permeable Cretaceous series;
(b) The ubiquitous presence of overlying marine Palaeogene clay series which can carry out the function of regional upper confinement;
(c) The existence of arid periods after Cretaceous sediment formation;
(d) The intensive uplift of the Tian-Shan mountain system in the Southeast of the region, which facilitated the active penetration of oxygen-bearing waters into the aquifer of the friable platform sediments;
(e) The formation of the large Chu-Sarysu infiltration type artesian basin.

The main uranium ore in the Chu-Saryssu basin is hosted in Cretaceous rocks, which are sediments of a large alluvial plain and for the most part, are grained sediments from fine-grained sand to gravel. Cretaceous rocks include clay beds amounting to not more than l0–20% of series thickness.

The alluvial origin of the Cretaceous sediments makes it difficult to divide the series into individual aquifers. At the same time, the separation of such stratigraphic units is very important for jointing ore intervals at various well lines. This was especially important during the first stages of the search, when imprecise jointing could lead to mistakes in choosing the direction and density of the exploration line grid of drilling holes. Additionally, the rate of exploration work may be decreased and costs increased.

Based on the sediment cycle segregation data and using electro-logging, the Cretaceous sediments were divided into 3 horizons. Each of these horizons is in turn divided into sub-horizons. Practically all the sub-horizons host uranium ores to a various degree. Thus, there are 9 ore-bearing sub-horizons within the Cretaceous sediment.

Tectonic activity weakly influences the distribution of ore bodies in the Cretaceous sediments within the Chu-Saryssu basin. Apparently, favourable facies distribution more effectively influences ore body distribution. The position of these facies depends on the expansion and orientation of the paleo-valleys. At the same time, in the Palaeogene sediments in the south of the region tectonic activity is more intensive.

The Cretaceous and Palaeogene sediments are a hydro-geologic complex, including a huge volume of the underground waters of the artesian Chu-Syr Darya Basin. The recharge area of these waters is the Tian-Shan mountain system region. The Tian-Shan range dictated the hydrodynamic regime of the basin and the northwest direction of the underground water flow. This flow direction was preserved despite the Karatau Range uplift in the Quaternary. The uplift of the Karatau Range had little influence on the basin hydrodynamic. Changes in the mineralization and the direction of the underground waters are noticeable only near the Karatau Range, and are practically non-existent in the Zhalpak-Budyonovskoe ore belt region. Discharge of the underground waters occurs beyond the Zhalpak-Budyonovskoe ore belt region. The natural velocity of the ground water movement is not more than 2 m/day. The level of mineralization of Cretaceous waters varies from 1 to 6 g/1. The water in the Palaeogene is fresh and is a source of drinking water for the local population.

### 4.2. *Bed oxidation zone expansion, formation and morphology of ore bodies*

The expansion of the bed oxidation zone is a very important factor in ore formation in the permeable Cretaceous sediments of Chu-Saryssu basin. The BOZ is developed from the Tian-Shan mountain range and extends up to 500 km. The infiltration nature of the artesian basin and long-continued (beginning from Oligocene [3]) period of BOZ development created very favourable conditions for BOZ expansion. In addition, the primarily speckled-coloured character of the basin sediments did not require significant oxygen consumption. Therefore, the redox front expanded such a significant distance and is located in the grey-coloured sediments of the paleo-valleys.

Under expansion at such a significant distance, the BOZ oxidized the large volume of sediments and also mobilized and transported a large quantity of uranium from the oxidized rocks. Organic material was also oxidized, with the generation of hydrocarbon gases, which could create reducing conditions. The generation of hydrocarbon gases explains large-scale ore formation on the redox front. Cretaceous sediments are characterized by a low organic carbon content (not more than 0.04%), and this fact does not allow one to explain the creation of the essential reducing conditions.

Thus, BOZ directly fulfilled several functions. These include:

(a) uranium mobilization from oxidized sediments;
(b) uranium transportation in a dissolved state over significant distances;
(c) reduced conditions of formation on the redox front;
(d) uranium sedimentation on the redox front.

Therefore, the BOZ is the ore-generating and ore-forming agent and the uranium deposits formed in the friable sediments at the redox front should be called BOZ deposits.

The alluvial character of the sediments conditioned a formation of horizons and sub-horizons, such as the large sediment macro-cycles. They are divided into a great number of micro-cycles with varying permeability, in which small tongues from 1-2 to 5-10 m in thickness are developed. At the attenuation of such tongues, in favourable conditions the ore bodies form both rolls with different wing lengths, as well as bed bodies with a form, which depends on the lithological composition of the sediments. Various conditions caused the variety of the ore body morphology. Nevertheless, the main morphology elements are the bag and wing parts of the rolls. The bag part reaches some 10-20 m in thickness, and the wing parts reach several metres as well. Uranium ore sometimes extends along the redox front for 10-20 km, forming the highly profitable ore bodies.

### *4.3. The degree of study of the Zhalpak-Budyonovskoe ore belt*

At present, the Zhalpak-Budyonovskoe ore belt has not been uniformly studied. Zhalpak, Akdala and Mynkuduk deposits have been explored up to commercial categories. At the same time, at the Inkay deposit only one (Central) section has been explored up to commercial categories. At the Budyonovskoe deposits, only search-estimation work has been carried out, and at one section preliminary exploration has begun. However, the revelation of 280,000 t of proven uranium reserves at the Mynkuduk and Inkay deposits and as well as the results of the estimation work along the entire Zhalpak-Budyonovskoe ore belt allows one to include this region in the ranks of large world uranium regions.

Field tests of uranium production by the ISL method are carried out at the Mynkuduk, Inkay, Akdala deposits. Commercial uranium production is being successfully carried out at the Eastern section of the Mynkuduk deposit. Starting this year, the second field test was begun at the Inkay deposit to study uranium recovery from ore bodies without lower confinement. At the Akdala deposit a test-commercial trial is being carried out with the extremely successful results. The uranium concentration of the pregnant solution averaged 600 mg/l for a period of 10 months.

## 5. Summary

The proposed search and exploration method includes wide experience obtained during the carrying out of uranium exploration in Uzbekistan and Kazakhstan. The use of the described method when studying the Zhalpak-Budyonovskoe ore belt allows us to successfully realize these important advantages of the method:

(a) High-speed exploration was conducted and the high commercial value of the Zhalpak-Budyonovskoe ore belt was determined over a short period (1971-1991) using the wide practice of drilling without core recovery.
(b) All reserve calculation data were obtained using gamma-logging interpretation with the use of the necessary correction factors determined by special investigations.
(c) The technological properties of the ore were characterized using the integrated method of geo-technological mapping.
(d) The applied geological block method for reserve calculation was simple and effective and took into account in the best possible way all the peculiarities of uranium extraction by the ISL method.
(e) A high level of extraction from uranium ores with low costs for the leaching reagent (up to 20-100 kg per 1 kg of extracted uranium) has been proven by field tests.

## 6. Conclusion

Use of the proposed method allows one to very effectively reveal, estimate and explore uranium deposits. Thus, at the Mynkuduk deposit where commercial category reserves are 95% of total deposit resources, about 2.4 million meters of wells were drilled with total costs of about USD 71.0 million, including spending for roads and settlement construction for personnel. In this case, specific costs are about USD 0.50 per 1 kg of explored uranium reserves.

For comparison we may turn to world data [5] where specific costs for 1 kg of explored uranium reserves widely vary, beginning at USD 0.48 (Australia, 1967-1983) up to USD 12.41 (USA, 1971-1983). World cost data for 1 kg of explored uranium reserves averages USD 2.50-2.80.

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# Australia's Honeymoon Project — From acquisition to approval — 1997 to 2002

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**Abstract.** Australia's Honeymoon project was acquired by Southern Cross Resources Inc in 1997 and has progressed through a demonstration phase and the detailed approval process. This progress is reviewed with emphasis upon the regulatory requirements, demonstration plant experience and the steps necessary to advance a new project to the commitment stage. Particular emphasis will be placed upon the hydrogeological and bleed disposal aspects of the approval process. The planned ISL facility will have an initial rated capacity of 750 tonnes per year of $U_3O_8$e production and will use acid leaching and solvent extraction with bleed stream disposal to the 20g/l TDS aquifer. The decision making process is outlined for the main wellfield and process plant and the plans for development are detailed.

## 1. Introduction

Southern Cross Resources Australia Pty Ltd (parent company Southern Cross Resources Inc) obtained access to the Honeymoon uranium deposit and nearby sedimentary uranium prospects in 1997 when it acquired various leases, licenses and assets in the Curnamona region of South Australia from Mount Isa Mines Limited and Sedimentary Holdings NL.

Since that time, the company has progressed the project through a 30 month demonstration phase, a comprehensive joint Commonwealth/State EIS and all government approvals are now in place. Honeymoon is poised for a formal project commitment which will result in it becoming South Australia's third uranium producer and the fourth Australian producing facility [15,16,17]. It will join the Heathgate Resources' Beverley project [13] as an Australian user of the acid In Situ Leach (ISL) process.

The Honeymoon site is located 75 km northwest of Broken Hill and some 61 km by road from Cockburn on the New South Wales-South Australia border as shown in Figure 1. The area within a 25 km radius of the site is an almost featureless plain, covered mainly with saltbush and bluebush, with trees confined to the few ephemeral watercourses that drain the area towards Lake Frome, 100 km to the northwest. Kalkaroo Station is one of a number of similar pastoral properties in the region carrying mainly sheep and some cattle.

## 2. History to 1983

Exploration for Tertiary sediment hosted uranium occurrences in the southern Lake Frome region by Carpentaria Exploration Company Pty Ltd and by E.A. Rudd Pty Ltd commenced in 1968 and 1969 respectively. Separately, Sedimentary Uranium NL and Mines Administration Pty Ltd – Teton Exploration Drilling Inc., through the Minad-Teton Australia Joint Venture, were also active during the 1970s. Exploration methods employed open-hole rotary drilling and wire-line geophysical logging as a reconnaissance exploration tool, although surface geophysical methods, primarily resistive and gravity surveys, were also used with limited success to locate and map Tertiary palaeochannels.

*FIG. 1. SXR project location map.*

Exploration by Minad-Teton Australia led to the discovery of the Honeymoon deposit in November 1972 and to the discovery of the Gould Dam Prospect in 1973. Previously, the East Kalkaroo Deposit and Yarramba Prospect had been discovered by Sedimentary Uranium NL in 1970 (Fig. 2). At Honeymoon, drilling programmes over the next four years established the extent of the deposit, but feasibility studies concluded that it was too small to be mined economically by conventional open-cut or underground mining methods. By the late 1970s all of these resources and areas of exploration potential were controlled by Minad-Teton Australia through a number of joint ventures.

Coincident with this exploration success, was the development, predominantly in the USA, of solution mining or in-situ leaching (ISL) techniques for uranium recovery. The size, geology and hydrology of these Australian deposits seemed well suited to the ISL technique and limited pilot testing was carried out at Honeymoon between 1977 and 1979. These, and additional laboratory tests carried out by the Australian Mineral Development Laboratories (Amdel) in Adelaide, confirmed the feasibility of uranium recovery at Honeymoon by the ISL method [1]. This in turn led to the decision to install a nominal 250,000 lbs $U_30_8$/year demonstration plant at Honeymoon. Government approval to proceed to the next phase of development was subsequently granted and in 1982, Minad established a demonstration ISL facility at Honeymoon. The facility comprised a pilot leach wellfield of three 5-spot leach patterns, a liquid disposal well, monitor well and a processing plant designed to treat pregnant leach solution at a rate of 25 L/s. Supporting infrastructure included an accommodation camp, office complex and workshop [9]. Although built, the plant was never operated due to changes in both Commonwealth and State Governments at that time and the project was placed under care and maintenance.

It would be interesting to speculate on the degree of development of uranium production from the Curnamona area that may have occurred had the political environment been different. At that time, uranium prices were high and there were a number of prospects and companies active in the area.

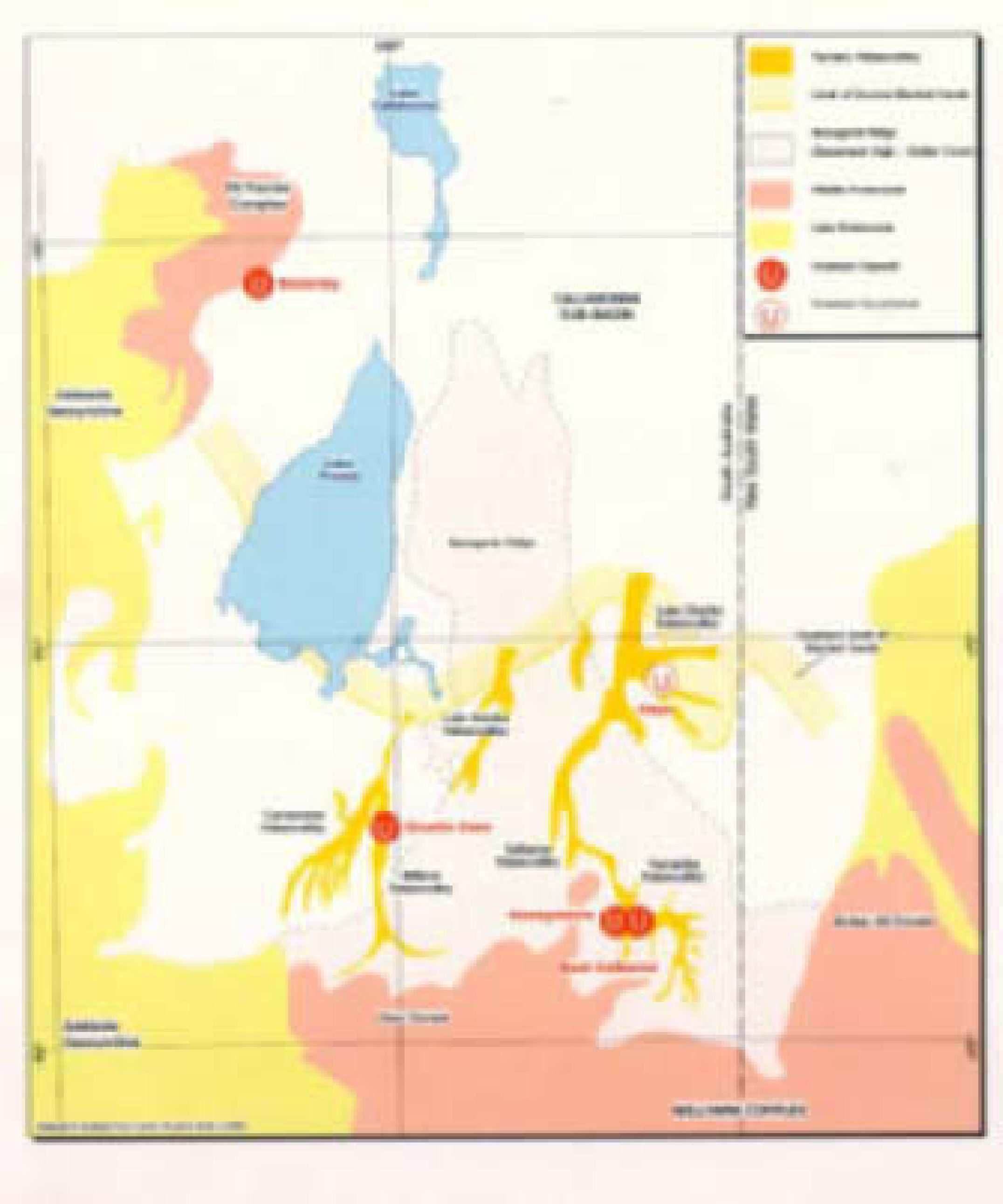

*FIG. 2. Simplified Curnamona area map.*

## 3. Acquisition and company formation

Southern Cross Resources Inc was founded in 1997 as a public Canadian company listed on the Toronto Stock Exchange with the acronym SXR [22]. Its genesis was the belief by its principal founders that there was an opportunity to develop a new uranium production company in a changing environment. This opportunity related to the changed political situation in Australia towards uranium mine developments, and the potential increased uranium demand resulting from a growing nuclear electricity market as the full implications of greenhouse gases became evident.

Early in 1997, SXR acquired two important but undeveloped uranium properties in South Australia:

(a) An 85.8% interest in Tertiary uranium in a 452 km$^2$ exploration tenement located approximately 75 km northwest of Broken Hill. This interest was acquired from Sedimentary Holdings, a listed junior exploration company.

The Honeymoon leases, demonstration plant and the remaining 14.2% interest in Tertiary uranium in the tenement were acquired from Mount Isa Mines Limited (MIM).

(b) The Gould Dam uranium tenements from MIM. This deposit is located 80 km northwest of Honeymoon.

The uranium in these projects had been discovered in the early 1970s. The projects remained undeveloped and the demonstration plant had been placed under care and maintenance until SXR's acquisition.

These two deals in 1997 meant that SXR acquired two known but undeveloped uranium deposits and a purpose built uranium demonstration plant [2].

SXR raised initial funding in 1997 to fund the evaluation, environmental assessment and permitting phase for the planned commercial development at Honeymoon. SXR established an Australian project office initially in Brisbane and subsequently relocated to Adelaide to manage the project.

The uranium production industry is highly regulated and development applications normally face close scrutiny. The permitting phase for Honeymoon took longer than originally expected and SXR raised additional funding to cover costs in 1999, 2000 and 2001. During this phase, Resource Capital Fund LP, a specialist resource fund in Denver, USA provided a loan and additional equity funding and became the largest shareholder in SXR. To date this has involved the expenditure of about C$30 million.

## 4. Development strategy and plans

The main strategy was to develop, after a demonstration field leach trial and regulatory approval process, a commercial in situ leach uranium recovery operation, based initially on the adjacent Honeymoon and East Kalkaroo Uranium Deposits. Yellowcake would be produced as uranium peroxide ($UO_4$ $2H_2O$) at a nominal rate of 1,000 metric tonnes per annum $U_3O_8$ equivalent and wholly exported for use in the electric power generating industry.

The initial step was preparing a Declaration of Environmental Factors (DEF) and obtaining the necessary approvals to undertake demonstration-scale ISL recovery of uranium (Field Leach Trial). Following the DEF approval, SXR refurbished existing infrastructure, particularly the demonstration plant and pilot wellfield. The company also re-established supporting infrastructure, including an office complex, accommodation camp and electricity generation facilities. Subsequently it recommissioned and operated the pilot wellfield and demonstration plant at an initial rate of 6 L/s during the last six months of 1998. In early 1999 SXR augmented the pilot wellfield with new wells and increased the feed to the demonstration plant to the design rate of 25 L/s. The company has also undertaken additional technical, environmental, financial and marketing studies and prepared a proposal for the construction of a commercial production facility.

In parallel with these site activities, the formal EIS process was undertaken with investigations and consultant activities.

Marketing and corporate strategy was to develop a proactive market presence and there was a planned effort in this area. It was the intention to have a number of established sales contracts in place well before the approval process was completed.

## 5. Regulatory requirements

The dominant approval process is through the Environmental Impact Statement (EIS) and involves both the South Australian State Government and the Australian Commonwealth Government. The initial step in the EIS process was the release of draft guidelines for public comment in late 1997. The resulting comments were considered in finalizing the guidelines, which were agreed to by SXR and the relevant Federal and State authorities. The draft EIS document was then prepared by SXR taking into account these guidelines and incorporating the wide variety of expert reports commissioned by the company and the information gathered by the Field Leach Trial [11]. The draft EIS was issued for public comment in mid 2000 and there were a number of public consultation mechanisms. The comments from the public, NGOs, Government agencies and interested parties were incorporated into the company’s Response Document, which was formally published in November 2000 [19,20]. The two documents formed the basis for the formal review by the State and Federal authorities. Prime approval is given by the Commonwealth Environment Minister with consequent formal actions for the Commonwealth Resources Minister and the State Mines Minister.

In February 2001, the Environment Minister gave conditional project approval whilst requiring that additional work be undertaken, primarily in the areas of palaeochannels and hydrology characterization and modelling of groundwater [12]. This field and office work was completed and submitted in July 2001 and formal final approval by the Commonwealth Ministers followed in November 2001. State approval to issue Mining Leases was given in December with the mining leases being formally granted in February 2002. A range of other plans relating to radiation, environment and management will be agreed prior to commercial production [18].

## 6. Technical issues

Upon acquisition of the project there were, in addition to areas specifically directed towards the EIS process, three prime technical areas that required close attention and the development of predictable performance prior to any commercial production decision [4,5,6]. These areas were in the geology of the uranium resources and confidence in the ground and hydrological conditions, the wellfield performance and the allied bleed stream disposal method and in the uranium extraction metallurgical method.

## 7. **Geology** [3,8,10]

The initial geological assessment involved the gathering of all historical data and its re-interpretation, the drilling of a number of check holes at the Honeymoon/East Kalkaroo project, further exploration near the Gould Dam prospect and the application of modern sedimentary geology practice.

The hydrological aspect was handled with the installation and subsequent performance monitoring of a number of widely spaced wells in the three different aquifers occurring in the Yarramba palaeochannel. The geology practice and emphasis up to 2000 was on this characterization exercise, primarily for the EIS and little new exploration was undertaken. An enhanced understanding of the geological environment was gained and is briefly described.

The Honeymoon, East Kalkaroo and Gould Dam deposits occur in unconsolidated sands in buried palaeovalleys. The palaeovalleys are incised into Mesoproterozoic basement rocks of the Curnamona Craton. The basement includes gneisses and schists of the Willyama complex as well as intrusive and anatectic granites (Figs. 4 and 5).

Uplift during the Tertiary generated a series of valleys in the basement that were later infilled with sands and clays of the Eyre Formation. Further burial of the valleys by lacustrine clays of the Namba Formation followed. The palaeovalleys extend for many tens of kilometres and are up to six km wide. They have broad flat floors bounded by steep sided banks, which are typical of valleys that have undergone widening after initial incision. The floors have a depth below surface of about 120 m and banks are generally 70 m below surface.

The Yarramba palaeochannel is incised into weathered Precambrian basement and is overlain by a clay sequence of the Namba Formation, typically 70 m thick. The Yarramba palaeochannels, as shown, typically contains a 55 m thick sequence of uncemented, poorly consolidated interbedded sands and clays of the Eyre Formation and averages 3 km in width but is up to 6 km wide east of Honeymoon. The geology and structure of underlying rocks, as evidenced by drilling results and regional aeromagnetic interpretations, control its shape and sinuosity.

The sands and clays of the Eyre Formation are repetitive sequences of coarse-grained highly permeable gravels and sands (aquifers), which decrease in grain size upwards through fine grained micaceous silts to clays (aquitards). Each sequence is considered to represent a basal braided stream environment grading upwards into flood plain and lacustrine environment. However, some clays may not be present due to the erosive action of a younger river bed. Similarly, some clay rich zones are interpreted to be reworked material deposited in low energy regions of a braided stream environment, rather than deposited in a strictly lacustrine environment. Three major aquifers (Basal, Middle and Upper) are recognized.

Uranium mineralisation at Honeymoon occurs predominantly within sands of the Basal Aquifer of the Eyre Formation towards the outer margin of a major bend in the Yarramba Palaeovalley (Fig. 3). The uranium occurs as uraninite coatings on pyritic quartz sand. The distribution of mineralisation within the aquifer system is characteristic of roll front type mineralisation with observable zonation relating to oxidation-reduction interfaces. The uranium is considered to be derived from weathered granitic basement. Uranium is dissolved and transported in solution by migrating oxidised groundwater along the palaeovalley aquifer system. The interaction of this groundwater with reduced sediments results in the re-precipitation of uranium minerals. The deposition of economic mineralisation at Honeymoon is thought to be strongly influenced by a combination of factors including: the coincidence of a sharp bend in palaeovalley with a basement bar which dramatically changes the hydrological flow regime; the convergence of two tributaries resulting in fluid mixing; and a possible change in the reduction potential of the basement lithology.

Uranium mineralisation is not entirely confined to the Basal Aquifer and also occurs in the overlying Middle and Upper Aquifers. However, this mineralisation is more sporadic and tends to be of lower grade. Currently SXR is only intending to mine from the Basal Aquifer System.

Mineralisation at Honeymoon extends for nearly 1,000 m along the channel margin, is 400 m wide at its maximum and averages 5 m in thickness. The East Kalkaroo Deposit is very similar to Honeymoon but is lower grade and extends over 3,000 m. At Honeymoon the pyrite content is high (~7%) and total organic carbon averages 0.3%. In the Basal Aquifer, the salinity of the formation ground water ranges from 16,000 mg/L to 20,000 mg/L TDS.

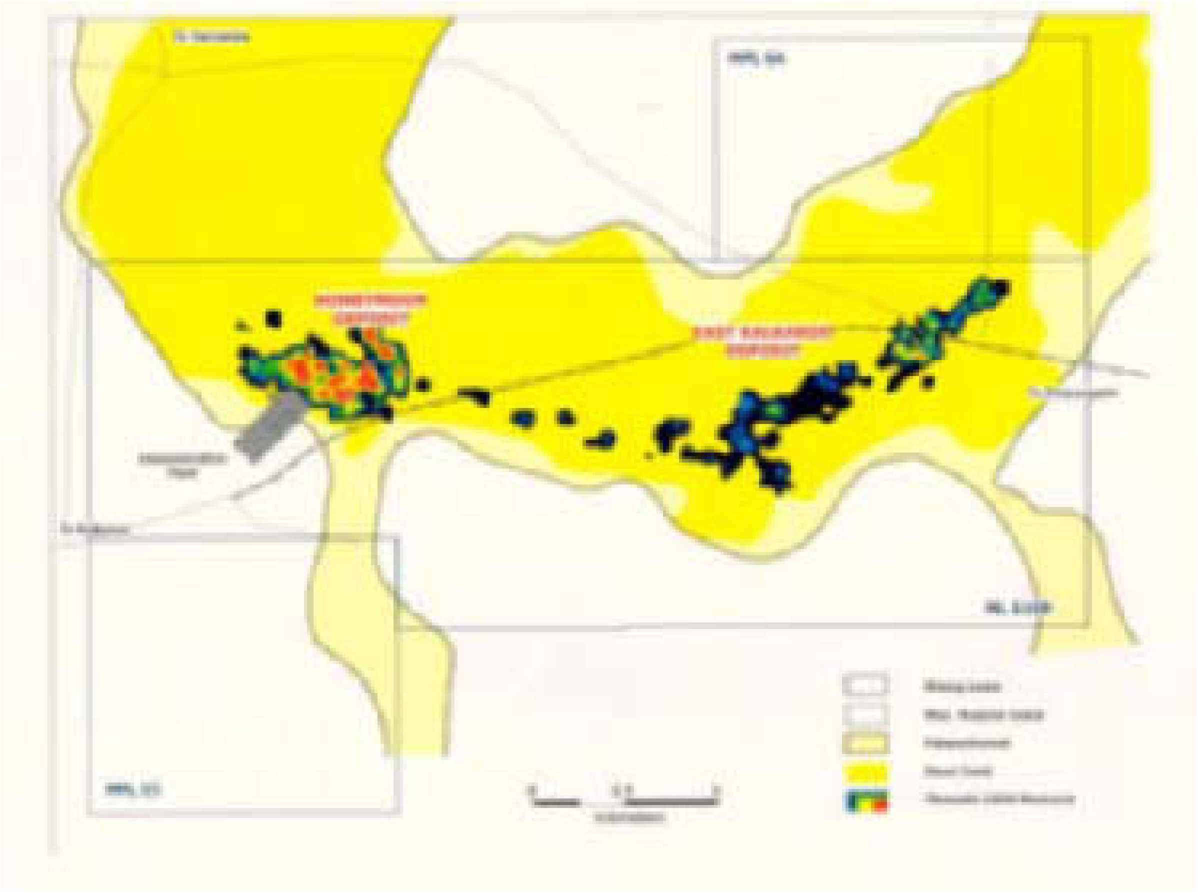

FIG. 3. Honeymoon resources.

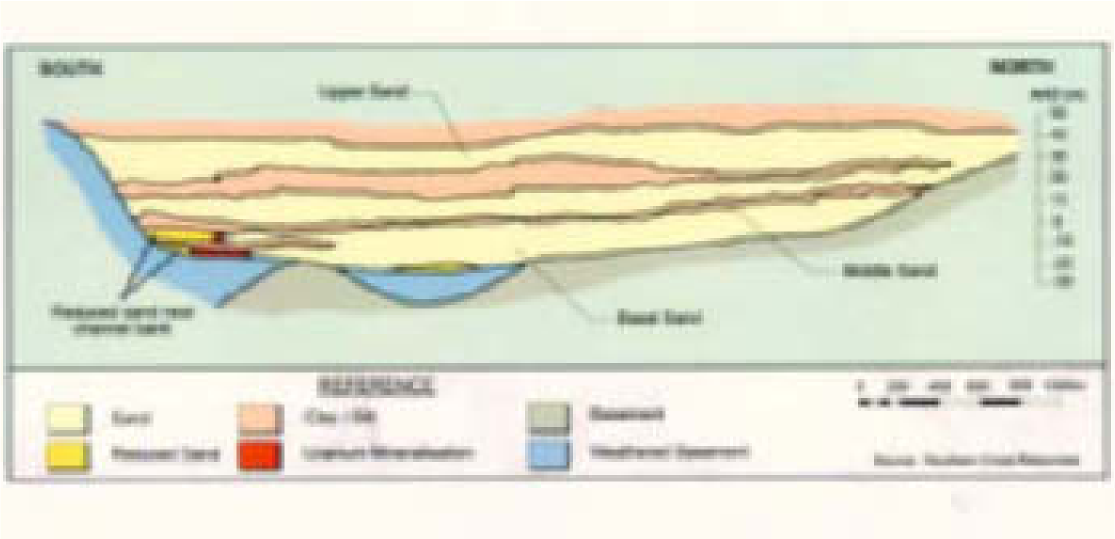

FIG. 4. Honeymoon cross-section.

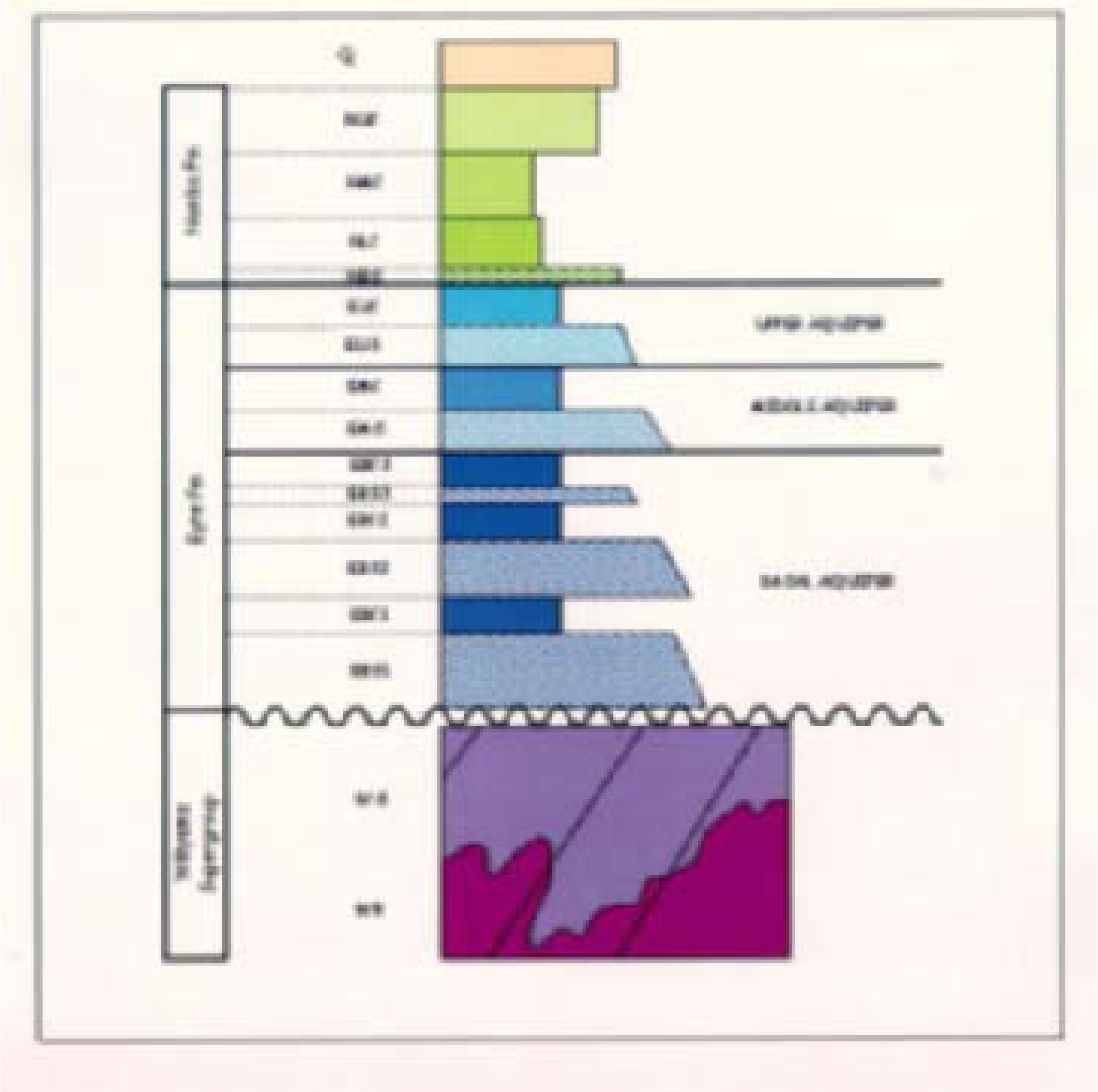

FIG. 5. Stratigraphic column.

Drill hole information has been compiled into databases for the palaeovalleys containing Honeymoon, East Kalkaroo and Gould Dam deposits. In excess of 3,000 holes are listed including 367 drilled by Southern Cross Resources. Drill hole data includes location, geological logs, geophysical logs and geochemical analyses. Electric logs are used to identify lithotypes and gamma logs are used to estimate equivalent uranium grades. By comparing radiometric grades with chemical grades it is possible to estimate uranium content from equivalent uranium grades. In future drilling programs, it is proposed to use an alternative advanced geophysical method, which directly measures uranium grades and overcomes the problems of disequilibrium.

Resources have been estimated for the Honeymoon and East Kalkaroo orebodies from historical and recent data, which has been reinterpreted to develop a sedimentological model. Sand and clay units in the model were then used to constrain the estimation of mineral resources. Equivalent uranium grades are calculated from gamma logging and a grade-variable disequilibrium factor was applied prior to the application of a cutoff grade. Mineral resources were estimated between upper and lower digital terrain modelled surfaces, within a selected minimum grade*thickness (GT) contour, using SURPAC v3.2P mining software. Grade allocation was by inverse distance weighting of all available grades within a 100 m search radius.

For the Basal Sands resource estimation, a minimum grade cut-off of 0.01% $U_3O_8$ and a GT cut-off contour at 0.20 m% $U_3O_8$ equivalent was applied. Current resources for Honeymoon and East Kalkaroo are tabulated below (Table 1).

TABLE I. STRATIGRAPHIC MINERAL RESOURCE AT 0.20M% $U_3O_8$ GT CUTOFF - BASAL SANDS ONLY.

| Deposit | JORC Category | Avg. Thick. (m) | SG | Tonnes (Mt) | Avg. Grade (%$U_3O_8$) | Avg. GT (m% $U_3O_8$) | $U_3O_8$ (t) |
|---|---|---|---|---|---|---|---|
| Honeymoon | Indicated | 7.1 | 1.9 | 2.8 | 0.12 | 0.84 | 3,300 |
| East Kalkaroo | Indicated | 5.2 | 1.9 | 1.2 | 0.074 | 0.38 | 910 |
| Total Resources | Indicated | 6.4 | 1.9 | 4.0 | 0.10 | 0.67 | 4,200 |

Note: Any apparent summation mismatch is due to post-computational rounding to 2 significant figures.

A stratigraphic model of the Yarramba palaeochannel was developed and proven during the drilling of the 25 L/s wellfield in 1999 and subsequent stratigraphic drilling in 2000- 2001. A high degree of confidence was developed in the model for predicting the depths at which the target sands are encountered. The ability to predict the locations of sand units has application in both the wellfield development and monitoring for the proposed operation. This stratigraphic drilling confirmed that the entire Eyre Formation package lies within the palaeochannel as defined by drilling on the northern margin. The previously interpreted channel boundary was confirmed. The northern margin, north east of Honeymoon and north of the East Kalkaroo deposits was shown to be quite steep with basement elevation changes of up to 34 m over a distance of 100 m.

The south margin, south east of the East Kalkaroo deposit, has a shallower profile compared to the northern margin. The package of Eyre Formation sediments, in this area, is clay rich compared to the sandy facies observed on the northern margin.

The results of two hydrological testing programmes indicated that ground water level, flow direction, and hydraulic gradient are similar in all three aquifers. Thus, the water bearing layers are at or near hydraulic equilibrium, and flow is restricted to within the palaeochannel in a generally northeast to southwest direction.

The analysis of all the test pumping data, using a number of techniques provided convincing evidence of a hydraulically lateral constricted channel that is bounded to the north and the south by impermeable boundaries. A leaky strip aquifer was simulated using analytical models derived from the well equations. Further, the groundwater hydraulic evidence for laterally impermeable boundaries was in good agreement with concurrent program of stratigraphic drilling.

The rate of flow (average linear velocity) was calculated to be in the range from 10 to 16 m/y for the Basal and Middle Sands units and was similar to that determined in the 1982 work. A flow of less than 1 m/y in the Upper Sand unit was determined in the more recent work. Aquifer throughflow was calculated using cross sections and indicated that the volume of water flowing through the palaeochannel may be in the order of 90 ML/y.

The aquifer system was considered “closed”, as the sediments were bounded by the sides of the channel and were overlain by the Namba Formation clays. In such an aquifer system, water is neither lost nor gained along the flow path, except for the contributions of tributary channels. Such tributary channels were identified in the 1970s. One such tributary channel was also identified by drilling at Honeymoon in 1999, and is thought to make a small contribution to Yarramba palaeochannel flow downgradient of the Honeymoon site.

A multi layered numerical groundwater flow model was constructed, calibrated and tested using all available geomorphologic and monitoring data to represent the conceptual model of aquifer geometry and flow conditions. This model was used to simulate the effects on the groundwater regime from start up of a commercial operation. It incorporated an ISL wellfield array and disposal of reverse osmosis plant (RO) reject brine and ISL barren solution bleed at various alternative locations. The extraction of raw water from the system for RO plant feed was also introduced. An important element in the analysis was the estimation of inter-layer leakage induced by pressurization and dewatering effects due to injection and extraction stresses.

A numerical solute transport flow model was also constructed and was based on the calibrated flow model, to incorporate advection-dispersion and simplified adsorption processes. This model was used to carry out a robust sensitivity analysis on the assumed solute adsorption coefficients to ‘bracket’ expected solute migration. The analysis was based on the production of breakthrough curves showing time-variant water quality concentrations at particular locations for chemical species of interest.

Another objective of the modelling was to enhance the current state of knowledge concerning solute migration from the Honeymoon operations, which were based previously on advection and dispersion only using a conservative species approach. The numerical solute transport flow model was used to simulate transient changes in the distribution of contaminant concentration.

In addition to simulating the advection and dispersion of the chemical compounds, linear sorption theory was used to account for the likely adsorption of dissolved solute to the mineral surfaces of the receiving aquifer. An extensive literature review was conducted to obtain linear sorption values representative of the Yarramba palaeochannel system. A concentration contour of 1% variation was adopted to assess the migration of disposal solutions. This contour represents 1% of the difference between the baseline concentration of a source compound in the natural groundwater and the concentration of the same element in the disposal fluid. This was used to track the progress of the solute plume resulting from the disposal of waste solutions.

It is unlikely that the conservative solute case with an adsorption value of zero is at all representative of actual conditions in the basal aquifer. It is far more likely that partial sorption would occur between the source solute ions and minerals in the aquifer material.

In cases where higher sorption characteristics were assumed, only minor differences between the baseline concentration in the natural groundwater and the concentration of the same element in the disposal fluid were reported at the monitoring locations over the time periods considered. This result shows pronounced localization of the solute plume within a 125 m radius of the disposal points.

The removal of contaminants was determined to be rapid and residual concentrations confined to the immediate vicinity of the injection wells. It is reasonable to expect, therefore, that disposal solutions will equilibrate to natural background levels well within the proposed seven-year monitoring period following cessation of operations.

## 8. **Wellfield** (Fig. 6)

During the Demonstration phase, an upgraded five-pattern trial wellfield with associated monitoring, wellfield control center and necessary plumbing was installed using techniques specifically designed for Honeymoon. This wellfield provided a reliable input for the demonstration plant and was central to the development of in situ leach conditions. One of the individual patterns was in continuous operation from August 1999 until the shutdown of leaching (a year later), with an average uranium content exceeding 75 mg/L and a flow rate of approximately 8 L/s. Other wells were in operation for shorter periods of time as they were brought into production progressively and used for differing testing. Flow rates and grades varied from production well to production well and demonstrated the variability of the deposit.

The equipment and materials used during the installation of the demonstration wellfield and ancillary plant were identical to those proposed for the commercial operation (Fig. 7). Consequently, there is no need for further scale-up. This equipment and material included:

(a) well casing - selected to be of a suitable pressure rating that would accept the standard 150 mm downhole pump selected;
(b) corrosion resistant downhole pumps - the 150 mm downhole pumps are intended to be used during the operation of the commercial wellfield; and
(c) injection and recovery lines - selected to match the performance of the down-hole pumps, and will be used in the operation of the commercial wellfield.

The determination of the optimal leaching conditions for uranium extraction and the management of the regeneration of the circulating leach solution was in integral part of the Field Leach Trial. This enabled the successful trial of a number of leaching agents under a variety of operating conditions and resulted in an optimization process. There is, therefore, a high degree of confidence in the commercial viability of the ISL process proposed for use at

Honeymoon. Optimum trial leaching conditions involve operating at relatively high pH levels (pH 2.2 – 2.5), resulting in much reduced sulphuric acid input, and the use of oxygen and sodium chlorate as oxidizing agents.

TABLE II. AVERAGE VALUES FOR AQUIFERS AND PREGNANT SOLUTIONS.

| | | **Pregnant solution** | | **Groundwater in basal sands** | |
|---|---|---|---|---|---|
| | **Unit** | **Average values** | **Range** | **Average values** | **Range** |
| $U_3O_8$ | µg/L | 75 | 20-1,000 | 1.2 | 0.02-7.3 |
| Fe | mg/L | 260 | 110-370 | <1.0 | <1.0 |
| Mo | µg/L | 3 | <0.5-10 | 13 | 1-40 |
| V | mg/L | 4 | 2-8 | <0.02 | <0.02 |
| $SO_4$ | mg/L | 5,300 | 3,580-6,800 | 1,770 | 1,100-2,670 |
| Cl | mg/L | 8,470 | 7,650-6,7060 | 7,850 | 4,020-9,740 |
| $SiO_3$ | mg/L | 115 | 45-330 | 8 | 5-10 |
| Ca | mg/L | 940 | 810-1,050 | 870 | 100-1,480 |
| Mg | mg/L | 210 | 90-460 | 390 | 200-560 |
| Al | mg/L | 15 | 0.2-70 | <1.0 | <1.0 |
| Cu | mg/L | 7 | 1-20 | 0.02 | 0.01-0.12 |
| Zn | mg/L | 110 | 80-130 | 0.19 | 0.03-0.67 |
| Se | µg/L | 55 | 40-70 | 30 | 13-75 |
| Na | mg/L | 6,170 | 5,150-7,200 | 4,310 | 2,820-5,250 |
| $HCO_3$ | mg/L | <5 | <5 | 145 | 90-270 |
| $NO_3$ | mg/L | <0.5 | <0.5 | 0.3 | 0.1-1.4 |
| F | mg/L | 0.6 | <0.3-0.9 | 0.6 | 0.5-1.1 |
| Ra-226 | Bq/L | 830 | 510-1,300 | 169 | 30-450 |
| TDS | mg/L | 16,430 | 15,300-20,000 | 16,100 | 9,400-20,000 |
| Spec Cond | mS/cm | 34 | 32-39 | 23 | 14-28 |
| pH | | 2.2 | 1.8-2.6 | 7.1 | 6.5-8.1 |

| | | **Middle sand** | | **Upper sand** | |
|---|---|---|---|---|---|
| | **Unit** | **Average values** | **Range** | **Average values** | **Range** |
| $U_3O_8$ | µg/L | 18 | 1-35 | 25 | 7-45 |
| Fe | mg/L | <1.0 | <1.0 | 1.0 | <1.0-1.0 |
| Mo | µg/L | 10 | 7-20 | 9 | 7-11 |
| V | mg/L | <0.02 | <0.02 | <0.02 | <0.02 |
| $SO_4$ | mg/L | 1,540 | 1,130-1,860 | 1,445 | 1,360-1,610 |
| Cl | mg/L | 5,370 | 4,710-6,260 | 4,800 | 4,610-5,220 |
| $SiO_3$ | mg/L | 6 | 4-10 | 6.6 | 5.5-7.4 |
| Ca | mg/L | 560 | 480-710 | 485 | 440-545 |
| Mg | mg/L | 270 | 85-390 | 260 | 245-295 |
| Al | mg/L | <1.0 | <1.0 | <1.0 | <1.0 |
| Cu | mg/L | 0.03 | 0.01-0.1 | 0.008 | 0.005-0.010 |
| Zn | mg/L | 0.2 | 0.02-1.1 | 0.20 | 0.03-0.46 |
| Se | µg/L | 19 | 10-30 | 14 | 11-22 |
| Na | mg/L | 3,385 | 2,335-3,600 | 2,815 | 2,570-3,010 |
| $HCO_3$ | mg/L | 160 | 28-210 | 195 | 180-210 |
| $NO_3$ | mg/L | 0.9 | 0.1-1.6 | <0.5 | <0.5 |
| F | mg/L | 0.9 | <0.5-1.8 | 1.0 | 0.5-1.2 |
| Ra-226 | Bq/L | 4.1 | 0.2-17 | 3.1 | 0.2-6.6 |
| TDS | mg/L | 11,400 | 10,000-12,900 | 10,300 | 10,000-11,000 |
| Spec Cond | mS/cm | 17.3 | 15.3-18.9 | 15.4 | 14.9-16.6 |
| pH | | 7.3 | 6.7-8.9 | 7.5 | 7.0-8.0 |

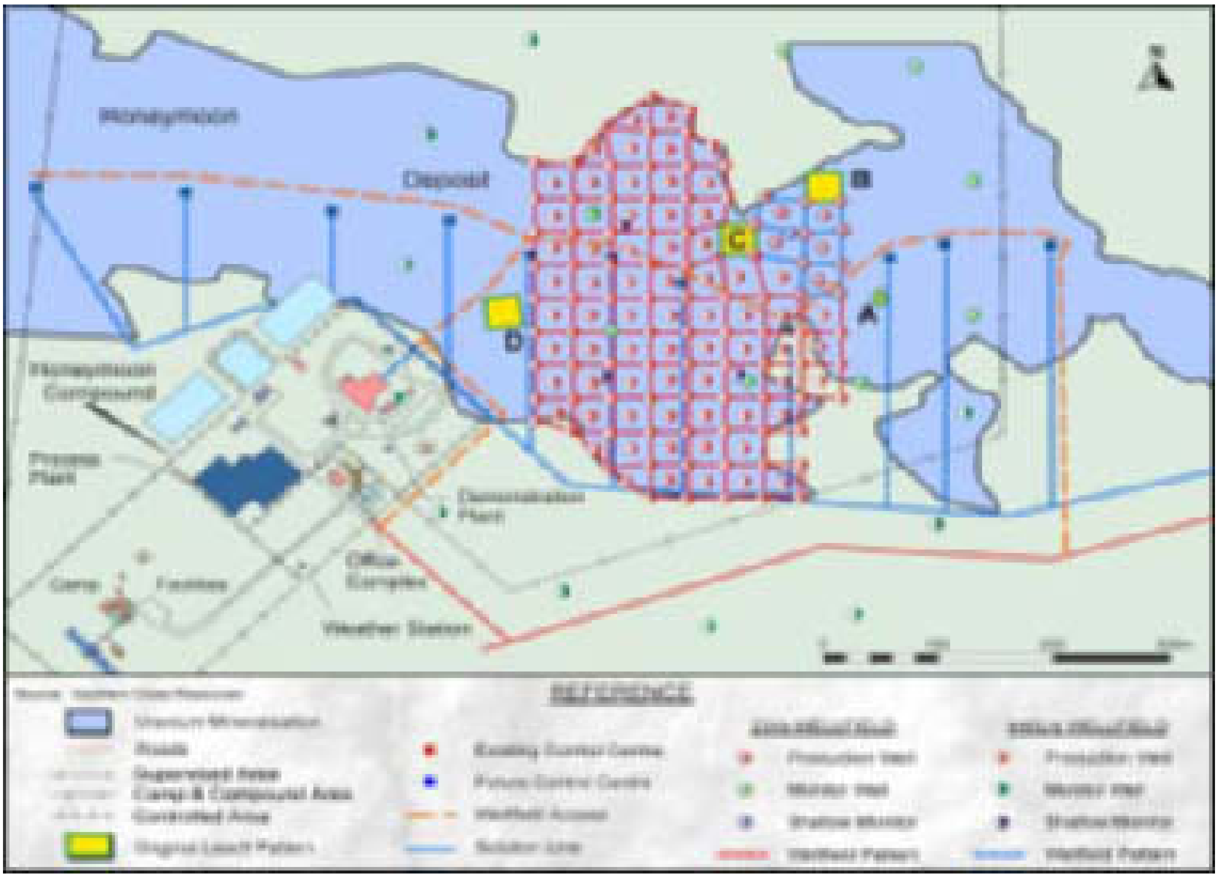

FIG. 6. Honeymoon wellfield.

Operation of an in situ leach pattern is characterized by an initial rise in solution grade, as easily mobilized uranium is contacted with leach solution. This is followed by a gradual reduction of solution grade over time.

## 9. **Metallurgy** (Fig. 8)

The high salinity of the groundwater (TDS 16,000 to 20,000) in the Basal Sands aquifer of the Yarramba paleochannel at Honeymoon sets it apart from other ISL operations and metal recovery plants using ion exchange recovery techniques. The water quality is a determining factor in the selection of a processing route for the recovery of the uranium (Table 2).

There are two principal leaching methods employed in ISL recovery; acid leach and alkaline leach. Acid (and alkaline) ISL methods have been used in the Republic of Kazakhstan for the production of yellowcake for the past 20 years. It was also tested successfully at a number of uranium deposits in the United States including Nine-Mile Lake and Irigaray in Wyoming and is in use at the Beverley Deposit in South Australia [14].

Alkaline (carbonate) leaching is widely used in commercial ISL uranium operations in North America in potable water. Acid leaching is not an economically viable option in these deposits due to the high calcium content that raises acid consumption to uneconomical levels and leads to the formation of gypsum in the deposit.

Acid leaching has proved more effective than alkaline leaching at Honeymoon. Laboratory column leach tests demonstrated that uranium leached more rapidly with acid leach than with alkaline leach, and the overall recovery was greater. The time required to recover 80% of the uranium by alkaline leach was approximately four times that required for acid leaching.

The measured differences in leach rates for the two leaching methods would have a significant impact on the size of the wellfield needed to support a commercial operation. The Field Leach Trial demonstrated the effectiveness of acid leaching at Honeymoon, with lower than expected acid consumption.

Alkaline leaching at Honeymoon would require maintenance of leach solutions at or near the natural pH (average 7.1) of the groundwater in the Basal Sands. Any minor increase in pH to levels would cause precipitation of groundwater calcium as calcium carbonate, thereby reducing the permeability of the ore and its amenability to ISL recovery.

There are two methods for recovering uranium from ISL solutions; resin ion exchange and liquid ion exchange (commonly referred to as solvent extraction). Each of these recovery methods works effectively under different conditions (see Table 3 below).

TABLE III. URANIUM RECOVERY METHODS.

| **Recovery method** | **ISL method** | |
|---|---|---|
| | **Acid leach** | **Alkaline leach** |
| Resin Ion Exchange | Effective at <3000 mg/L chloride concentration | Effective at <3000 mg/L chloride concentration |
| Liquid Ion Exchange (Solvent Extraction) | Effective at high chloride Concentrations | No solvents available |

Recovery of uranium by resin ion exchange, using commercially available resins, is effective with either acid or alkaline leach solutions, where the groundwater contains less than 3000 mg/L dissolved chloride. However, with chloride concentrations greater than 3000 mg/L, the efficiency of recovery decreases markedly because chloride ions in the leach solution displace uranium ions from the resin.

The Basal Sands groundwater at Honeymoon has chloride levels in excess of 7000 mg/L. Under these conditions, ion exchange with commercially available resins will not work efficiently with either acid or alkaline solutions, and solvent extraction is the only option. Solvent extraction is a well-proven method for uranium extraction and proved effective at Honeymoon during the Field Leach Trial.

Commercially available solvent extraction reagents, however, are not compatible with alkaline solutions. Consequently, acid leaching combined with solvent extraction is the only practicable uranium extraction technology suitable for the Honeymoon deposits. The flow sheet adopted is conventional in that it represents standard practice part from the organic reagents as noted in the following paragraphs.

The trial period enabled optimization of the process chemistry, additives and management. This has served as an invaluable base for the design and operation of the commercial plant.

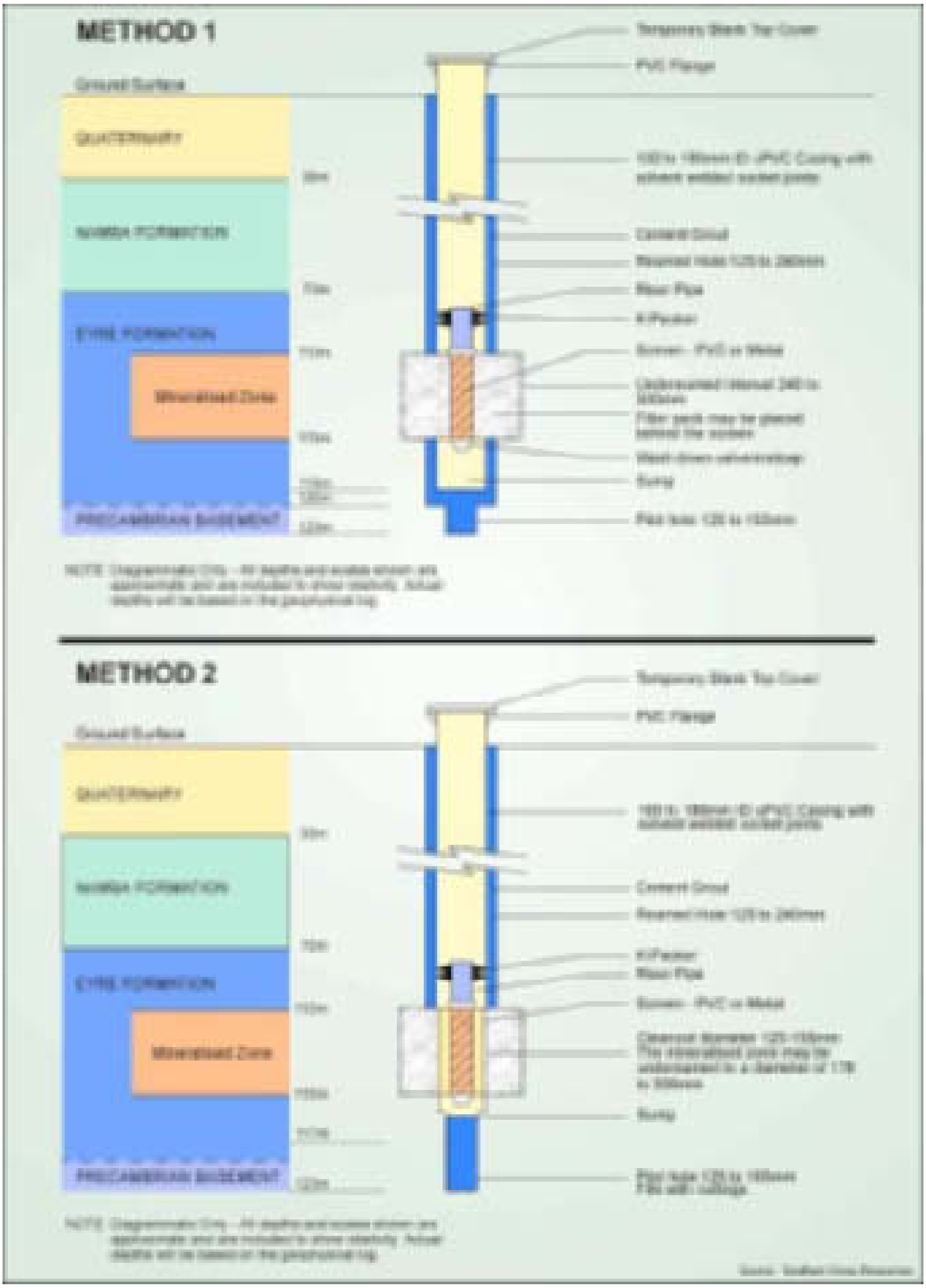

*FIG. 7. Well construction.*

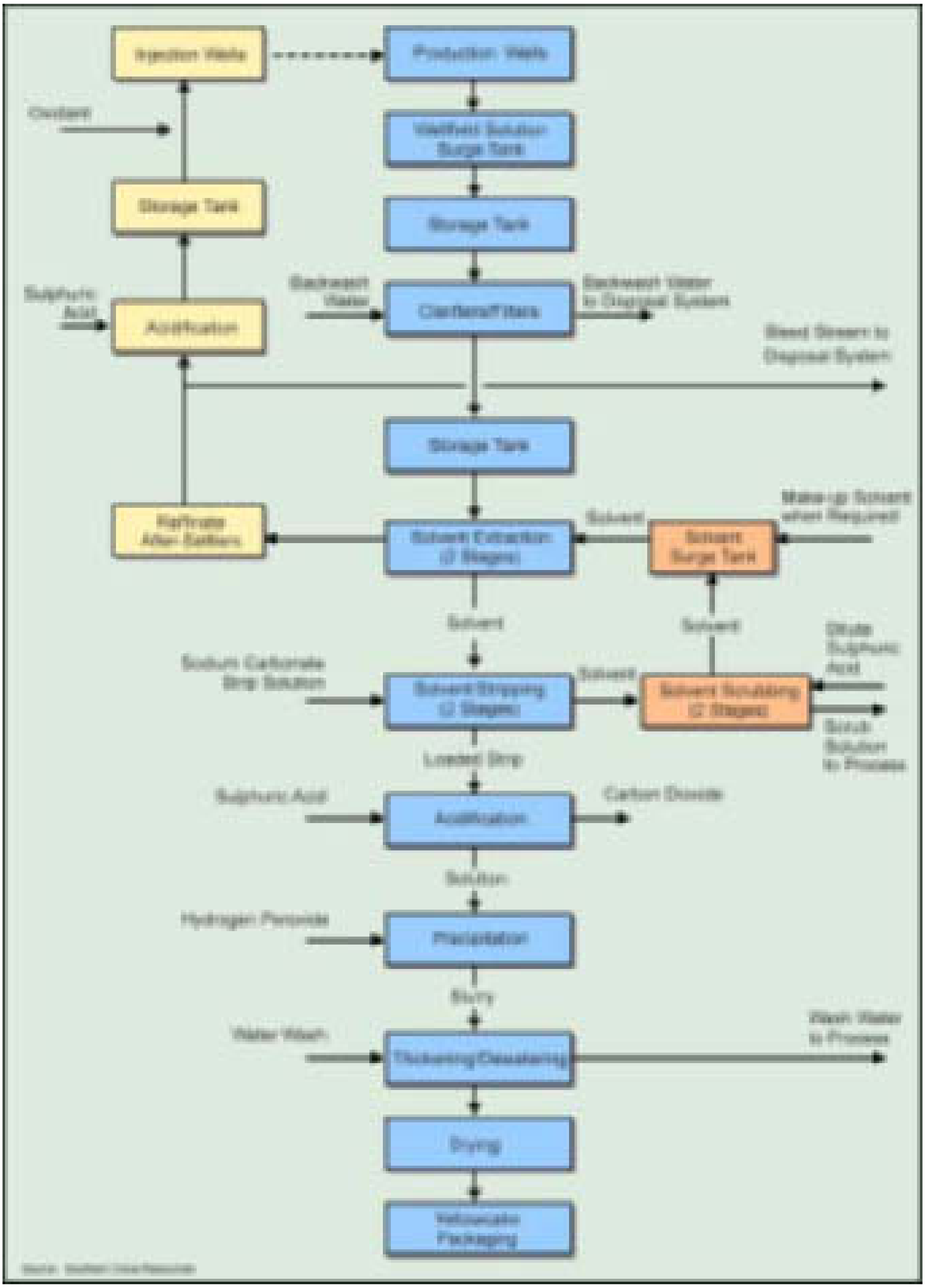

*FIG. 8. Flow sheet.*

Uranium solvent extraction plants around the world use a tertiary amine and isodecanol combination in the organic phase. This chemistry is not suitable for the high concentrations of competing ions in the Honeymoon saline pregnant solutions. An alternative chemistry was therefore developed to obtain high uranium recoveries and high solution grades from pregnant solutions.

The successful alternative organic reagent suite was comprised of di-(2-ethylhexyl) phosphoric acid (DEHPA), tertiary amine and tributyl phosphate (TBP) dissolved in high flash point kerosene. These organic extractants were able to achieve uranium recoveries from pregnant solutions of 97%. There were no problems with jarosite formation or excessive scale build-up in the plant.

The organic extractants were submitted to long-term tests under continuous operating conditions over a range of uranium concentrations in the feed solutions. The data generated from these trials has been used in the design of the commercial plant.

Metallurgical development work concentrated on solvent extraction kinetic work, ion loading characteristics, the use of various extractants, phase disengagement measurements and the yellowcake precipitation circuit.

## 10. Demonstration phase

The Field Leach Trial was authorized by the relevant South Australian authority in March 1998 and commenced in the following month. Initially, use was made of the refurbished original three patterns from the 1982 trial and throughput was limited to 6 L/s. Subsequently the decision was made to install a new five-pattern trial wellfield using the same sizing and equipment planned for the commercial phase. This was completed in May 1999 and was operated under varying wellfield and plant conditions until August 8, 2000.

The demonstration plant and wellfield were operated up to the design rate of 25 L/s, developing additional technical, financial and environmental data for use in final feasibility, engineering and design studies for the project. The radiation and environmental information collected will form the basis for radiation and environmental monitoring and management plans being developed for the commercial operation.

The recovery of uranium by solvent extraction methods is used worldwide. It has never been commercially applied with highly saline water. Much of the technology had only been tested in the laboratory and during limited small-scale pilot testing at Honeymoon in 1982. The Field Leach Trial was designed to test the technology under field conditions at a scale that provided a high degree of confidence in the design and operation of a commercial plant.

The operation employed 22 people during this period and was operated with the full range of management, geological, metallurgical, analytical, environment and radiation skills.

The trial was essential to the development of the project and formed a firm basis on which the planned commercial phase can be confidently developed.

## 11. Approval process experience and issues

The Honeymoon approval process formalities are detailed earlier and the project benefited from the proximity in timing and largely similar Beverley development, which preceded it through the approval process. There was a heightened degree of education about ISL and the important hydrological and bleed stream disposal characteristics amongst the authorities. Particular attention was paid to hydrological and stratigraphic characterization and to examining all options for bleed stream and process liquid disposal. The operation of the Field Leach Trial for an extended period also enabled comprehensive radiation monitoring to be undertaken, adequately understood, well documented and passed onto the relevant technical agency.

The conditional approval by the Commonwealth Environment Minister also raised the need for additional work in the areas of geological confirmation of the palaeochannels margins in some sectors, positive hydrographic measurements by pump testing to prove margins impermeability and further modelling work to show the benign effects of the planned commercial bleed stream re-injection into the Basal Aquifer. This had the practical effect of involving the expenditure of considerable funds and making the practical "approval" date some nine months later than had been provided for in original planning.

It should be emphasized that all authorities displayed a high degree of professionalism, rigorous scientific knowledge and adherence to agreed formal procedures and timing commitments. SXR also appreciated the coordinated approach whereby one agency and its nominated person acted as the prime point of contact, action and information.

## 12. Exploration

Exploration in the last two years has been limited to the follow up of historical data and the margins of the known Honeymoon and East Kalkaroo deposits. A concerted effort has been put into extending the tenement area and this has been accomplished in two ways. In addition to direct tenure purchase or acquisition by application for vacant ground, SXR has been able to joint venture existing tenements for Tertiary uranium in palaeochannels by agreement with other exploration license holders. This strategy has suited the development of an exploration tool, which is able to cover large areas at relatively low cost. The AEM aerial geophysical technique is suited to the flat topography and the saline palaeochannels being sought and is proving a valuable and accurate method of palaeochannels detection and definition (Fig. 9). It is planned to now carry out "greenfields" drilling campaigns based on these results and targeting perceived favourable geological environs. On past results, it is known that the Yarramba and Billeroo palaeochannels are uranium rich and the challenge is to find further economic concentrations within the palaeochannels [21].

## 13. Present status [16]

Since acquiring the project in early 1997, the critical timeline for the development has successively been the refurbishment and operation of the Demonstration phase and then the EIS Approval process.

The project timetable has also been challenged by the timing of Federal and State elections and the policies towards new development of the major parties. There should now be no political impediment to the project's development. This history and timing milestones are shown (Fig. 10).

History since 1996:

| | |
|---|---|
| 1996 | Commonwealth Government changes to Coalition. Policy to encourage uranium mining. |
| 1997 | Southern Cross Resources acquires MIM and Sedimentary Holdings' interests in uranium. |
| May 1997 | Project bought from MIM. Refurbishment. Commenced advertising for Declaration of Environmental Factors (DEF). |
| March 1998 | DEF issued. |
| May 1998 | Demonstration operation commenced. |
| August 1998 | EIS guidelines issued. |
| June 2000 | EIS issued for public review. |

| | |
|---|---|
| August 2000 | Demonstration operation ends. |
| Nov. 2000 | Response document issued. |
| Feb. 2001 | Commonwealth Environment Minister requests additional work. |
| July 2001 | Additional report submitted. |
| Nov. 2001 | Commonwealth Environment approval, Commonwealth Export approval, State Mining Lease offer. |
| Feb. 2002 | State Mining Lease issued. |

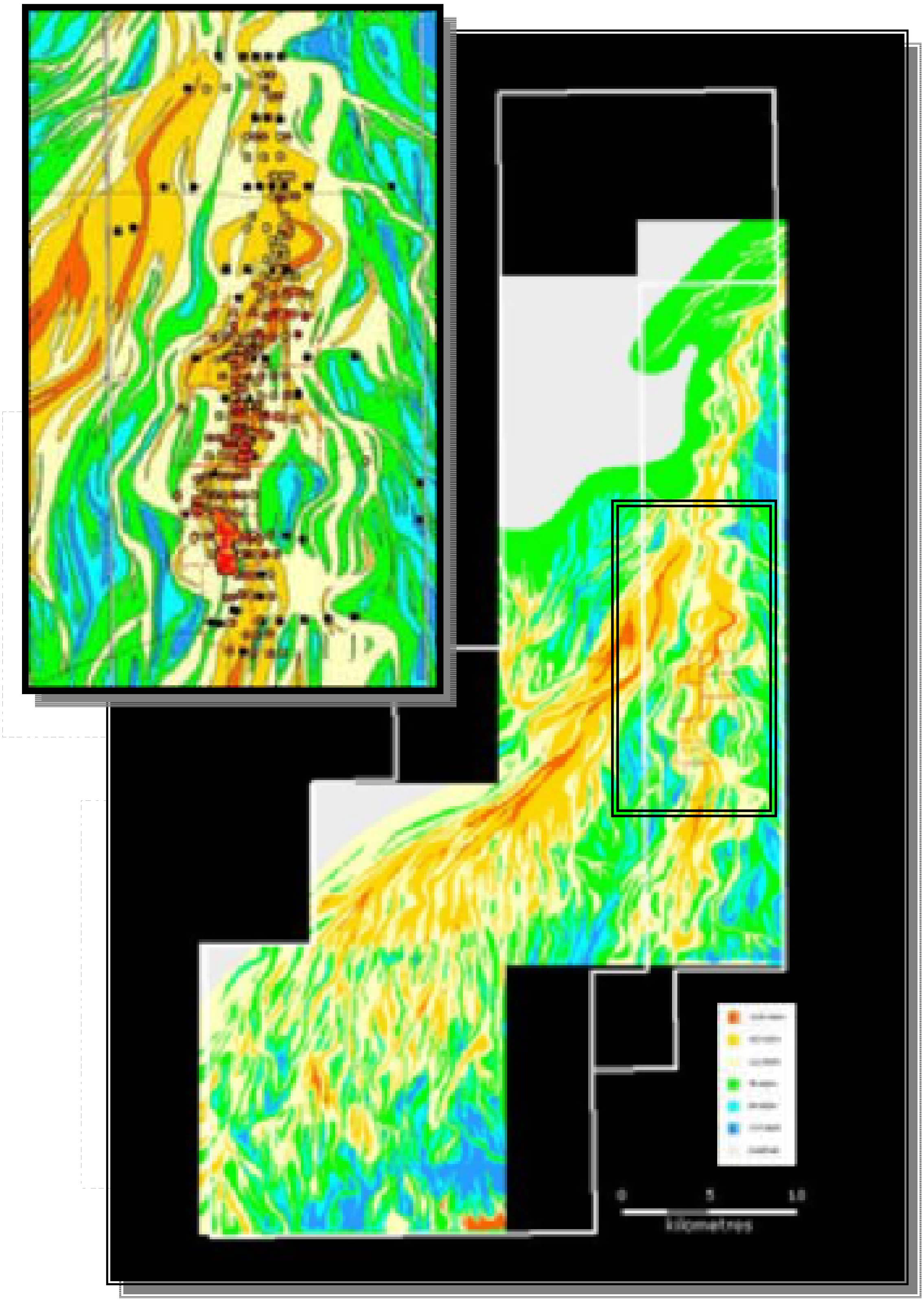

*FIG. 9. Goulds Dam Project – Interpreted Airborne Electro-Magnetics.*
(100m Conductivity Depth Slice) Insert shows existing drilling with thematic $U_3O_8$ distribution

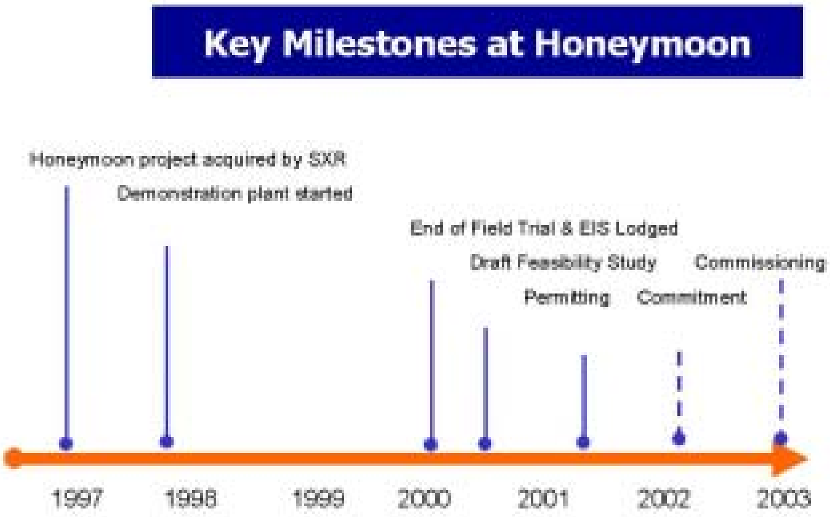

FIG. 10. Key milestones at Honeymoon.

The Honeymoon site area is now subject to two native title claims. Over the last five years there has been extensive and protracted contact with native title claimants and groups. The company has in place comprehensive native title mining agreements with the Kuyani and Adnyamathanha claimants. These agreements cover areas of commercial and administrative arrangements, cross cultural education, employment and contract opportunities, heritage clearances and ongoing consultation.

In the first half of 2002, a number of steps were taken to move towards financial and Board commitment. These have included:

(a) Recruitment of the Senior Management Team in the areas of Commercial, Administration, Operations, Project Management and Geology.
(b) Relocation to a larger "permanent" Adelaide office.
(c) Update previous studies as to project characteristics, engineering and cost.
(d) Further ground acquisition and exploration including a comprehensive AEM survey.
(e) Finalize arrangements for debt/equity funding particularly in the areas of due diligence, marketing and timing.
(f) Commitment to an exploration programme aimed at identifying further economic deposits.

The aim is to be in a position later in 2002 to formally commit to the project. Total expenditure into production (including working capital etc) is of the order of A$48 million with a 12 month construction period. Initial production rate will be in the range of 750-1,000 tpa of $U_30_8e$. There will be 45 employees/contractors on site on the basis of commuting from Broken Hill. Particular emphasis is being placed on service items such as road access, power supply and telecommunications needs.

## 14. **Commercial development** [7]

The commercial development at Honeymoon (Fig. 11) is planned to feature:

(a) A new solvent extraction based metallurgical plant producing up to 1,000 tpa $U_3O_8$ equivalent as drummed product.
(b) A number of wellfields operating at a nominal average uranium concentration of 75ppm $U_3O_8$ at 340 L/s to the plant with associated monitoring, bleed disposal and development wells.
(c) Upgraded road access and telecommunications facilities and a 5 MVA capacity 65 km long 22 Kv power line from the existing infrastructure near Broken Hill.
(d) Upgraded and expanded camp and support facilities.

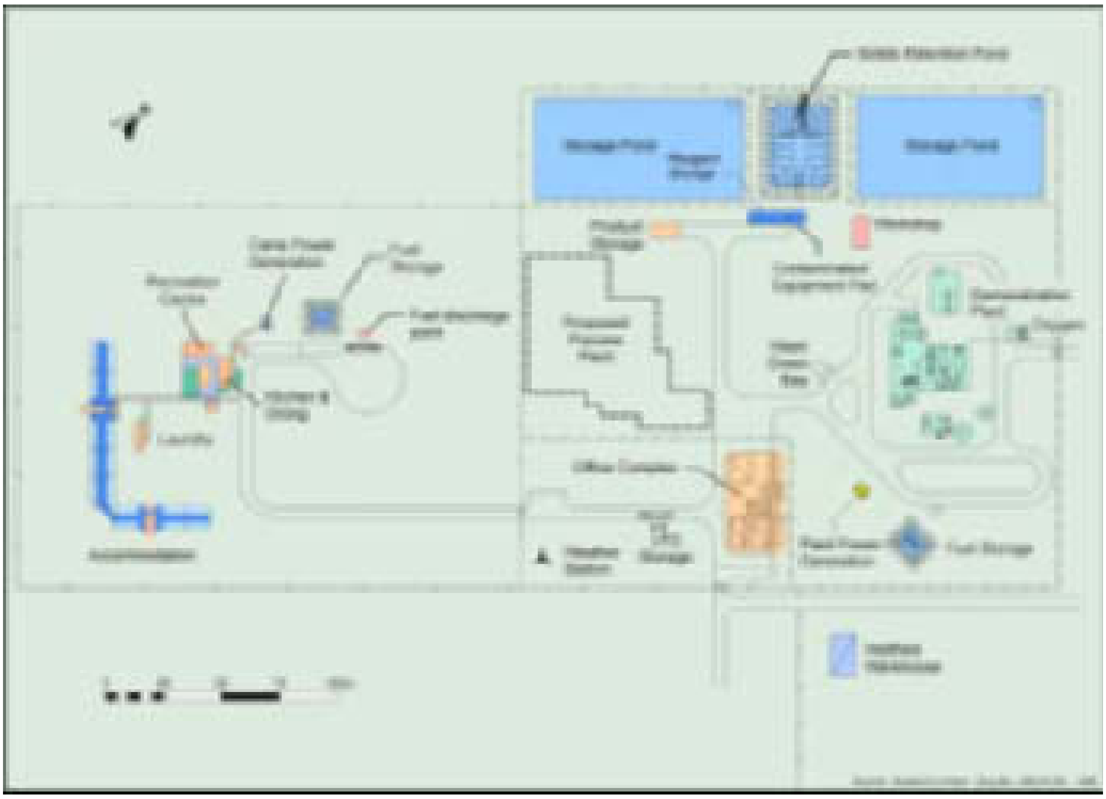

*FIG. 11. Honeymoon planned layout.*

Development philosophy is to initially concentrate production on the Honeymoon field and then move to the east to East Kalkaroo. An ongoing exploration effort will be undertaken to identify further economic deposits within the Yarramba palaeochannels and within economic pumping distance of the Honeymoon plant. Appropriate investigation and regulatory approval procedures will be put in place as necessary to ensure continued operation.

Longer term plans are to ultimately develop the Gould Dam deposit in the Billeroo palaeochannel some 80 km to the west. Such development would require further studies and regulatory approval and the relocation of the Honeymoon plant and facilities.

The development of Honeymoon has been justified by the low projected operating costs for the project. Cash costs for the Honeymoon/East Kalkaroo deposits are projected to be below US\$6.00 per pound $U_3O_8$ equivalent.

## 15. Summary

The Honeymoon project is proceeding towards a positive formal commitment decision. The company has built up a strong land position in the Curnamona area in South Australia and has now, through the trial and approval process, built up a strong basis for commercial operation. The market position for yellowcake is improving and there is a considerable gap between demand and mine production. The Honeymoon project economics are robust and there is high confidence in being able to achieve low operating costs and the tonnage production targets.

The project will be the first commercial ISL operation using solvent extraction from saline groundwater.

## ACKNOWLEDGEMENT

The efforts of all those involved in advancing the Honeymoon project to its present level are acknowledged. The contributions of Dr. Phil Bush and Oliver Lennox-King have been especially valuable.

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# In situ leach uranium mining in the Russian Federation (status and prospects)

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**Abstract.** ISL uranium mining is performed in Russia on two deposits, the Dalmatovskoe and Khiagda deposits. Each of them has its own specifics, which require individual mining approaches. Dalmatovskoe deposit is located in the Transural region. Deposit is of basal channel (paleo-valley) type, and occurs at a depth of 450-600 m. Depth of mineralization is the main mining difficulty, which affects development costs. Khiagda deposit is located within the Republic of Buryatiya. Mineralization occurs at a depth of 160 to 180 m. Specific features of the deposit, which may influence mining are: presence of volcanic rocks on top of mineralized formation, low temperature (2-4ºC) and static levels of ground-waters, zone of permafrost within the deposit area. Different measures are performed by research and design organizations to improve ISL mining in these specific conditions: reduction of drilling costs, of acid and energy consumption, study of uranium leaching process at low temperature, process of pregnant solutions. Environmental issues, including aquifer restoration, are studied through geological and hydro-geological modelling of the deposits, and the development of new logging tools.

## 1. Specific features of the Russian Federation in situ leaching sites

In situ borehole leaching is currently being carried out in Russia at the Dolmatovskoye (Transural District) and Khiagda (Republic of Buryatia) uranium deposits.

Each deposit has a number of characteristics, which call for a special approach when organizing in situ leaching (Tables I and II).

Table I. Specific features of the Dolmatovskoye deposit.

| No. | Deposit features | Implications of specific deposit features |
|---|---|---|
| 1. | The deposit is located in a region with a protracted winter and low temperatures (minus 25-30°C) | Process pipes need to be heated; drilling is more expensive in winter. |
| 2. | Depth of mineralization: 450-500 metres | Engineering difficulties in constructing boreholes in view of the depth; stripping of deposits is more expensive. |
| 3. | High static levels leading, in specific cases, to self-discharge of the boreholes | Technical resources needed to pump leaching solutions and oxidants into the ore horizon. |

Table II. Specific features of the Khiagda uranium deposit.

| No. | Deposit features | Implications of specific deposit features |
|---|---|---|
| 1. | The deposit is located in a region with a protracted, severe winter. In the winter months the temperature falls to minus 50-55°C. | Process pipes need to be heated; laying of "associated pipes" containing hot water; difficulties drilling boreholes in winter; need for an energy reserve. |
| 2. | Permafrost rocks cover the entire deposit area. | During drilling using a washing fluid the borehole walls heat up, creating drilling difficulties. |
| 3. | Predominance of very solid hard rock in the geological section. At a mineralization depth of 160-180 m hard rock is up to 120-130 m thick. | Solid hard rock in the deposit section slows down drilling, prolongs borehole construction and substantially increases drilling costs. |

| | | |
|---|---|---|
| 4. | Low static groundwater levels | At low levels, submersible pumps with relatively little motor capacity are used to pump water. |
| 5. | Low groundwater temperatures (+2-4°C) | Lower temperatures reduce the rate of the mass transfer processes. Uranium sorption by anionites slows down. This calls for an increased one-time resin loading and a consequent increase in total resin consumption. |

Soviet uranium companies never practised in situ leaching at such low groundwater temperatures. The usual temperature range for working deposits was +18–40°C. The actual conditions at the Khiagda deposit required research to investigate uranium leaching and sorption processes at low temperatures.

Parallel leaching trials were carried out in columns of sulphuric acid solution in a concentration of 23 g/L at temperatures of +18–20°C and +2–4°C. The leaching process at +24°C has a number of specific features (see Figure 1). First of all, in the initial period until the liquid/solid ratio (L:S) reached 0.8 (duration of leaching: 3 days), uranium extraction at the lower temperature was substantially greater than at the usual temperature. The specific acid consumption in both cases was similar: 16 kg and 18 kg per tonne of ore. Extraction was then seen to level off and there was a reduction in the specific acid consumption in the case of leaching by cold solutions. The extraction level was the same (84-86%) by the end of the process, at a L:S ratio of 2.2. Whereas specific acid consumption during leaching by cold solutions did not exceed 18 kg/t, at room temperature it went up to 22 kg/t.

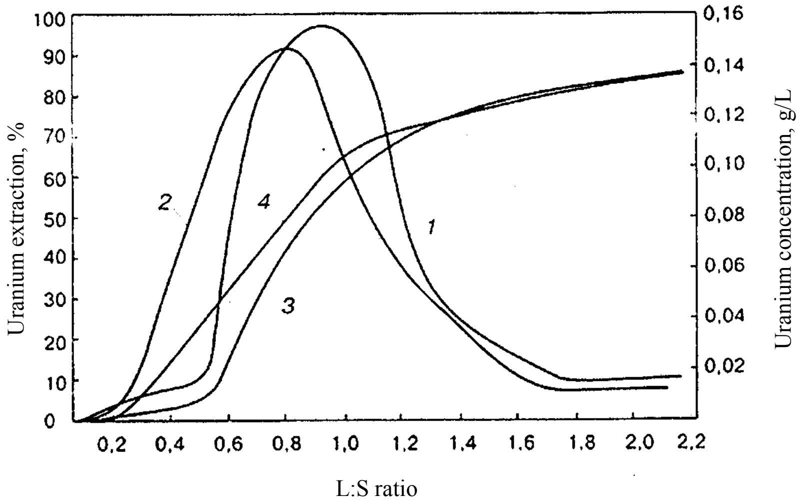


*FIG. 1. Uranium concentration in pregnant solutions (1,2) and extraction (3,4) as a function of the L:S ratio; 1,3 - solution temperature +18–20°C; 2,4 - solution temperature +2–4°C.*

The results obtained show that, for the Khiagda deposit ores, a low (above zero) temperature does not, in general, affect the leaching rate. The lower specific acid consumption can be explained by the natural slowing down of the acid's interaction with the country rock. However, under actual in situ leaching conditions, when leaching solutions are in contact with the ore for longer, the sulphuric acid consumption will most likely reach values similar to those at the usual temperature.

We know that a lower temperature reduces the rate of the mass exchange processes in both homogeneous and heterogeneous systems, including in the "sorbent-solution" system. We should expect therefore that uranium sorption by anionites will be substantially slower when pregnant solutions are at a low temperature. We can also assume that the uranium sorbent capacity will be lower than the corresponding values obtained at the normal temperature. These assumptions were tested by means of special experiments.

For uranium sorption using a Rossion-3 anionite solution at a concentration of 80 mg/L, modelled on actual pregnant solution impurities, the process was significantly slower at a low temperature than at the usual temperature. The volume of anionite after 24 hours of contact was 32 mg/t and 58 mg/t, respectively. Even more significant was the difference in kinetic sorption from solutions with a low uranium concentration (-5 mg/L). Sorption equilibrium in the “resin-cold solution” system is not achieved even after 60 hours, compared with 24 hours at room temperature. Thus, the most important features of uranium sorption at a low temperature are its significant slowing down and the reduction in the equilibrium and effective capacities of the sorbent. Under actual process conditions this will call for an increased one-time sorbent loading, and a consequent increase in total sorbent consumption.

## 2. Geo-ecological research

Russia’s ecological services are extremely careful about making expert appraisals of projects involving in situ leaching. General analysis of the impact of in situ leaching on the air basin, day surface and aquifers of the hydrogeological systems perforated by operating boreholes indicates that the underground part of local ecosystems is subject to the greatest contamination. Consequently, the solution to all environmental conservation problems is in the geo-ecological sphere.

It is best to carry out integrated geo-ecological and geo-technological research at all stages in the exploitation of hydrogenous uranium deposits. A diagram of the environmental monitoring carried out at uranium deposits is given in Figure 2. It contains a whole set of recommendations on geo-ecological research and is based on the results of work done [1,2,3].

The “Ecology of Groundwater” application package is of great assistance in carrying out comprehensive geo-ecological investigation of uranium deposits as it offers a methodical solution to the problem of predicting the groundwater components in the dislocation area of a site at any point in time after the start of operation. The package comprises a mathematical model of the environment, a mathematical hydrodynamics model, a mathematical model of contaminant migration, tools for fitting the package to specific mining and geological conditions and on-site operating conditions for each contaminant, and for graphic representation of the mathematical modelling results. It plots geological sections for any given profile and maps the planar distribution of water physical properties at any given horizon level; hydrodynamic diagrams of the structure of seepage flows taking into account macro- and microdispersion, the dynamics of how the seepage front of the process solutions changes spatially over time, without taking account of the physical and chemical processes of solutions interacting with rock, and the zone of influence for water intake; hydroecological maps showing the front of the maximum permissible concentrations of the contaminant under investigation, both in a plane and in a section of the modelled horizon. Application packages were first used to model in situ leaching sites in Russia using source data for the production company at the Khiagda deposit.

The Russian Federation State Committee for Construction (Gosstroj), by agreement with the State Committee for Ecology, has drawn up recommendations for taking environmental concerns into account in investment and construction projects [4]. On the basis of these, a basic flow diagram for the taking of environmental protection measures during a uranium in situ leaching project has been drawn up (Fig. 3).

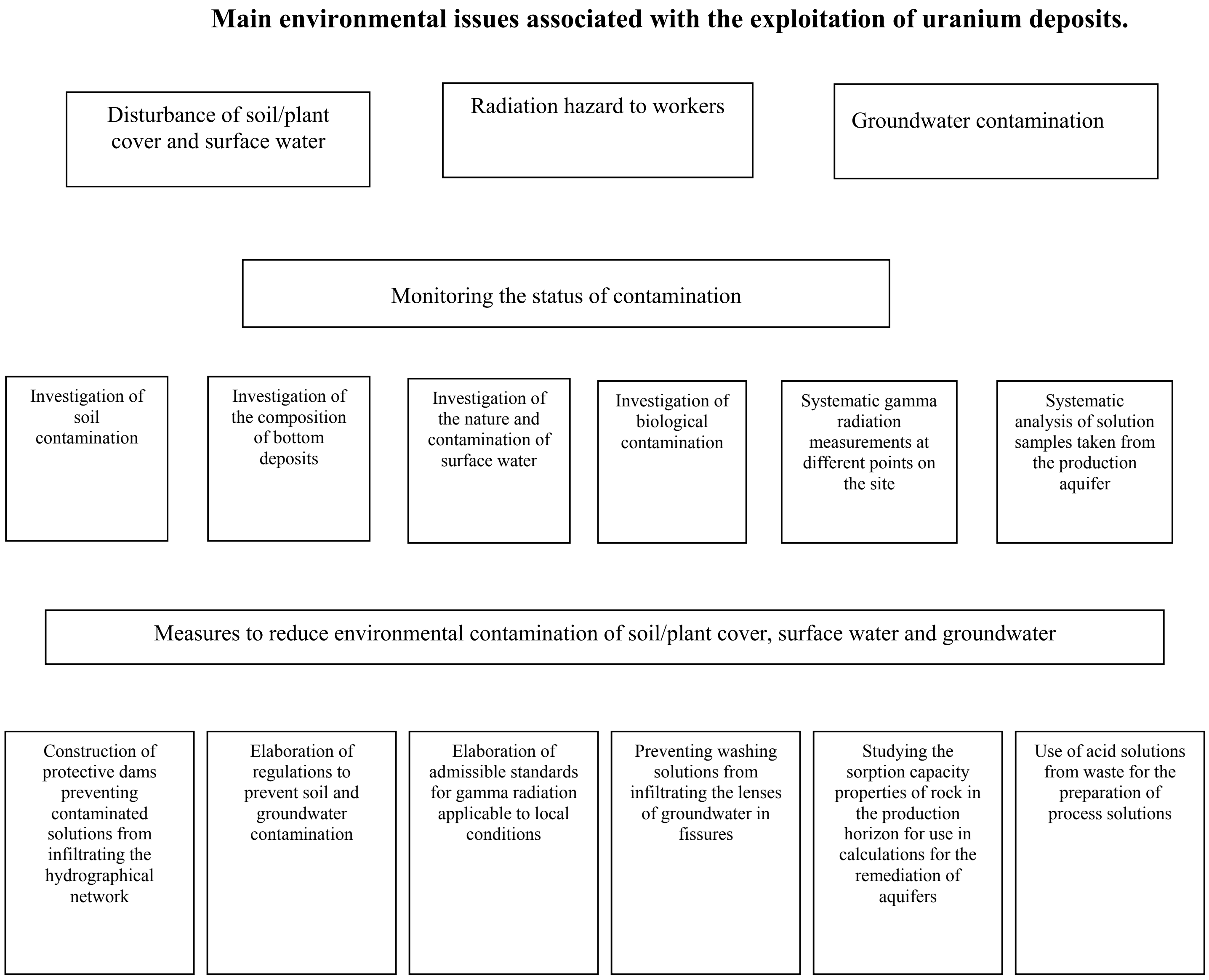
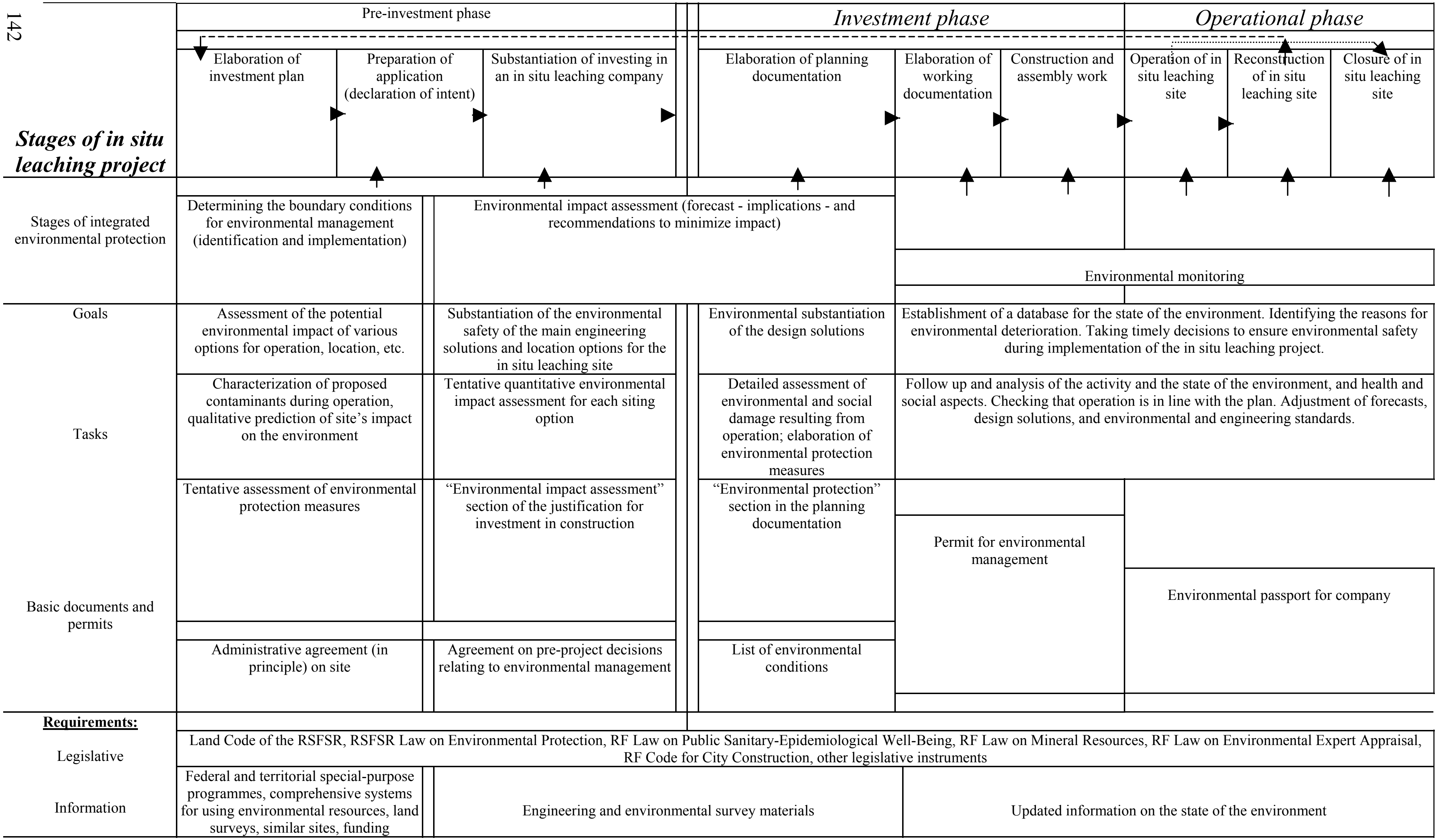


*FIG. 2. Diagram for environmental monitoring of uranium deposits.*



| | Pre-investment phase | | | *Investment phase* | | | *Operational phase* | | |
|---|---|---|---|---|---|---|---|---|---|
| ***Stages of in situ leaching project*** | Elaboration of investment plan | Preparation of application (declaration of intent) | Substantiation of investing in an in situ leaching company | Elaboration of planning documentation | Elaboration of working documentation | Construction and assembly work | Operation of in situ leaching site | Reconstruction of in situ leaching site | Closure of in situ leaching site |

| | | | | | |
|---|---|---|---|---|---|
| Stages of integrated environmental protection | Determining the boundary conditions for environmental management (identification and implementation) | Environmental impact assessment (forecast - implications - and recommendations to minimize impact) | | Environmental monitoring | |
| Goals | Assessment of the potential environmental impact of various options for operation, location, etc. | Substantiation of the environmental safety of the main engineering solutions and location options for the in situ leaching site | Environmental substantiation of the design solutions | Establishment of a database for the state of the environment. Identifying the reasons for environmental deterioration. Taking timely decisions to ensure environmental safety during implementation of the in situ leaching project. | |
| Tasks | Characterization of proposed contaminants during operation, qualitative prediction of site's impact on the environment | Tentative quantitative environmental impact assessment for each siting option | Detailed assessment of environmental and social damage resulting from operation; elaboration of environmental protection measures | Follow up and analysis of the activity and the state of the environment, and health and social aspects. Checking that operation is in line with the plan. Adjustment of forecasts, design solutions, and environmental and engineering standards. | |
| Basic documents and permits | Tentative assessment of environmental protection measures | "Environmental impact assessment" section of the justification for investment in construction | "Environmental protection" section in the planning documentation | Permit for environmental management | Environmental passport for company |
| | Administrative agreement (in principle) on site | Agreement on pre-project decisions relating to environmental management | List of environmental conditions | | |
| **Requirements:** | | | | | |
| Legislative | Land Code of the RSFSR, RSFSR Law on Environmental Protection, RF Law on Public Sanitary-Epidemiological Well-Being, RF Law on Mineral Resources, RF Law on Environmental Expert Appraisal, RF Code for City Construction, other legislative instruments | | | | |
| Information | Federal and territorial special-purpose programmes, comprehensive systems for using environmental resources, land surveys, similar sites, funding | Engineering and environmental survey materials | | Updated information on the state of the environment | |

*FIG. 3. Basic flow diagram of environmental protection measures during a uranium in situ leaching project.*

Thus, the industry now has the methodological documentation and standards needed to ensure integrated environmental protection at uranium in situ leaching companies.

## 3. Avenues of scientific R&D in the field of uranium in situ leaching

The primary consideration when planning scientific R&D is to select an area, which will help reduce acid and oxidant consumption, energy consumption and the cost of drilling. Scientific R&D to improve in situ leaching techniques and technologies is grouped as follows:

(a) Development and introduction of technologies which increase performance, reduce drilling costs, and improve filtration properties around the seepage area of boreholes;
(b) Study of the geological, hydrogeological, mineralogical, geochemical, and geotechnical features of deposits exploited using in situ leaching;
(c) Research into the chemical interaction of reagents with the rocks of the ore-bearing horizon, with a view to raising the rate of transfer of useful components to pregnant solutions;
(d) Improving the technology for processing pregnant solutions;
(e) Improving logging methods in investigation;
(f) Geo-ecological research.

Avenues of research and expected results are given in Table III.

Table III. Avenues of scientific R&D for in situ uranium leaching and expected results.

| No. | R&D avenues | Expected results |
|---|---|---|
| 1. | Development and introduction of technologies which increase performance, reduce drilling costs, and improve filtration properties around the seepage area of boreholes; | 1.1. Development of specialized borehole drilling equipment, taking into account in situ leaching specifications up to depths of 300 and 500 metres.<br>1.2. Choosing the most effective oscillators, developed by Russian design organizations, to increase the permeability of productive horizons |
| 2. | Study of the natural properties of deposits exploited using in situ leaching | Using deposit properties to model leaching at all stages of the process, from acidification to restoration of aquifers. |
| 3. | Research into the chemical interaction of reagents with the rocks of the ore-bearing horizon with a view to raising the rate of transfer of useful components to pregnant solutions. | Selecting effective oxidants for in situ uranium leaching, regulations for extracting associated useful components. |
| 4. | Improving the technology for processing pregnant solutions | 4.1. Establishing an improved sorption system for processing pregnant solutions using high-speed sorption apparatus, increasing sorption efficiency by a factor of 2-3 and reducing sorbent loading by 20-30%<br>4.2. Creating electromembrane apparatus to process desorbates and obtain a higher quality concentrate |
| 5. | Improving logging methods in research | Widespread introduction of hydrochemical probes to solve a number of geological, hydrogeological, hydrogeochemical and engineering problems |

Hydrogeochemical logging is a new avenue of development. A hydrogeochemical probe is a complex measuring device comprising five measurement methods: thermometry, barometry, conductometry, amperometry and potentiometry.

It is very important for the study of the restoration of groundwater quality through natural neutralization and demineralization of residual in situ leaching solutions.

Table IV lists the hydrogeological, hydrogeochemical and process parameters that can be measured using a hydrogeochemical probe.

Besides Russia, this work is being carried out in Kazakhstan. The leading scientific research organization in this area is the Institute for Ore Deposit Geology, Petrography, Mineralogy and Geochemistry, Russian Academy of Sciences (IGEM RAN).

Table IV. Hydrogeological, hydrogeochemical and process parameters of groundwater and in situ leaching processing solutions that can be measured using a hydrogeochemical probe (device diameter - 42 mm).

| | Parameters | Conventional symbol |
|---|---|---|
| 1. | Depth to which device lowered, m | H |
| 2. | Hydrostatic pressure, m | P |
| 3. | Temperature, °C | T |
| 4. | Specific conductance | E |
| 5. | Acid-base indicator | pH |
| 6. | Oxidation-reduction potential | Eh |
| 7. | Dissolved oxygen concentration | $O_2$ |
| 8. | Nitrate ion concentration | $NO_3^-$ |
| 9. | Sodium ion concentration | $Na^+$ |
| 10. | Calcium ion concentration | $Ca^{2+}$ |
| 11. | Ammonium ion concentration | $NH_4^+$ |
| 12. | Dissolved hydrogen sulphide concentration | $H_2S$ |
| 13. | Hydrogen concentration | $H_2$ |
| 14. | Carbon dioxide concentration | $CO_2$ |
| 15. | Carbonate anion concentration | $CO_3^{2-}$; $HCO_3^-$ |
| 16. | Sulphate ion concentration | $SO_4^{2-}$ |
| 17. | Nitrite ion concentration | $NO_2^-$ |

This R&D will help to improve the technical and economic indicators for uranium deposit exploitation and make uranium extraction environmentally friendly and profitable.

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# Uranium related activities in the Russian Federation

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**Abstract.** Russia plans to accelerate uranium exploration and production activities to guarantee steady development of mining enterprises. The amount and quality of known uranium resources and current production rates cannot provide the planned requirements. The basic directions in uranium production development are development of active mining facilities, revaluation of stand by uranium deposits, uranium joint production in Kazakhstan. To provide effective mining for the next 30 years at Priargunsky center modernization of mining and technological equipment is conducted currently. Two new uranium producing centers Dalur and Khiagda are under construction. Both operate sandstone basal channel deposits using sulfuric acid ISL technology. Large uranium deposits in Aldan district will be studied for high-grade mineralization distribution and effective ore processing. Realization of presented activities on uranium production development must considerably reduce the rates of stocks depletion and provide fuel requirements of the Russian nuclear industry up to 2025-2030.

## 1. Introduction

During the last decade, development of the world uranium industry was extremely unstable. It is connected, first of all, with discrepancy between fuel needs of the nuclear power stations and natural uranium production. Prior to the beginning of 90th uranium production prevailed over its needs because of the high uranium prices and strategic military interests of the countries. As a result of this overproduction, a significant amount of uranium was stocked. Demilitarisation and world political changes in 90th resulted in the active sold of stocked uranium and in uranium prices falling. The uranium production decreased accordingly and its total shortfall (a difference between requirements and production) for last decade amounted over 200 000 tons.

World problems [1,2] related to uranium shortfall, stocks exhaustion and deficit of low cost geological resources are inherent in Russia. The analysis of various sources for nuclear fuel production in Russia to 2020 has shown, that they will be provided on 37% with material from stocks, on 36% with domestic uranium production, on 15% with uranium import and on 12% with nuclear fuel reprocessing (Fig.1).

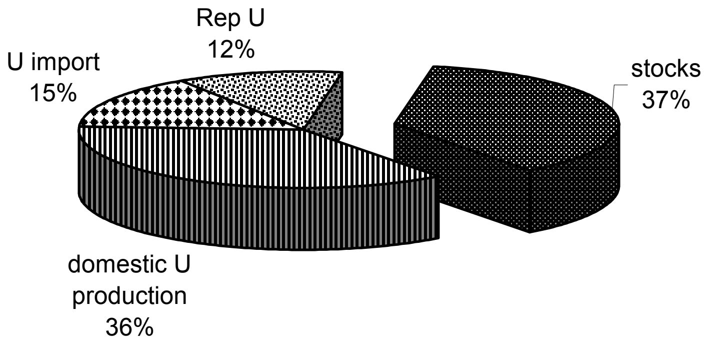

*FIG.1. The structure of sources for nuclear fuel production in Russia to 2020.*

Russia as the world leader in nuclear fuel production, should have its own reliable resources, which will guarantee steady development of the mining enterprises. The amount of known uranium resources and current production rates cannot cover the planned requirements. The basic directions in uranium production development are the following:

(a) Development of active mining facilities;
(b) Revaluation of stand by uranium deposits;
(c) Uranium purchase and (or) joint production in Kazakhstan, Uzbekistan and Ukraine.

The location of uranium bearing districts and facilities in the Russian Federation is shown on Figure 2.

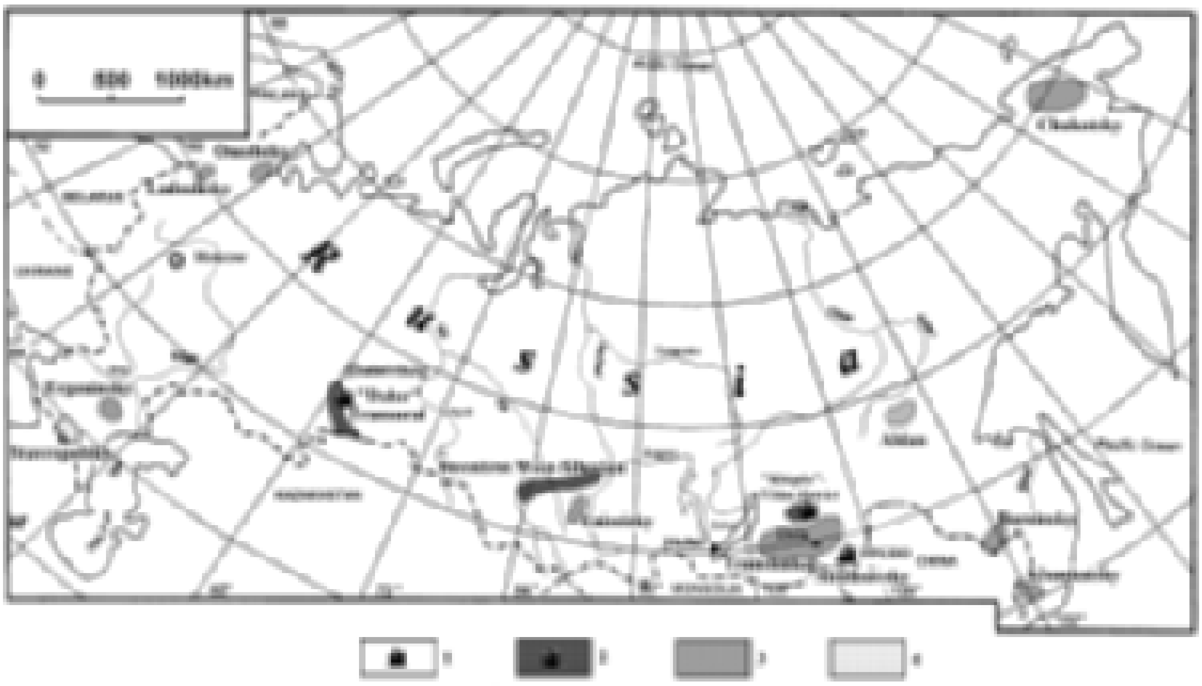

*FIG. 2. Uranium facilities and districts in Russian Federation: 1-active mining (Streltsovsky-PPGHO); 2-planned mining (Khiagda, Dalur); 3-potential; 4-depleted.*

## 2. Active uranium producing facilities

### *Priargunsky industrial mining-chemical association (PPGHO)*

“Priargunsky Mining-Chemical Production Association” (PPGHO) was the only active uranium production centre in Russia in last decade. It is located in Chita region of Russia, 10-20km from the town of Krasnokamensk with a population of about 60 000 inhabitants. The production is based on 19 volcanic-type deposits of Streltsovsk U-ore region at the square 150 km$^2$ with the average U grade about 0.2%. Mining has been operated since 1968 by two open pits (both are depleted) and four underground mines (2 are active and 2 stand by). Milling and processing has been carried out since 1974 at the local hydrometallurgical plant by sulphuric acid leaching with subsequent recovery by sorption-extraction ion exchange scheme.

Mineralization is related to volcanics and largely controlled by structures as reflected by predominantly vein and stockwork ore lodes. Deposits are therefore classified as structure-bound volcanic-type [3,4]. Two principal ore varieties are distinguished, monometallic uranium and polymetallic uranium-molybdenum ores.

Uranium mineralization occurs to a depth of about 1100 m and lower. Approximately 75% of the resources of the Streltsovsk district are at a depth interval of 200 to 600 m below surface where ore lodes are distributed on several levels in stratified sedimentary volcanogenic rocks of Jurassic-Cretaceous age. About 25% of the resources are situated at lower levels between 400 and 900 m deep. Two large and high-grade deposits are hosted by Paleozoic granite and by marble of the Lower Proterozoic basement.

More than 100 000 tU have been produced at Priargunsky through 2003. This high level of total production marks Priargunsky as one of the outstanding uranium production centres worldwide. The annual production in the last five years was 2 500 to 3 100 mtU. The dominant part comes from underground mining and insufficient amount is produced from the low-grade ores by heap leaching and in place leaching methods. Open pit mining has been stopped in 1997.

Low world uranium prices forced to mine relatively high-grade ores during the last 5 years. As a result, the average uranium grade of the remaining resources has considerably decreased (from 0.232% to 0.165%).

To provide effective mining during the next 30 years reconstruction of mining and technological equipment is conducted. It includes:

(a) Development of heap leaching and underground block leaching mining for the low-grade ores;
(b) Technical modernization of mining complexes;
(c) New sulfuric acid plant construction.

Conventional mining is applied for high-grade ore with contents in excess of 0.25% U, using sublevel caving or cut and fill methods, and hydrometallurgical processing. Acid heap leaching is used for ores with intermediate grades of 0.15 to 0.25% U. Each pile of ore has a magnitude of 1 to 2 million tonnes, a height of 20 to 30 m, and is leached by sulphuric acid for about one year, but factual leaching duration depends on the size of the heap, lithologic ore composition and leaching efficiency. Uranium recovery is about 60%, but it is considered that it can be improved by more advanced technology. Underground acid block leaching is applied to low-grade ores grading 0.1 to 0.25% U. Amenable ore blocks are blasted into subjacent excavations and the muck is treated with sulphuric acid. Pregnant solutions are collected in special containments beneath the muck pile from where they are pumped to the surface for ion exchange treatment. Final processing of the slurries from the ion exchange plant is carried out in the mill.

New mines are planned to come into operation after 2010. It is necessary to take into account that more than a half of the remaining reserves are hosted in carbonate rocks and that their processing requires reconstruction of the technological circuit.

## 3. Dalur

Dalur facility is based on sandstone basal channel type deposits of Transural district: Dalmatovskoe, Khohlovskoe and Dobrovolnoe. RAR resources at 10ths.t are estimated only at the Dalmatovskoe deposit. In addition, preliminary EAR-II resources of about 10ths.t are estimated for the Khohlovskoe deposit Probable resources amounting about 80 000.t show for the high potential of new deposits discovery in the area.

Paleodrainage systems consist of 1 to 5 km wide channels filled with 30 to 120 m thick permeable alluvial-fluvial sediments. Deposits are located in Upper Jurassic-Lower

Cretaceous and Paleogene-Neogene platform alluvial sediments. The productive horizon is presented by alternating sand, gravel, clay and siltstone strata, which occur on volcanic Paleozoic basement. Uranium and associated mineralization occurs along redox interfaces [3,5].

Dalmatovskoe deposit: A number of ore bodies occur at a depth of 360 to 500 m in a main 11km long and a tributary 8km long paleovalley. Both are up to 1.5 km wide. Single ore bodies are 400 to 4500m long, 50 to 700m wide, 2 to 12 m thick. Thickness of the front part of roll can reach 20m. Channel facies are Middle-Upper Jurassic alluvial sediments composed of yellow oxidized and grey reduced sandy gravel, sandstone and conglomerate interbedded with silty mudstone. Uranium is present as coffinite and pitchblende. Uranium grades vary form 0.01 to 3%. High-grade U sections may contain Sc, Re, Mo and REE minerals. Uranium distribution is controlled by redox boundaries in sand-gravel aquifers. Most ore bodies are lenticular or roll in shape elongated along the valley axis. In cross-section, mineralization occurs in single lenses or stacked at several levels separated by argillaceous aquicludes.

Deposit Dalmatovskoe is completely prepared for industrial ISL mining. However, its proven reserves can be mined within the next 15 years. New developments relate to preparation of the Khohlovskoe deposit for mining after 2007. Multi-well ISL test is planned for the Khohlovskoe deposit in 2003-2004. Expected technical and economic parameters of this deposit are better, than at Dalmatovkoe.

The annual uranium production in 2002 amounted about 100mt and is planned to reach 700mt by 2010.

## 4. Khiagda

The Khiagda facility is located about 140 km north of the town of Chita in the NE part of Buryatia Autonomous Republic of Russia. Each of the 8 close located basal channel sandstone-type deposits of Khiagda ore fields includes several close situated ore bodies. The RAR and EAR1 resources are 44 800mt U at 0.042% U grade. Prognosticated resources are about 60,000mt U.

The largest same named Khiagda deposit contains about 15,500 mt U at an ore grade averaging 0.05% U. Mineralization occurs in permeable low consolidated Neogene fluvial sediments, which fill paleovalleys of relatively narrow tributaries [3]. The basement is presented by Paleozoic granite. Ore hosting sediments are overlapped by Neogene-Quaternary basalts. The thickness of ore hosting horizon vary from some m to 120m. The depth of mineralization averages 170m. Ribbon and lens like ore bodies dimensions are 850 to 4000m long, 15 to 400m wide and 1 to 20m thick. Uranium minerals occur in dispersed form. Principal minerals are pitchblende, coffinite, sooty pitchblende.

Multi-well experiments at the Khiagda deposit are in progress since 1999. The obtained data show satisfactory technical and economic parameters for ISL mining. The results of pilot tests were used as the basic data to develop a feasibility report for investments in the enterprise construction. At present time more than 50 tons of uranium is produced at about 50% recovery and average uranium concentration in solutions is 118 mg/l.

## 5. Other deposits

Eleven uraniferous districts (Fig.1) totalling more than 500 000 t of uranium in numerous small and middle-size deposits of vein, volcanic, and metasomatic types with higher cost resources and low uranium grades. Most of them were studied in the 60s to 80s and were unfavourable for production at that time. Now they should be re-evaluated according to the current economic conditions.

Aldan district is the biggest potential district of Russia containing significant uranium resources (over 200 000 t). They are currently sub-economic due to remote location, low uranium grades and deep mineralization occurrence. It should be studied for high-grade mineralization distribution and effective ores processing. Four deposits were investigated by underground workings, and five by drill holes to a depth of 2000m. Ore grade average 0.1 to 0.15% U, while gold value range from 1ppm to several ppm. Generally gold-uranium deposits occur in altered by feldspar metasomatism linear cataclasm and mylonitization zones within Mesozoic activation of Epi-Archean cratons. Location, shape and dimensions of uranium-gold mineralization are primarily controlled by reactivated ancient and neotectonic NW oriented and steeply dipping faults of Mesozoic age and surrounding feldspar alteration zones [3,6]. Principal uranium mineral is brannerite.

The other exploration target is uranium deposits in Transbaikalia district located not far from existing Priargunsky center. Fifteen uranium deposits have been discovered but none has been mined to date. Types of deposits include volcanic vein-stockwork, sandstone and granite-related vein deposits. Some of them can be effectively mined using heap or in block leaching methods.

## 6. Uranium purchase and production in Kazakhstan

Ministry of Atomic Energy of Russia consider to cover a part of requirements by producing or purchasing natural uranium abroad, and first of all, in Kazakhstan. Cooperation in this direction is determined by the intergovernmental agreement between Russia and Kazakhstan.

Kazakhstan has significant amount of known uranium geological resources (2nd place in the world), develops its own enterprises, and also co-operate actively with foreign companies.

At the end of 2001 Russian-Kirgyzstan-Kazakhstan joint venture “Zarechnoe” was established to mine the same deposit in Southern Kazakhstan. It was planned that the enterprise will start production of uranium at the end 2003 and will reach nominal capacity of 500mtU/year in 2005.

## 7. Conclusion

Realization of presented activities on uranium production development must considerably reduce the rates of stocks depletion and provide fuel requirements of the Russian nuclear industry up to 2025-2030. However, it is necessary to accelerate uranium exploration activities to cover the long-term needs. Domestic and foreign experience show that the period between large deposit discovery and beginning of mining is about 20 years.

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# LICENSING

# Licensing of in situ leach recovery operations for the Crownpoint and Church Rock uranium deposits, New Mexico: A case study

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**Abstract.** Licensing of in situ leach recovery operations in New Mexico, adjacent to the Navajo Indian Reservation, required significant effort on the part of Uranium Resources, Inc. and the subsidiary, Hydro Resources Inc., since the original application in 1988. On January 5, 1998, the U.S. Nuclear Regulatory Commission issued the license to operate following a lengthy Environmental Impact Statement process jointly managed by the U.S. Nuclear Regulatory Commission, the U.S. Bureau of Indian Affairs, and the U.S. Bureau of Land Management. The principal stakeholders include the State of New Mexico, the Navajo Nation and a number of citizen groups. The U.S. Environmental Protection Agency reviewed the Environmental Impact Statement. Since licensing, Hydro Resources Inc. overcame legal challenges to the source material license from groups opposed to uranium development and obtained the necessary water rights from the State of New Mexico on October 19, 1999. On January 19, 2000, the Navajo Nation lifted its 1983 moratorium on uranium mining for uranium in situ leach recovery. Since then, Hydro Resources Inc.'s focus has changed to preparing the Restoration Action Plan for Church Rock Section 17 site, Crownpoint Unit One, and Crownpoint. The U.S. Nuclear Regulatory Commission has since approved these plans. The Grants Uranium Region is located in northwestern New Mexico and is part of the Colorado Plateau physiographic province. The Jurassic Westwater Canyon Member of the Morrison Formation in the San Juan Basin hosts the uranium. The Crownpoint and Church Rock ore trends are monometallic, regional redox-controlled, roll-front type uranium deposits and occur as stacked roll-fronts. Other uranium deposits in the Grants Uranium Region include humate-type sandstone deposits including the Ambrosia Lakes District. Total low-cost Reasonably Assured Resources (RAR) for properties controlled by Hydro Resources Inc. includes 38,462 Tonnes U (100 million lbs $U_3O_8$). This paper reviews the process of developing and licensing this resource.

## 1. Introduction

### *Uranium Resources, Inc.*

Uranium Resources, Inc. ("URI") was incorporated 1977 with the primary objective to acquire, develop, and place into production, uranium deposits in the southwestern United States using in-situ leach ("ISL") technology. Uranium ISL has proven to be a recovery method that minimizes front-end capital investment, environmental impact, and the cost sensitivity of depth to mineralization. The technology utilizes well-established water treatment techniques, oil secondary recovery subsurface approaches, and uranium roll-front geology.

Over the past 25 years, URI has constructed and operated ISL projects in Texas and Wyoming and participated in numerous joint venture projects. On standby, URI has the Kingsville Dome, Rosita and Vasquez commercial ISL projects developed, with nominal annual production capacity of 5,200 Tonnes U (2 million lbs $U_3O_8$). The company has successfully produced and restored the Longoria and Benavides commercial ISL projects in Texas and the North Platte pilot in Wyoming. Joint ventures included companies such as Western Nuclear, Inc.; Coastal Corporation; Conoco; Framco; Saarberg Interplan; and Urangesellschaft. The company has also conducted consulting on non URI ISL projects for other companies including Amoco, Conoco, Union Oil, Framco, and Wyoming Fuels Co. URI designed and turn-key constructed an ISL plant in Texas for Tenneco in 1980 to 1981.

URI's current strategy is to acquire the best-known U.S. resources properties and associated intellectual data available, obtain the necessary permits and licenses and maintain its technological staff to be prepared to resume production when the market prices allow. To allow fulfillment of the strategy, URI currently owns properties in Texas and New Mexico (Figure 1) containing large, high quality-low cost resources in an advanced permitting stage. URI's properties can compete with international uranium production based on operating costs.

### *Hydro Resources, Inc.*

Hydro Resources, Inc. ("HRI") is a wholly owned subsidiary of URI whose role is the operating company for acquisition, permitting (licensing) and developing of the New Mexico properties. The corporation has invested over $20 million in New Mexico since 1986 because the San Juan Basin is the most prolific uranium province in the United States with historical production of over 133,000 Tonnes U (347 million lbs $U_3O_8$) nearly matching several of the world class Australian and Canadian deposits.

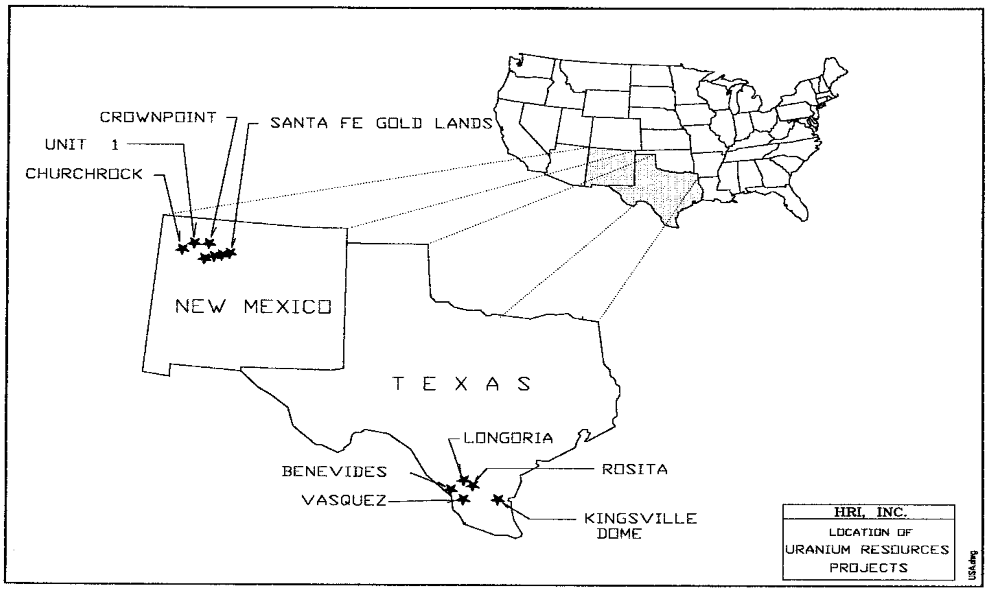

*FIG. 1. Synoptic map of Western USA, URI holdings.*

During the 1970s and early 1980s large oil and uranium companies conducted major exploration campaigns in the province, discovering and delineating vast uranium resources. In the mid 1980s, HRI began acquiring data bases from these major companies, and in the late 1980s acquired leases and fee lands in order to own the majority of the known deposits, as well as consolidating a land position allowing control of to-be-discovered deposits that will result from evaluation of the regions vast potential. Specifically, property acquisition began in 1986 with the purchase of the United Nuclear Corp.'s Church Rock Section 8 patented claims. In October 1988, the Crownpoint property was purchased from Westinghouse. In October 1991, HRI entered into leases with certain Navajo Allottees for what is now called the Unit 1 properties. In 1995 the Church Rock Section 17 adjacent to Section 8 and other Church Rock holdings were purchased. HRI's final acquisition in March 1997 was with Santa Fe where an extensive collection of proven uranium properties was obtained throughout Grants Uranium Region.

Collectively, all HRI uranium properties are within the Grants Uranium Region, which extends from Church Rock on to the west to the Laguna deposits, approximately 161 km (100 mi) to the southeast and include patented and unpatented mineral claims, mineral leases and some surface leases from private parties, the Navajo Nation and Navajo Allottees. With each acquisition, HRI receives and maintains all exploration data and interpretation, and the results of all ISL testing that was performed by the previous owners.

In keeping with its overall corporate strategy, HRI's development plan for its New Mexico properties will proceed incrementally, subject to timely permitting, the availability of water rights, the availability of sales contracts, and the availability of capital. HRI plans to develop the Church Rock district first and the Crownpoint district next.

## 2. **Property description** [4]

### *Church Rock*

*The property* - The Church Rock properties (Fig. 2) encompass 900.4 Ha (2,225 ac) and include mineral leases, patented mineral claims and unpatented mining claims. The properties are located in McKinley County, New Mexico, and consist of three parcels, known as Section 8, Section 17, and Mancos. None of these parcels lies within the area generally recognized as constituting the Navajo Reservation. HRI owns the mineral estate in fee for both Sections 17 and the Mancos properties. The surface estate on Section 17 is owned by the U.S. Government and held in trust for the Navajo Nation. HRI owns patented and unpatented mineral claims on Section 8. The unpatented claims currently require an annual payment of \$100 per claim payable to the Bureau of Land (the "BLM") to remain in full force and effect. On March 25, 1997, HRI acquired from Santa Fe the fee mineral interests in Section 17 and Mancos, thereby acquiring the position owned by the lessor and extinguished certain of the royalty obligations on those properties.

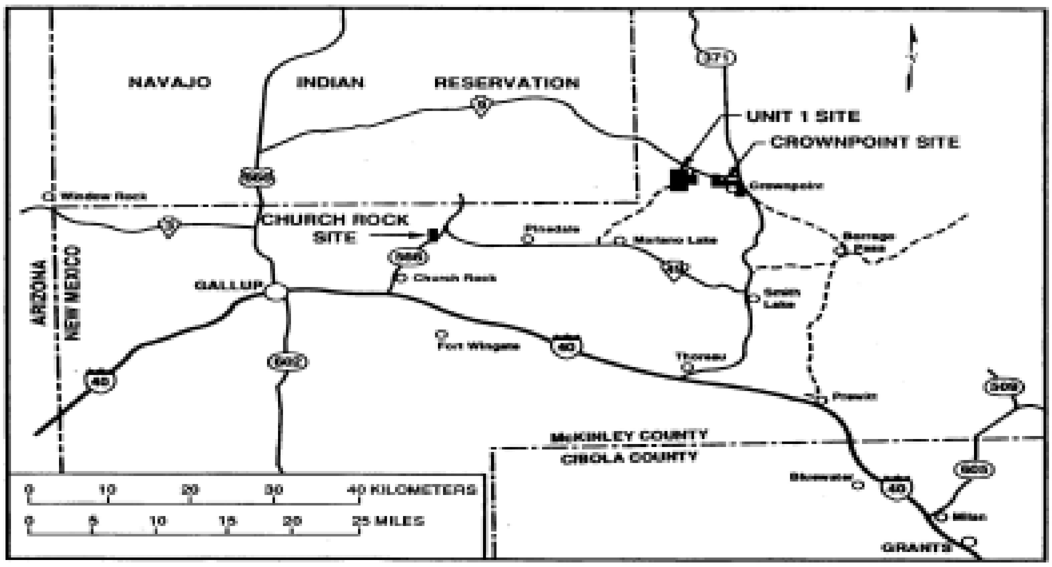

FIG. 2. Property locations in McKinley County, New Mexico.

*History* – Phillips began drilling in the Church Rock areas in 1957 and they encountered uranium mineralization in several wide-spaced drill holes. Additional drilling delineated the old Church Rock and Section 8 ore. Drilling continued until 1959 when work began on the shaft of the old Church Rock Mine. United Nuclear Corporation acquired a 50% interest in the mine in 1961 and mining continued until 1962. United Nuclear Corporation then began a drilling programme to evaluate other shows encountered by Phillips. This drilling resulted in the discovery of the Northeast Church Rock mine. Drilling continued until 1967 when mining was commenced on the Northeast Church Rock mine. After the Northeast Church Rock mine began producing, the Old Church Rock mine was dewatered and mining was restarted in 1978. All of United Nuclear Corporation's mines were shut down in 1982. Total production from the Church Rock mines was 3,460 Tonnes U (9 million lbs $U_3O_8$).

*Resource* – Section 8, Section 17, and the Mancos property contains approximately 2,500 Tonnes U (6.5 million lbs $U_3O_8$), 3,230 Tonnes U (8.4 million lbs $U_3O_8$), and 1,615 Tonnes U (4.2 million lbs $U_3O_8$) of in-place RAR resources respectively [7,8,9,10,11,12].

*Development plan* – HRI's properties will be developed in accordance with the licenses issued by the NRC. It is anticipated that the first property to be developed will be Church Rock Section 8.

*Exploration potential* – The in-place RAR resources in Section 8, Section 17, and Mancos encompass only portion of the Church Rock properties owned by HRI. HRI believes that substantial additional mineralization exists on these properties.

### **Crownpoint** [1]

*The property* - The Crownpoint properties are located in the San Juan Basin, 35.4 km (22 mi) northeast HRI's Church Rock deposits and 56.4 km (35 mi) northeast of Gallup, adjacent to the town of Crownpoint. The properties consist of 638.6 Ha (1,578 ac), as follows:

(a) 65.6 Ha (162 ac) on Section 24: HRI has 100% of the mineral estate on this property pursuant to a combination of a 40% fee interest, a mineral lease on the other 60% of the mineral estate and unpatented mineral claims. This property is subject to an obligation of HRI to pay a production payment on the first 19,230 Kg U (50,000 lbs $U_3O_8$) produced and an override based on uranium sales.
(b) 388.1 Ha (959 ac) on Sections 19 and 29 pursuant to a lease from private mineral owners (expiring August 2014) which provides for royalties and an override based of uranium sales.
(c) 184.9 Ha (457 ac) of unpatented mineral claims in Sections 9, 24, and 25.

In addition to the foregoing, HRI has 582.7 Ha (1,440 ac) of mineral leases hereinafter referred to as "Unit 1" from Navajo Allottees who are the beneficial owners of the surface and mineral rights. The leases are subject to approval by the Bureau of Indian Affairs (the "BIA"). None of these properties lies within the area generally recognized as constituting the Navajo Reservation.

*History* – Conoco and Westinghouse initially explored and developed this property for underground mining in the late 1970s. Three shafts were developed on the Section 24 location. The Unit 1 properties were explored extensively and had been subjected to extensive successful ISL pilot testing by Mobil Oil Company in the 1970's.

*Resources* – The Crownpoint property contains approximately 15,000 Tonnes (39 million lbs $U_3O_8$) of in-place RAR resources. HRI estimates that Unit 1 contain approximately 10,385 Tonnes (27 million lbs $U_3O_8$) of in-place RAR resources [7-12].

*Development plan* – HRI's properties will be developed according to the license conditions issued by the NRC. Under the license, the first operating property will be Church Rock followed by Unit 1 and Crownpoint.

***Santa Fe.***

*The properties* – In March 1997, HRI acquired from Santa Fe certain uranium mineral interests and exploration rights for uranium in New Mexico. The properties consist of 14,975 Ha (37,000 ac) where HRI acquired a fee interest in the entire mineral estate, excluding coal and approximately 56,650 Ha (140,000 ac) where HRI acquired the fee interest in uranium.

*History* – The Santa Fe properties were inherited from the land grants given to the Old Santa Fe Railroad in the 1860's as civilization was spreading westward in the United States. As incentive for developing a transcontinental railroad, the U. S. government gave the railroad every other square mile of land (minerals and surface) in a checkerboard pattern, stretching 32.2-64.4 km (20-40 mi) on either side of the railroad.

The property has been a tremendous source of mineral income for Santa Fe including uranium, gold, oil and gas, and coal revenues. A number of mining companies have conducted exploration programmes on the Santa Fe lands. As part of the acquisition, HRI has obtained the past uranium exploration records which are maintained to substantiate the RAR resource base and provide the foundation for future exploration programmes.

*Resources* – HRI estimates that the Santa Fe properties contain approximately 5,650 Tonnes U (14.7 million lbs $U_3O_8$) of RAR resources [7-12].

*Development plan* – The planned development strategy is to integrate qualified properties from the Santa Fe lands into the production plans for Church Rock and Crownpoint.

*Exploration potential* – Because the quantity of acreage is large and the location is completely within the Grants Uranium Region, there is significant exploration potential for the Santa Fe properties. Numerous ore grade holes drilled on the properties demonstrates this potential.

## 3. **Geological overview** [13,6]

### ***Grants uranium region***

The Crownpoint and Church Rock uranium deposits are located in the Grants Uranium Region. The Grants Uranium Region is located in northwestern New Mexico and is part of the Colorado Plateau physiographic province. The Grants Uranium Region has been the most prolific producer of uranium in the United States [5]. With production as early as 1948 (Fig. 3), over 133,000 Tonnes U (347 million lbs $U_3O_8$) has been produced from the region, mainly during the years 1953 through 1990. The district achieved a maximum production of 7,208 Tonnes U (18.7 million lbs $U_3O_8$) in 1978.

Regional subsidence has preserved about 1,000 m (3,000 ft) of Triassic, Jurassic, and Cretaceous Sediments in the San Juan Basin. Stratigraphically, this series of sediments accumulated as a major transgressive sequence. The Triassic dominantly contains aeolean massive cross-bedded dune sands that continued into early Jurassic time. In late Jurassic time, major uplifts occurred to the west in the vicinity of the present Mogollon rim of Arizona causing deposition of massive arkosic alluvial fan deposits across northeastern Arizona and into northwestern New Mexico.

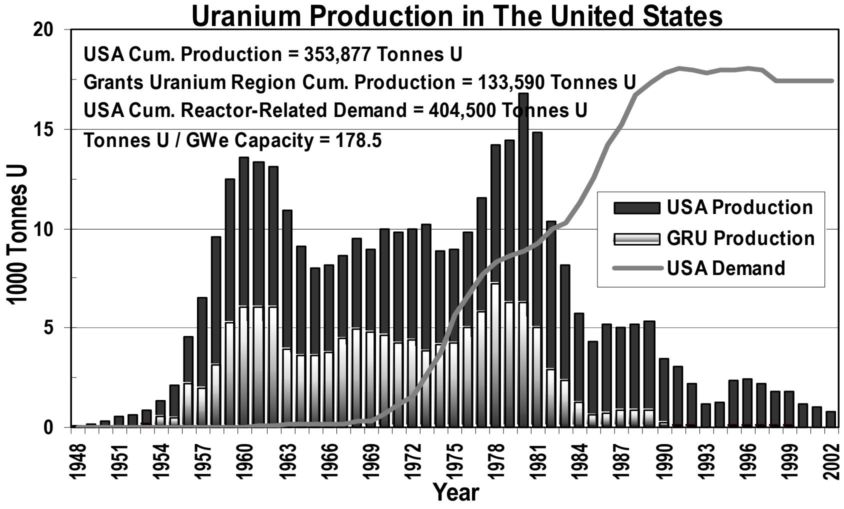

*FIG. 3. Uranium production and demand in USA.*

The Westwater Canyon member of the Morrison formation contains the majority of uranium deposits and was emplaced during this type of depositional regime. During deposition of this regional alluvial fan, abundant volcanic activity was also occurring which was deposited as interbedded tufts over the entire area of the San Juan Basin. At the beginning of the Cretaceous, a major subsidence occurred throughout the Rocky Mountain Geosyncline and Cretaceous seas transgressed the Jurassic continental deposits.

During the Jurassic period, abundant vegetation was present. With the decay of the vegetation, humic and fulvic acids migrated and were concentrated in channel sands upon burial. In addition to the vegetal material, volcanic tufts that were deposited with the sands yielded uranium in the groundwater. Where the humate concentrated, uranium was adsorbed from the groundwater and formed high-grade ore pods.

Through subsequent uplift and remobilization of groundwater, oxidized solutions reconcentrated uranium in rolls or stacked ore during both the Cretaceous and Tertiary. Many of these redistributed deposits, such as HRI's properties, are large and high-grade deposits amenable to ISL, and are relatively shallow. The Westwater Canyon Member shows a regional pattern of alteration from hematite at a distance from the redox front, to limonite in proximity to the front, and finally pyrite at and behind the front (Figure 4).

### *The Church Rock/Crownpoint Sites*

Successful ISL recovery relies upon the occurrence of uranium ore, which is responsive to the technique, the appropriate stratigraphic conditions, and an ore zone, saturated with ground water. As described below, these conditions are present in the Church Rock and Crownpoint areas.

HRI's ore deposits are associated with well-developed channel sandstones in the upper three-fourths of the Westwater Canyon Member. Ore zones are irregular in configuration and elongated parallel to depositional features. Varying rates of ground-water flow controlled by sedimentary facies in each stratigraphic zone in the Westwater Canyon produced stacked ore deposits near one another, but not necessarily vertically above and below one another (Peterson, 1980). The deposits are found as irregular pods, or as the classic c-shape roll-fronts.

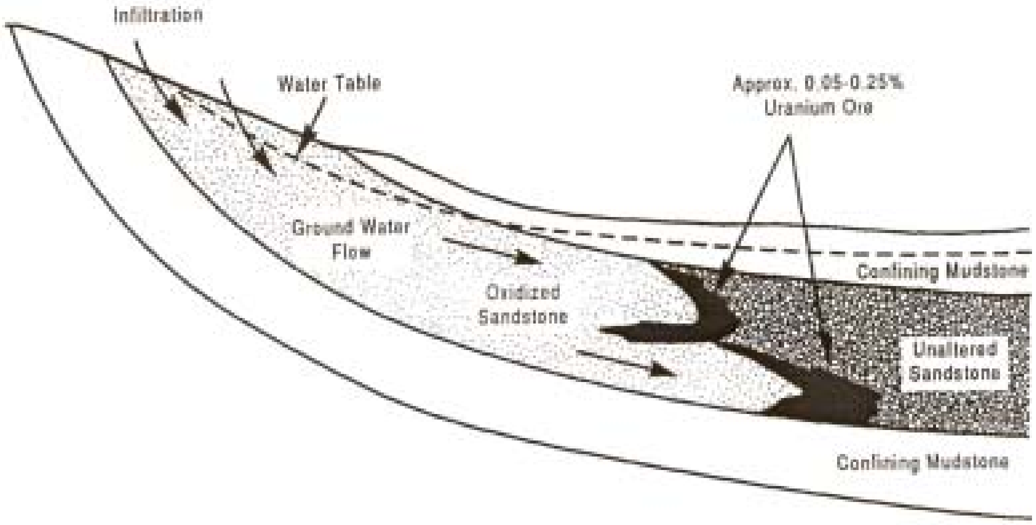

*FIG. 4. Simplified cross-section of roll-front uranium deposits formed by regional groundwater migration.*

Uranium ore deposits that are amenable to ISL as planned by HRI must have been redistributed. All of HRI's in place resources originally related to organic material in the Westwater sandstone, and were largely deposited contemporaneously with the sandstone and since have been remobilized by oxidizing conditions in migrating groundwater and redeposited elsewhere when reducing conditions were again encountered. These natural geologic conditions in the production zone exhibit the required characteristics that favor uranium ISL. The effect of ore redistribution has been a natural refining process through which various trace metals have been selectively removed from some ore deposits. These conditions may play a role in the ease with which restoration proceeds in aquifers being produced using ISL recovery methods.

Most uranium mineralization in the region occurs as pore fillings or coatings in sandstone of the Morrison Formation, and less importantly in the Dakota Sandstone and Todilto Limestone (Hilpert, 1963) [2]. The major mineral is coffinite with minor amount, of uraninite, andersonite, bayleyite, uranophane, tyuyamunite, and carnotite present.

Mineral resources found at the Church Rock site varies in thickness, but averages 3 m (9 ft) thick in each zone. Because the ore bodies are stacked, it has a combined thickness of about 24 m (80 ft). Overall dimension of the ore body is a 1,600 m (5,300 ft) long and up to 300 m (1,000 ft) wide. Near Crownpoint, mineral resources are similar to the Church Rock deposits, varying in thickness, but averaging nearly 4 m (11 ft) thick in each zone. The stacked ore zones have a combined thickness of about 37 m (120 ft). The combined dimensions of the Unit 1 and Crownpoint ore bodies exceed 8km (5 mi) long, and their width varies from 290 to 760 m (950 to 2500 ft) wide.

## 4. ISL Technology

Historically, the majority of U.S. uranium production resulted from either open pit surface mines or underground shaft operations. These conventional mining methods are, in many cases, capital and labor intensive and are not cost competitive with the majority of non-U.S. conventional producers. The ISL uranium recovery process differs dramatically from conventional mining techniques. The ISL technique avoids the movement and milling of significant quantities of rock and ore as well as mill tailings waste and generally results in a more cost-effective and more environmentally benign extraction operation in comparison to conventional uranium mining.

The ISL process was first tested for the production of uranium in the mid-1960s and was first applied to a commercial-scale project in 1975 in South Texas. The ISL process had become well established in the South Texas and Wyoming uranium districts by the late 1970s, where it was employed in connection with approximately twenty-five commercial projects, including four operated by URI.

With the ISL process, groundwater fortified with oxygen and other solubilizing agents is pumped into a permeable ore body causing the uranium contained in the ore to dissolve. The resulting solution is pumped to the surface where the uranium is removed from the solution and processed to a dried form of uranium that is shipped to conversion facilities for sale.

Not all in situ uranium is amenable to ISL development. There are a number of core elements that must be reviewed to determine if a uranium ore body is a candidate for ISL. These include:

### *Ore body evaluation*

Ore bodies that are currently being produced by the ISL process are associated with groundwater saturated permeable sandstone formations typically located between 30 and 600 m (100 and 2,000 ft) below the surface. Some important factors in evaluating an ore body for the ISL process are permeability, the thickness of the ore zone, depth, size, grade of ore, shape of the ore body, nature of uranium mineralization, host rock mineralogy, and the hydrology. These factors are important in determining the design of the wellfield, the type and flow of the leaching solution and the nature of the surface ISL facilities.

### *Wellfield design*

The wellfield is the mechanism by which the leaching solution is circulated through the ore body. The wellfield consists of a series of injection, production (extraction) and monitoring wells drilled in specified patterns. These patterns will vary primarily with the configuration of the ore and the hydrologic characteristics of each deposit. Determining the wellfield pattern is crucial to minimizing costs and maximizing efficiencies of production.

### *Lixiviant chemistry*

The lixiviant, consisting of native groundwater fortified with an oxidant and an anionic complexing agent, is introduced via the injection wells to the ore bearing aquifer. The oxidant (gaseous oxygen) changes the uranium valence state making the uranium soluble in the lixiviant. The lixiviant (sodium bicarbonate) complexes with uranium to form a soluble ion, uranyl dicarbonate, which allows the uranium to be dissolved. The dissolved uranium then flows to the surface with the lixiviant fluid that is circulated through the ore body until economic recovery is achieved. The lixiviant chemistry must be efficient in leaching the uranium from the formation and, following the recovery process, be compatible with U.S. environmental requirements for post mining ground water quality restoration.

### *Uranium recovery process*

The uranium recovery process consists of a lixiviant circuit, an elution/precipitation circuit and a drying and packaging process. The lixiviant circuit flows from the ore body, where the uranium is dissolved. The lixiviant stream is then circulated to an ion exchange column on the surface where uranium is extracted from the lixiviant by absorption onto the resin beads of the ion exchange columns. The lixiviant is then refortified and reinjected into the ore body. When the ion exchange column's resin beads are loaded with uranium, the loaded uranium is removed and placed into the elution circuit where the uranium is flushed with a salt-water solution that precipitates the uranium from the beads. This leaves the uranium as slurry, which is then dried and packaged for shipment as uranium powder.

URI has historically utilized a central plant for the ion exchange portion of the production process. In order to increase operating efficiency and reduce future capital expenditures, URI began the design and development of wellfield-specific remote ion exchange methodology. Instead of piping the solutions over long distances through large diameter pipelines and mixing the waters of several wellfields together, each wellfield will be produced using a dedicated satellite ion exchange facility. This will allow ion exchange to take place at the wellfield instead of at the central plant. As planned, remote ion exchange will be utilized by HRI.

The remote ion exchange technology allows each wellfield to be leached using its own native groundwater, thus eliminating the problems associated with progressive buildup of dissolved solids in the groundwater, which ultimately results in scale buildup in the reservoir. This enhances leaching efficiencies and uranium recoveries. Each remote ion exchange unit is also equipped with its own groundwater restoration treatment equipment so that individual wellfields can be reclaimed shortly after production is completed.

### *Wellfield restoration*

At the conclusion of groundwater reclamation, the site is decommissioned and decontaminated and the wellfield is restored and reclaimed. Wellfield restoration involves returning the aquifer to a condition consistent with its pre-leaching use and removing evidences of surface disturbance. The restoration of the wellfield is accomplished by flushing the ore zone for a time with native ground water and/or using reverse osmosis to remove ions, minerals and salts to provide clean water for reinjection to flush the ore zone. Decommissioning and decontamination of the site entails decontamination, dismantling and removal for disposal or reuse of the structures, equipment and materials used at the site during the recovery and restoration activities.

### *Economic considerations*

The uranium resources held by HRI represent the largest undeveloped, high quality uranium resource known in the United States that can be developed by environmentally benign ISL technology. HRI's in-place RAR include 37,593 Tonnes U (100 million lbs $U_3O_8$) of resources with average direct product costs of $33.30 kg U ($12.81 lb $U_3O_8$). HRI projects with general and administrative costs added the fully loaded costs before tax is $38.50 / kg U ($14.81 / lb $U_3O_8$).

As described above, uranium ore deposits must meet certain criteria to allow recovery with the ISL as utilized in the U.S., including: the ore deposit must be water-saturated; the deposit must have adequate rock permeability; the deposit must be easily solubilized with oxygen; the ore must be of grade and thickness to provide economic feed into the process facility.

HRI has reviewed economic criteria for their resources and determined the production costs by conducting detailed orebody delineation, and performed preliminary design of wellfields (patterns of injection and extraction water wells) that best fit the natural hydrogeologic conditions. The delineation was detailed in that the geologic configuration of the ore body and its subsidiary uranium roll-fronts, as well as the configuration of the host sand and confining units was examined. This level of delineation was possible because of the availability of accumulated mapping information from multiple exploration borings, including data from lithologic and geophysical logging obtained by HRI from past exploration and development campaigns by other operators.

HRI's analysis of the various parameters described above resulted in calculated production costs for the Church Rock, Crownpoint and Unit 1 side described in Tables I and II below.

Table I. Uranium resource summary – Tonnes U.

| **Tonnes U** | RAR | Production Cost (kg U) | Production with G&A Costs |
|---|---|---|---|
| Location | | | |
| Church Rock – Sec. 8 | 2,511 | $35.20 | $40.40 |
| Church Rock – Sec. 17 | 3,248 | $35.20 | $40.40 |
| Crownpoint | 14,985 | $29.79 | $34.99 |
| Unit 1 | 10,385 | $33.04 | $38.24 |
| Church Rock - Mancos | 1,602 | N/A | N/A |
| Santa Fe Lands | 5,664 | N/A | N/A |
| Sub Totals | 7,265 | | |
| Totals | 38,395 | | |

Table II. HRI resource and cost summary – Lbs $U_3O_8$.

| **Lbs $U_3O_8$** | RAR | Production Cost ($lb\ U_3O_8$) | Production with G&A Costs |
|---|---|---|---|
| Location | | | |
| Church Rock – Sec. 8 | 6,529,000 | $13.54 | $15.54 |
| Church Rock – Sec. 17 | 8,443,000 | $13.54 | $15.54 |
| Crownpoint | 38,959,000 | $11.46 | $13.46 |
| Unit 1 | 27,000,000 | $12.71 | $14.71 |
| Church Rock – Mancos | 4,164,000 | N/A | N/A |
| Santa Fe Lands | 14,724,000 | N/A | N/A |
| Sub Totals | 18,888,000 | | |
| Totals | 99,819,000 | | |

## 5. Licensing and permitting

### *Strategic implications*

The production of uranium is subject to extensive regulations, including federal and state (and potentially tribal) environmental regulations, which have a material effect on the economics of the ISL operations and the timing of project development. Successful ISL recovery licensing strategy requires an overall understanding of all components of licensing, a sense for timing, and a coordinated legal and engineering team.

Needless to say, in the United States, basic production in all industrial sectors is significantly affected by the regulatory climate. Environmental issues require a major portion of a company's planning in order to make a prospect viable. The U.S. is not alone in these concerns. Canada as well as Australia has significant regulatory constraints that escalate costs and delay construction.

Environmental considerations include the prevention of groundwater contamination (through proper design and operation of the wellfield and the use of monitoring wells to detect any potential excursions from the wellfield) and the treatment and disposal of liquid and/or solid discrete surface waste or by-product materials (so-called "11e. (2) by-product material" under federal law). The majority of by-product material that is generated is liquid and generally is disposed of by a combination of reverse osmosis, brine concentration and evaporation or, after treatment, by surface deposition or discharge or through underground injection wells. The governing authority (s) having jurisdiction over that aspect of the HRI's activities must approve any such disposal.

The current regulatory track record for the ISL industry is well established. Many ISL projects have gone completely through the permit-operating-restoration cycle without any significant environmental impact. In fact, with nearly three decades of operations, the domestic ISL recovery industry has never caused a serious environmental, health or safety risks; or failed to restore an aquifer at on of its projects. However, the public anti-nuclear lobby can make environmental permitting difficult and permit timing less than predictable.

In New Mexico, there are two primary regulatory authorizations required prior to operations: a radioactive material license and underground injection control ("UIC") permits. In addition to its radioactive materials licenses and UIC permit, a prospective ISL operator may also be required to obtain a number of other permits or exemptions from appropriate governmental authorities, such as for waste water discharge, land application of treated waste water, or for air emissions.

Plate I illustrates the time-paths of all important activities associated with the Crownpoint and Church Rock deposits.

### *Radioactive materials license*

Uranium production is subject to regulation by the U.S. Nuclear Regulatory Commission ("NRC") under the federal Atomic Energy Act and requires a radioactive materials license. HRI has applied for one NRC license covering all properties located in both the Church Rock and Crownpoint districts (except the Mancos property) and has included the properties in both districts (except the Mancos leases) under one Final Environmental Impact Statement ("FEIS") which is a prerequisite for the NRC license.

*Submittal of application(s)* - HRI initiated the License Application process on April 13, 1988 by submitting an Environmental Report to the NRC. The Environmental Report was also provided to the BLM, BIA, and others. On April 25, 1988 HRI submitted an Application to the NRC for a Source Material License ("License") to produce uranium commercially using ISL recovery at its Church Rock property. HRI amended its Application on May 8, 1989, to include uranium recovery processing at an existing facility in Crownpoint and again on April 23, 1992 to include ISL recovery on Unit 1, west of the existing facility at Crownpoint. Finally, on July 31, 1992, HRI amended its Application to include ISL recovery on lands associated with the existing facility in Crownpoint. HRI's Application to conduct ISL recovery and processing at the Church Rock, Unit 1, and Crownpoint sites is referred to collectively as the Crownpoint Uranium Project.

*Environmental Impact Statement Process* - Pursuant to NRC's regulations for implementing the National Environmental Policy Act, in 1992 the NRC, BLM, and BIA initiated a scoping process to identify significant issues to be addressed in a Draft Environmental Impact Statement ("DEIS"). A Notice of Intent to prepare the DEIS was published in the *Federal Register* on August 29, 1992. Two public scoping meetings were held on September 24, 1992, in Window Rock, Arizona, and Crownpoint. At these meetings, NRC, BLM and the BIA described their review procedures and responsibilities, and HRI representatives described the proposed project. State, local, and tribal government agency representatives and concerned local citizens also made statements and asked questions at the meetings.

The NRC published the *Draft Environmental Impact Statement to Construct and Operate the Crownpoint Uranium Solution Mining Project, Crownpoint, New Mexico* in October 1994 [14] and conducted public comment meetings on it. The DEIS was prepared by an interagency review group consisting of the NRC, BLM and BIA. The BLM and BIA served as cooperating agencies to fulfill their statutory responsibilities to regulate mineral recovery activities on Federal and Indian Lands (Mining Law of 1872, Allotted Lands Mineral Leasing Act of 1909, Mineral Leasing Act of 1920, National Historic Preservation Act of 1966, Endangered Species Act of 1973, Federal Land Policy and Management Act of 1976).

The NRC conducted three public comment meetings to solicit oral and written comments on the DEIS. Two public comment meetings were held in Crownpoint, on February 22, 1995, and one was held in Church Rock, on February 23, 1995. A total of 76 participants provided oral comments at the meetings, and the NRC received 52 sets of written comments.

After compiling public comments, and other questions, NRC posed these to HRI as requests for additional information in letters dated Jan. 11, 1996, February 9, 1996, and July 15, 1996. HRI's responses to these documents were forwarded on to NRC on February 20, April 1, and August 15 respectively.

Following the public input to the DEIS, and HRI's responses, on the basis of its independent review, in February 1997, the NRC published the *Final Environmental Impact Statement to Construct and Operate the Crownpoint Uranium Solution Mining Project, Crownpoint New Mexico (FEIS)* [15]. *The FEIS* concluded that the potential significant impacts of the project can be mitigated, and that HRI should be issued a conditioned combined source and 11e(2) by-product materials license from NRC and minerals operating leases from BLM and BIA.

*Consolidated operations plan* - Because the licensing of the Crownpoint Uranium Project has taken a number of years, and included several property additions, with corresponding informational submittals, NRC has expressed concern that the Application information has become disjointed for the purpose of "tiedown provisions" in the operating license. To satisfy this concern and provide all the specifications and representations, which had been articulated to NRC in the past under one cover, in August 1997 HRI submitted a Consolidated Operations Plan. The Consolidated Operations Plan is an integral part of HRI's operating license.

*Safety evaluation report and license issued* – The NRC Safety Evaluation Report was issued on December 4, 1997. The Safety Evaluation Report was compiled pursuant to HRI's safety plan that was described in the Consolidated Operations Plan. The Safety Evaluation Report and the FEIS provided the basis for NRC's decision to issue the Radioactive Materials License. In January 1998 the NRC issued a license in that would allow operations to begin in the Church Rock district.

*Litigation* - In mid-1998, the Commission determined that certain Church Rock and Crownpoint residents and other environmental activists who requested a hearing had standing to raise certain objections to the license. It is believed that the environmental activists have made their opposition a high priority because they desire to thwart domestic nuclear power progress on the front end of the fuel cycle. They understand that historically the Grants Uranium Region provided a prolific supply uranium and that the uranium resources that HRI desires to develop would provide a secure and economical domestic source of fuel for the future.

An NRC Atomic Safety Licensing Board administrative law judge and his technical staff from the U.S. Geological Survey conducted a hearing in 1999. The hearing was broken into 9 distinct briefing subjects including performance-based licensing, liquid waste disposal, surface water protection, cultural resource issues, air emissions issues, HRI qualifications in training and experience, groundwater protection, adequacy of financial assurance, EIS and environmental justice considerations.

*License upheld* - Following the hearing the administrative law judge found that the project was safe and denied the opponent's request that the license be rescinded. The opponents then appealed the administrative law judge's ruling to the full Commission. On July 10 of 2000 the Commission denied the opponents appeal, stating their arguments "unpersuasive" and found that "Intervener's have identified no "clearly erroneous" factual finding or important legal error…". The Commission found that there was no reason to question the administrative law judge's finding that HRI was a qualified company and that the project was environmentally safe. With regard to groundwater quality, on January 31, 2001 the Commission concurred with the technical, substantive and legal findings of the administrative law judge's (i.e. that the project as planned safely protected groundwater resources).

*Abeyance denied* – Along with the Commission concurring with the technical, substantive and legal findings of the administrative law judge, they also denied abeyance and instructed HRI to proceed with the hearing process for all properties including Crownpoint or amend the License and remove them.

As required, on April 30, 2000, HRI notified the Commission of its intent to move forward with the Crownpoint hearing. Immediately, the administrative law judge contacted all parties and required a schedule be negotiated for the remainder of the hearing. On May 25, 2000 the administrative law judge approved the negotiated hearing schedule that required that HRI provide Restoration Action Plans for the Section 17, Unit 1 and Crownpoint location over the remainder of 2001 and litigation resumption in early 2002.

On Nov. 21, 2000, HRI submitted the requested Restoration Action Plan for the Church Rock Section 8 site. It was approved by NRC and is currently under review by administrative law judge. On July 24, 2001, HRI submitted the Restoration Action Plan for the Church Rock Section 17 site that NRC approved on August 22, 2001. On September 17, 2001, HRI submitted the Restoration Action Plan for Crownpoint Unit One that NRC approved on October 16, 2001. On November 21, 2001, HRI submitted the Restoration Action Plan for Crownpoint that NRC approved on December 20, 2001.

*Settlement* - In November 2001, with the concurrence of all parties, the NRC appointed a special judge to attempt to facilitate settlement among the parties that, if successful, would end the hearing process. No settlement agreement has been reached. This settlement process is expected to be finalized in October 2002.

### *UIC Permits*

*Primacy* - The Federal Safe Drinking Water Act ("SDWA") created a nationwide regulatory programme protecting groundwater, which is administered by the U.S. Environmental Protection Agency ("EPA"). To avoid the burden of dual federal and state (or Indian tribal) regulation, the SDWA allows for the permits issued by the UIC regulatory programmes of states and Indian tribes determined eligible for treatment as states to suffice in place of a UIC permit required under the SDWA. A state whose UIC programme has been determined sufficient for this purpose is said to have been granted primary enforcement responsibility or "primacy," and a UIC permit from a state with primacy suffices in lieu of an EPA-issued permit, provided the EPA grants, upon request by the permitting state, an aquifer exemption modifying the permitting state's UIC programme. New Mexico has been granted primacy for their UIC programme and NMED has jurisdiction under the New Mexico Water Quality Act to regulate UIC activities within the State of New Mexico.

The Navajo Nation has been determined eligible for treatment as a state but is not due to submit its programme for EPA approval for several years. Until such time as the Navajo Nation has been granted primacy, ISL uranium recovery activities within Navajo Nation jurisdiction will require a UIC permit from the EPA. By the terms of regulations issued by the EPA and the primacy determination made for the State, New Mexico's UIC primacy does not extend to New Mexico's exercise of UIC regulation or permitting over facilities located on "Indian Lands," a term whose geographic reach the EPA has defined as coextensive with that of "Indian Country". Despite some procedural differences, the substantive requirements of the New Mexico and EPA UIC programmes are very similar.

*Jurisdictional issues* - The Navajo Nation claims regulatory jurisdiction over a significant portion of HRI's development properties. These claims subject the development of those properties within the area claimed as Indian Country to uncertainties, including a potential for delays in UIC permitting. For certain properties not permitted by the EPA at the time a Navajo regulatory programme is promulgated and accepted by the EPA for a determination of primacy, HRI would then apply to the Navajo EPA for its UIC permits. Although a Navajo UIC programme may adopt unique application, permitting, and enforcement procedures, it would, nonetheless, be required to impose virtually the same substantive requirements as HRI is prepared to satisfy under existing New Mexico and EPA UIC programmes.

Specifically, the Navajo Nation has asserted jurisdiction over Section 8 as being a "Dependent Indian Community" which, on July 14, 1997, lead EPA to inform HRI that the regulatory jurisdiction of the property is considered to be in "dispute" and would require an EPA-issued permit prior to the commencement of operations. HRI and the State of New Mexico sued EPA in the Tenth Circuit Court over this determination seeking to avoid, if possible, a remand of the matter to EPA and to elicit, if possible, a judicial pronouncement as to whether HRI's Section 8 property lies within the civil regulatory jurisdiction of New Mexico or that of the Navajo Nation.

In February 1998, the United States Supreme Court in *Alaska v. Native Village of Venetie Tribal Government* interpreted the terms Indian Country and Dependent Indian Communities. Such interpretation stated that Indian Country includes "all Dependent Indian Communities within the United States" and that such lands refer to a specific category of Indian Lands that are not reservation nor allotted lands. Such lands must meet the following two criteria; (i) they must have been set aside by the Federal Government for the use of Indians as Indian Land; and (ii) they must be under federal superintendence. On the basis of this ruling HRI believes that its private fee lands and federal claims positions fall under the jurisdiction of the State of New Mexico for regulatory purposes.

On January 6, 2000 the Tenth Circuit Court denied the HRI and NMED petitions. In particular, the Court upheld EPA contention that there was a *dispute* as to the Indian Country status of the Section 8 property; however, it declined to decide HRI's claim that EPA had abused its discretion by failing to recognize the non-Indian status of the Section 8 property. Instead, it held the claim was not ripe for review because there had as yet been no EPA determination of the Indian Country status of Section 8. The Court remanded the matter back to EPA for determination with regard to the presence or absence of a set-aside under Alaska v.

Native Village of Venetie Tribal Government and the presence or absence of federal superintendence under Venetie.

On July 24, 2002, the New Mexico Supreme Court in State of New Mexico vs. Travis Frank adopted the Venetie two-prong test for determining how a "Dependent Indian Community" is defined. Consistent with Venetie, the New Mexico Supreme Court case supports the assertion that the facts and legal precedent regarding this matter favor State jurisdiction for HRI's fee lands and mining claims.

*Church Rock Section 8* - On April 13, 1988, an application for a State discharge plan was submitted at the same time the NRC License was initiated [3]. Discharge plan DP-558 was issued on November 2, 1989, which authorized ISL recovery at the Church Rock Section 8 location, was approved by the New Mexico Environment Improvement Division (now NMED). Prior to expiration of amended DP-558 on October 31, 1996, HRI made timely application to renew the permit for both of HRI's Section 8 and Section 17 properties. This timely application for renewal holds DP-558 in force until final NMED action on the application.

*Church Rock Section 17* - In March of 1993, HRI submitted an application to amend DP-558 by adding the Section 17 property. The Navajo Nation who claimed UIC regulatory jurisdiction over the site, based on the fact that the Navajo Nation owns the surface estate contested the permit for Section 17. A public hearing began in October of 1993 on the amendment and continued from time to time thereafter. The amendment was approved by NMED on October 7, 1994. The EPA, acting as an advocate for the Navajo Nation, has asserted the Navajo Nation's claim and has refused to amend its previously issued aquifer exemption covering Section 8 to add the portion of the Church Rock facility on Section 17.

*Aquifer Exemption* - An important component of the federal Safe Drinking Water Act is the legal authority that allows ISL mineral development in portion of geologic strata, which are also shared by drinking water supplies. This is specifically provided for in 40 CFR 144.8 as follows:

"An aquifer or a portion thereof which meets the criteria for an "underground source of drinking water" in § 146.3 may be determined under 40 CFR 144.8 to be an "exempted aquifer" if it meets the following criteria:

(a) It does not currently serve as a source of drinking water; and
(b) It cannot now and will not in the future serve as a source of drinking water because:

  - It is mineral, hydrocarbon or geothermal energy producing, or can be demonstrated by a permit applicant as part of a permit application for a Class II or III operation to contain minerals or hydrocarbons that considering their quantity and location are expected to be commercially producible.
  - It is situated at a depth or location that makes recovery of water for drinking water purposes economically or technologically impractical;
  - It is so contaminated that it would be economically or technologically impractical to render that water fit for human consumption; or
  - It is located over a Class III well mining area subject to subsidence or catastrophic collapse; or

The total dissolved solid content of the ground water is more than 3,000 and less than 10,000 mg/l and it is not reasonably expected to supply a public water system."

EPA must issue an Aquifer Exemption for each mine site before any ISL recovery can occur. On June 21, 1989, EPA, acting on the request of the State, modified New Mexico's EPA-approved Underground Injection Control (UIC) programme by designating the portion of the mine zone aquifer underlying HRIs Section 8 property to be an exempted aquifer within the meaning of that term under the SDWA. No aquifer exemption has been granted for Section 17, Crownpoint or the Unit 1 site.

### 6. Water rights

Water is essential to the ISL process. The use of water is administered through the New Mexico State Engineer subject to Indian tribal jurisdictional claims. The State Engineer carefully and strictly regulates obtaining new water rights, and the transfer or change in use of existing water rights. The State Engineer exercises jurisdiction over underground water basins with "reasonably ascertainable boundaries." The Gallup and San Juan Basin are closed; meaning future appropriation of ground water requires a specific permit from the State Engineer that will be approved in the order of the priority of the Application to Appropriate Groundwater ("Application").

Accordingly, new appropriations or changes in purpose or place of use or points of diversion of existing water rights, such as those in the San Juan and Gallup Basins where the Company's properties are located, must be obtained by permit from the State Engineer. Applications are required to be published and are subject to hearing if protested. There are three criteria for decision, that the application: (1) not impair existing water rights, (2) not be contrary to the conservation of water within New Mexico, and (3) not be detrimental to the public welfare. Applications may be approved subject to conditions that govern exercise of the water rights.

Jurisdiction over water rights may become an issue when an Indian nation, such as the Navajo Nation, objects to the State Engineer's authority to grant or transfer a water right or to award a temporary water right, claiming tribal jurisdiction over Indian Country. This issue could result in litigation between the Indian nation and the state, which may delay action on water right applications, and, depending on who prevails as to any particular property, could result in a requirement to make applications to the appropriate Indian nation and continuing jurisdiction by the Indian nation over use of the water.

#### ***Church rock water rights***

HRI acquired mineral leases on Sections 8 and 17 from United Nuclear Corporation and, in connection therewith, acquired certain water rights that were obtained during the years of conventional mining. Applications to use these water rights have been the subject of extensive administrative proceedings and litigation with the New Mexico State Engineer and the Navajo Nation over the nature and extent of United Nuclear Corporation's water rights.

*G-190 Hearing* - An application was submitted to transfer water rights at the Church Rock property to the State Engineer on February 14, 1991. The Navajo Nation protested this application on jurisdictional grounds. On February 13, 1992 the State Engineer determined that the consumptive use and diversion amount UNC originally sought to transfer for use by HRI were in excess of the rights held. The State Engineer denied the application on the grounds that the UNC rights were insufficient to support HRI's ISL operations and also denied the Navajo Nation assertion of jurisdiction. The Navajo Nation then appealed the jurisdictional ruling to state district court where the State Engineers rulings were upheld.

*G-11 Hearing* – On January 27, 1993 HRI revised its water budget to be consistent with the rights of UNC as determined by the State Engineer and reapplied for a transfer of United Nuclear Corporation's water rights. The new water budget placed emphasis on the fact that rather than simple consumption of extracted water, the ISL process largely recirculates a known volume or "corpus" of groundwater over the life of a mine. The State Engineer conducted a hearing in March 1998 regarding the application for the transfer of the water rights. The State Engineer's hearing officer denied a jurisdictional claim by the Navajo Nation because a similar claim and ruling in the prior proceeding was upheld by the state district court.

On October 19, 1999, the State approved the water rights application for HRI's Church Rock ISL project. HRI was granted rights based diversion and recirculation of a *corpus* of water for ISL leach uranium recovery. The approved appropriation provides sufficient water for the Church Rock ISL operational life.

*Corpus Aqueous* – In approving G-11, the State Engineer accepted HRI's explanation of recirculation and established the president by which future ISL related water right applications will be judged in New Mexico. The ISL process results in the circulation of a single calculateable pore volume or *corpus* of water over and over again within the confines of the mineralized portion of the aquifer, which contains the ore. The mine zone acts as much like a tank where water (lixiviant) is circulated in and out of the tank. Prior to HRI's application the concept of recirculation of a *corpus* of water has not been recognized in New Mexico water law.

The groundwater *corpus,* as determined in the G-11 case, is based on zone-by-zone calculation that quantifies the dimension of the production zone, and hence the amount of water that will be recirculated. In the production phase, ISL involves re-circulation through a mineralized aquifer the individual *corpus* of ground water. Only a production bleed is consumed during the actual recovery process. The *corpus* and the bleed volume comprise the annual consumption. For the restoration phase, the highest quantity of water is accomplished by using ground water sweep where all water is consumed and must be accounted for as consumption.

***Crownpoint applications***

HRI holds a number of unprotested senior water rights applications that when approved would provide sufficient water for the Crownpoint operational life. Priorities 1,2,3, for the San Juan Basin are Applications SJ-125, SJ-147 and SJ-146 respectively, whose priority, are maintained and confirmed by HRI. On January 4, 2001 the State Engineer remanded SJ-125, SJ-146 and SJ-147 to staff (and HRI) for further review and analysis (and action) ("the Order"). HRI's responses to the *Order* are discussed below.

*Application SJ 125* – The first priority Application for the San Juan Basin is SJ-125. Conoco, Inc filed SJ 125 on December 13 1976. It was duly advertised and no protests were filed. SJ-125 was subsequently transferred to Westinghouse, and then to HRI by Westinghouse on September 14, 1988. Approval of SJ-125 will provide the water required to implement HRI planned development of the Crownpoint properties.

In response to the *Order*, on May 11, 2001, HRI filed an amendment to SJ-125 that reduced the amount of groundwater requested for diversion and consumption and made no changes to points of diversion. The purpose of use was the same as the purpose contemplated by the Westinghouse SJ-125, although that purpose was to be carried out differently. The method by which uranium is to be recovered, subject to approval of the permit, was changed to ISL rather than underground mining. The amended SJ-125 was modeled after the Church Rock G-11 that has been approved by the State Engineer.

*Application SJ-146* - Mobil Oil Corporation “Mobil” filed SJ-146 on March 18, 1977. SJ-146 was duly advertised and no protests were filed. Mobil transferred it to HRI, INC. on April 6, 1993. In response to the *Order*, HRI notified the State Engineer that an amendment letter would be filed with respect to SJ-146 after the decision on SJ-125.

*Application SJ 147* – Mobil filed SJ-146 on March 18, 1977. The Application was duly advertised and no protests were filed. Approval of SJ-147 will be required to develop the Unit 1 properties. In response to the *Order*, HRI notified the State Engineer that an amendment letter will be filed with respect to SJ-147 after the decision on SJ-125.

***Navajo uranium mining moratorium***

*Executive Order* - The Navajo Nation Executive Order of 1992 was a moratorium on all uranium-mining activities on Navajo lands. It stated that “The Navajo Nation shall not approve any exploration, development, mining, milling, or transportation of uranium ore within the jurisdiction of the Navajo Nation unless and until the responsible party is able to certify and prove that the proposed activities will not contribute directly or indirectly to any further radioactive or heavy metal contamination of Navajo air, water, soil, vegetation, wildlife, or livestock”. The moratorium was placed on uranium mining activity until such a time that the Navajo people can be assured that all safety and health hazards related to such activity can be addressed and resolved.

*Navajo Nation Policy on Uranium Solution Extraction* - On January 19, 2000, after completing a review of open pit mining, underground mining, and ISL recovery, the Navajo Nation Tribal Council Resources Committee found that open pit and underground mining caused significant waste and mill tailings that are not associated with the ISL method. They noted that purpose of the Executive Order of 1992 was to prevent and eliminate harmful open pit and underground uranium extraction methods on the Navajo Nation. Concurring with the Executive Order, the Resources Committee stated that they would not allow uranium extraction by open pit and underground mining methods. At the same time the Resources Committee announced that the Navajo Nation Policy on Uranium Solution Extraction superseded the Executive Order of 1992.

The Policy specified requirements that a applicant or responsible party certify that a solution extraction activity protect Navajo air, water, soil, vegetation, wildlife and livestock through the mandatory compliance with Navajo laws, rules and regulations before a permit could be considered by the Resource Committee of the Navajo Nation Council. It requires compliance with the Navajo Nation Solid Waste Code, the Navajo Nation Pesticide Act, the Navajo Mine Land Reclamation Code, the Navajo Energy Development Policy, the Navajo Nation Environmental Policy Act, the Navajo Air Pollution Prevention and Control Act, the Navajo Safe Drinking Water Act, the Navajo National Discharge Elimination System Act Nation, Federal environmental laws that, when the Executive Order of 1992 was issues, were not yet approved.

The Navajo Nation Policy on Uranium Solution Extraction Activity on the Navajo Nation also required that an Environmental Impact Statement be required for a Uranium Solution Extraction Permit within the Navajo Nation by an inter-agency from the Nuclear Regulatory Commission, Bureau of Indian Affairs and the Bureau of Land Management. The Resources Committee of the Navajo Nation Council committed to review and approve Environmental Impact Statements that deal with oil and gas, uranium, coal, geothermal, or other energy or non-energy mineral resources production and related activities on Navajo lands.

## 7. Summary

In the U.S., a prospective uranium producer must deal with numerous strategic elements, including: acquisition of a land position with reasonably assured, high quality, uranium resources; acquisition of associated intellectual data as part of the land position to support the resource base and future developmental activities; ore that is demonstrated to be amenable to development by modern, socially accepted, competitive production technology; maintenance of technical expertise; and pursuit of necessary permits and licenses, with the core authorizations in place when the market prices allow production to begin.

Even with favorable uranium prices, the steps involved in pre production planning are time consuming and unless the preliminary work has been completed, even an economically viable project would not be able to fill requirements if there were a shortfall in world production and needs were immediate. After exploration is conducted and the resource is discovered, modern U.S. uranium recovery operations require extensive, time consumptive permitting and licensing before operations can begin. It is reasonable to assume that to bring a new greenfield exploration project on line to meet a supply shortfall would require one to two decades of preparation. Waiting on the market first will simply not work.

URI, a recognized leader in the field of ISL technology, and its subsidiary HRI, has set out and accomplished the parameters set forth in their uranium development strategy in earnest. Total cost of acquisition/permitting has exceeded \$20 million. HRI’s low cost uranium resource properties represent the highest quality resources known in the U.S. that are amenable to the ISL. HRI has obtained, and maintains, all of the associated exploration and development data banks, results and documentation. This level of exploration and development could have only been undertaken in the past when prices supported it.

HRI is in the advanced stages of a 10 plus year permitting campaign for a significant portion of the New Mexico resource properties. The FEIS process has been completed for all of the Crownpoint Project areas. The licensing of the Crownpoint Uranium Project has been the subject of a lengthy administrative review by a number of State and Federal regulatory agencies. The Church Rock Section 8 property, which represents the first step in HRI’s incremental development plan, is licensed. Water right precedents have been established to allow for the needed water to conduct ISL operations at HRI’s other locations. Relations with the Navajo Nation are good. Future permitting and licensing, is well advanced, so that after the first stage of production, the additional phases can be brought on incrementally to meet sustained production requirements.

## 8. Conclusion

As international requirements for mining operations become more uniform over time, companies will be required to develop compatible policies that clarify and guarantee environmental responsibilities and commitments as well as environmental justice for stakeholder groups. As stated in the ISO 14000 standards, policy commitments include legal compliance, environmental protection, pollution prevention, and continual improvement in performance. These company commitments include environmental performance evaluation, life cycle assessment, environmental auditing, quality assurance (ISO 9000) as well as a continual process of planning, implementation, checking, and corrective action.

As these objectives are implemented world- and industry-wide, licensing requirements will become more uniform and careful strategic planning will be required to optimize the critical path required for licensing. As demonstrated in this paper, in the United States, this licensing process requires a significant outlay of company resources and time. Future uranium recovery projects, regardless of location, will be licensed to comparable standards. The international community and the customers for the product will demand it.

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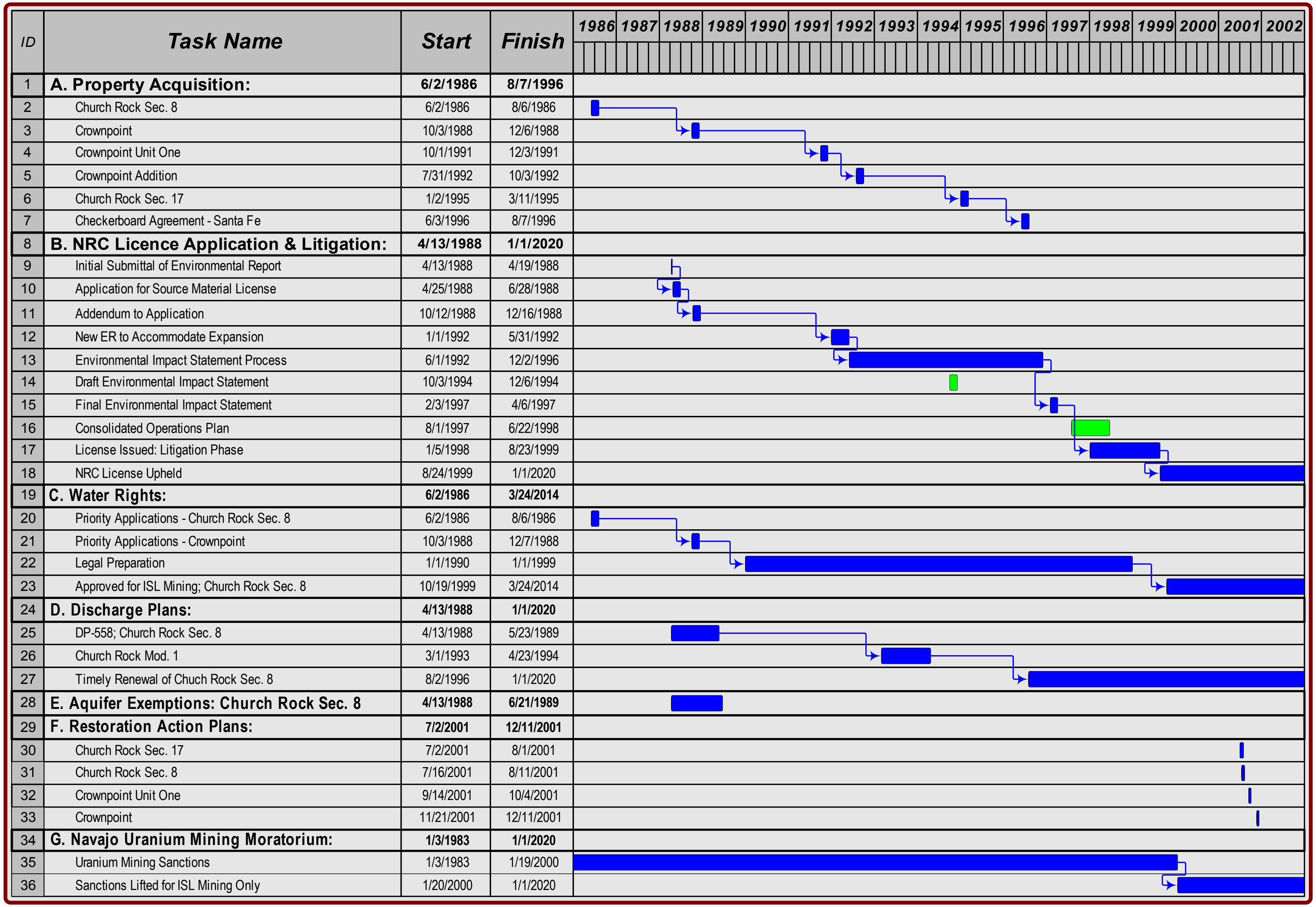
Plate 1. Gantt chart of primary tasks in licensing.



| ID | Task Name | Start | Finish |
|---|---|---|---|
| 1 | **A. Property Acquisition:** | **6/2/1986** | **8/7/1996** |
| 2 | Church Rock Sec. 8 | 6/2/1986 | 8/6/1986 |
| 3 | Crownpoint | 10/3/1988 | 12/6/1988 |
| 4 | Crownpoint Unit One | 10/1/1991 | 12/3/1991 |
| 5 | Crownpoint Addition | 7/31/1992 | 10/3/1992 |
| 6 | Church Rock Sec. 17 | 1/2/1995 | 3/11/1995 |
| 7 | Checkerboard Agreement - Santa Fe | 6/3/1996 | 8/7/1996 |
| 8 | **B. NRC Licence Application & Litigation:** | **4/13/1988** | **1/1/2020** |
| 9 | Initial Submittal of Environmental Report | 4/13/1988 | 4/19/1988 |
| 10 | Application for Source Material License | 4/25/1988 | 6/28/1988 |
| 11 | Addendum to Application | 10/12/1988 | 12/16/1988 |
| 12 | New ER to Accommodate Expansion | 1/1/1992 | 5/31/1992 |
| 13 | Environmental Impact Statement Process | 6/1/1992 | 12/2/1996 |
| 14 | Draft Environmental Impact Statement | 10/3/1994 | 12/6/1994 |
| 15 | Final Environmental Impact Statement | 2/3/1997 | 4/6/1997 |
| 16 | Consolidated Operations Plan | 8/1/1997 | 6/22/1998 |
| 17 | License Issued: Litigation Phase | 1/5/1998 | 8/23/1999 |
| 18 | NRC License Upheld | 8/24/1999 | 1/1/2020 |
| 19 | **C. Water Rights:** | **6/2/1986** | **3/24/2014** |
| 20 | Priority Applications - Church Rock Sec. 8 | 6/2/1986 | 8/6/1986 |
| 21 | Priority Applications - Crownpoint | 10/3/1988 | 12/7/1988 |
| 22 | Legal Preparation | 1/1/1990 | 1/1/1999 |
| 23 | Approved for ISL Mining; Church Rock Sec. 8 | 10/19/1999 | 3/24/2014 |
| 24 | **D. Discharge Plans:** | **4/13/1988** | **1/1/2020** |
| 25 | DP-558; Church Rock Sec. 8 | 4/13/1988 | 5/23/1989 |
| 26 | Church Rock Mod. 1 | 3/1/1993 | 4/23/1994 |
| 27 | Timely Renewal of Chuch Rock Sec. 8 | 8/2/1996 | 1/1/2020 |
| 28 | **E. Aquifer Exemptions: Church Rock Sec. 8** | **4/13/1988** | **6/21/1989** |
| 29 | **F. Restoration Action Plans:** | **7/2/2001** | **12/11/2001** |
| 30 | Church Rock Sec. 17 | 7/2/2001 | 8/1/2001 |
| 31 | Church Rock Sec. 8 | 7/16/2001 | 8/11/2001 |
| 32 | Crownpoint Unit One | 9/14/2001 | 10/4/2001 |
| 33 | Crownpoint | 11/21/2001 | 12/11/2001 |
| 34 | **G. Navajo Uranium Mining Moratorium:** | **1/3/1983** | **1/1/2020** |
| 35 | Uranium Mining Sanctions | 1/3/1983 | 1/19/2000 |
| 36 | Sanctions Lifted for ISL Mining Only | 1/20/2000 | 1/1/2020 |

# Licensing and regulatory requirements for uranium mining and milling in Brazil

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**Abstract.** This paper describes the primary objectives, principles and requirements used in the regulation of uranium mining and milling facilities in Brazil, providing an understanding of the licensing process. Some specific aspects of the regulatory process are discussed in detail to show where regulations should be updated and improved. The author believes that is necessary to establish some balance between the risks of the project and the assessment effort required. The views expressed in this paper are personal considerations of the author and do not represent those of the Brazilian Nuclear Regulatory Body.

## 1. Introduction

Brazil has the sixth largest geological uranium resource in the world and only 30% of its territory has been prospected. Since 1991, the systematic prospecting of uranium in Brazil has been stopped. Considering Brazil covers an area of about 8,500,000 Km$^2$, if new exploration expenditures were to be carried out, the known resources may easily double, due to favorable existing geological conditions.

Brazilian Nuclear Industries (INB) is a state-owned company responsible for all the nuclear fuel cycle activities in Brazil, which has exclusive rights for the exploration and mining of the uranium deposits. Commercial operation of uranium mining and milling started at the Poços de Caldas Site in 1982. With the nuclear policy change that approved the construction of the second nuclear power plant in Brazil (Angra II), INB decided to shift its uranium production from insufficient high-cost deposits at Poços de Caldas to lower cost deposits at Lagoa Real.

The Poços de Caldas Unit was shut down in 1997. Impact assessment studies concluded that Poços de Caldas activities were conducted within the acceptable limits of radiation exposure [1]. However, environmental solutions taken could not be considered adequate by today's standards. About $9.5\times10^7$ tons of waste rock and $2.0\times10^6$ tons of tailings were disposed of during the operations [2]. Considering the end of mine exploitation, interdisciplinary studies for proper decommissioning are being conducted [3]. The overall decommissioning plan for the installation should mainly consider the acid drainage aspects. The long time scale involved [4] affirms the need for permanent remedial actions. These actions must be affordable and cost-effective.

Nowadays, the entire production of uranium in Brazil is being performed in Lagoa Real Site by open pit methods. Its surface heap leaching plant started operation in 2000. Resources are estimated to hold 100,000 tons of uranium with a geological grade of about 3,055 ppm ($U_3O_8$). This amount is enough to supply the Brazilian demand of the two existing nuclear power plants for many years.

These two cases illustrate the history of the uranium production in Brazil. In addition to these two districts, Brazil has other known uranium deposits and, as a whole, it is estimated that Brazil has over 300,000 tons of $U_3O_8$ in resources [5].

According to Brazilian legislation, uranium has been seen as a strategic material, which should only be produced on behalf of the Government and for supply of Brazilian needs. The present law discourages further significant investments for exploration activities.

Brazilian Nuclear Energy Commission (CNEN) regulates the development and use of atomic energy in Brazil. CNEN has the technical and legal competence to evaluate the radiological impacts, the safety, and the adequate control required for nuclear facilities. CNEN is also responsible for issuing standards and regulations related to nuclear safety and radiation protection.

All Brazilian uranium mining and milling facilities are classified as nuclear facilities. Under the regulations, CNEN assesses licensee's capabilities to meet established regulatory standards, and conducts compliance and regulatory inspections, and the corresponding enforcement mechanisms, to ensure that its requirements and license conditions are being fulfilled.

## 2. Uranium exploration in Brazil

Systematic prospecting and exploration of radioactive minerals in Brazil began in 1952. The exploration was accelerated by the availability of funds for this purpose from 1970 onwards. There was active exploration through the use of geological, geophysical and geochemical surveys, and related research. As a result, a number of other occurrences were identified, namely: Figueira, Quadrilátero Ferrífero, Amorinópolis, Campos Belos, Itataia, Lagoa Real and Espinharas [6]. With changes in nuclear policies and, consequently, uranium requirements, investments fell sharply. Since 1991, all uranium prospecting has been stopped. The status of major Brazilian known resources is shown in Table I; some smaller uranium resources have been omitted.

Table I. Uranium geological resources in $U_3O_8$ tons [7].

| Deposits | Measured and Indicated | Inferred | TOTAL |
|---|---|---|---|
| Lagoa Real/Caetité | 94.000 | 6.700 | 100.700 |
| Itataia | 91.200 | 51.300 | 142.500 |
| Other | 39.500 | 26.500 | 66.000 |
| TOTAL | 224.700 | 84.500 | 309.200 |

Brazilian uranium resources occur in a number of geological environments and, consequently, belong to several deposit types; some of them hosted in near surface. In addition to known resources, there is a high potential for further discovery of economic uranium deposits. Areas favorable for uranium resources not yet explored covers 50% of the Brazilian territory.

Brazil has been producing uranium since 1982. Between 1982 and 1995 the cumulative uranium production was 1,030 tU from the Poços de Caldas Unit, and 280 tU from the Lagoa Real Unit between March of 2000 and July of 2002. Brief information on main uranium sites is given:

### *Poços de Caldas Site*

The Poços de Caldas Site is located at one of the biggest alkaline intrusions in the world. Discovered in 1948, its deposit was developed into an open pit mine. Poços de Caldas conventional acid-leach plant started production in 1982 with a design capacity of 425 tU/year.

The closure of Poços de Caldas Unit in 1997 brought to an end the exploitation of a low–grade ore deposit, which produced vast amounts of waste rock. Studies for proper decommissioning are being conducted by INB.

### *Lagoa Real Site (Caetité Unit)*

Lagoa Real is currently the only operating uranium site in Brazil. Open pit and surface heap leaching methods have been used. Plant has a design capacity to produce 300 t/year of $U_3O_8$ and there are plans for expansion. Nowadays, exploration activities have been focused on the extensions of mineralized zones for further evaluation of the albititic deposits of Lagoa Real.

### *Itataia Site*

Discovered in 1976, Itataia deposits account for almost 50% of the total known low cost resources in Brazil. The deposit is suitable for open pit mining with uranium recovery estimated at 70% [8]. In the planned Itataia Unit, uranium would be recovered as a co-product of phosphate from apatite and collophanite bearing episyenites. The $U_3O_8$ grade varies from 500 to 9,000 ppm. Development of the uranium-phosphate Itataia project will depend on numerous factors, including the markets for both products.

### *Rio Cristalino Site*

Discovered in the 1980s, INB recently carried out a geophysical survey in order to detail some occurrences. The results defined a series of occurrences distributed in meta-sedimentary rocks consisting of meta-arkose and metavolcanics underlying a quartzitic sequence of the Gorotire Formation of the Precambrian age. Some geologists believe that these occurrences are unconformity related.

## 3. Regulatory approach

CNEN was created on 1956 to control and regulate the development and use of atomic energy in Brazil. Under the regulations, siting, design, construction, commissioning, operation and decommissioning of nuclear facilities requires a license from CNEN. The fundamental objective is to provide the public with the assurance that nuclear facilities are designed and built to ensure safe operation, and finally that operation are being conducted with no undue radiation hazard to the workers, the general public, and the environment.

Before issuing a license, CNEN requires sufficient information to show how acceptable safety standards will be met and maintained. In exercising its responsibilities, CNEN assesses licensee’s capabilities to meet established regulatory standards and conducts compliance and surveillance activities to ensure that its requirements are continually met.

### *Licensing process*

CNEN regulatory control is achieved through a comprehensive licensing process designed to assure proper consideration of nuclear safety, environmental protection, and security. For all nuclear facilities CNEN has established the same administrative steps [9]. These consist of site acceptance, construction license, authorization for operation, and closure authorization. In Brazil there is no specific regulation for in situ leaching (ISL) mining facilities.

Site Approval involves a written submission describing design and operation of proposed facility, site characteristics, and the possible environmental impact of the facility. Background radiation and baseline environmental data should be provided. The results will be reviewed by CNEN in assessing the acceptability of the proposal. The conceptual design of the facility is approved at this stage. Guidelines for the preparation of this submission and the assessment criteria for mining and milling facilities are on draft. In this phase, the applicant is required by the environmental agency to prepare an environmental impact statement and submit it to a formal hearing and review process.

For Construction License the proposed mining and milling facility should be described in sufficient detail to enable a clear prediction and understanding of resultant impacts of proposed activities upon the safety of the general public and the environment. The application must contain information such as: description and schedule for construction activities, assessment of potential impacts, proposed measures for preventing or controlling radiation doses to the workers and the general public, description of waste management systems, results of any relevant pilot plant tests conduced, analyses of postulated accident conditions, conceptual plans for responding to accidents, conceptual decommissioning plans and any other information necessary to evaluate the application. The basic project is approved before construction and compliance inspections are done through a continuous reviewing process during construction.

Authorization for Initial Operation is issued after a detailed safety analysis report is submitted and approved. It is issued for a limited period of time and renewed periodically provided compliance with the license has been satisfactory. The submissions for this stage include an estimation of the total operation period, detailed description of the site and design of the facility as built, and detailed description of the conceptual plans and procedures approved on the previous stage. Details for these submissions will be available in the form of guidelines.

Authorization for Permanent Operation application must contain complementary data or any other relevant information that had not been presented on the previous stages. The license will be issued when there is reasonable assurance that the operation of a permanent nature can be conducted with no undue radiation hazard to the workers, the general public, and the environment. During the operational phase, CNEN conducts compliance and regulatory inspections to ensure that established regulatory standards and license conditions are being fulfilled.

For suspension or cessation of licensed activities and abandonment of the site, the licensee will be required to propose and implement appropriate maintenance procedures designed to ensure the safety of the general public and the environment. A written application must be submitted and includes: the most probable date of suspension of the licensed activity, preliminary plans that guarantee the safety of the workers and the public individuals in the previous phases to the suspension of licensed activities, and report of the performed work, site conditions and its future uses.

CNEN is involved at all stages of the sitting, construction, operation and decommissioning of nuclear facilities. The staged licensing process provides assurance that the facility, when developed, will conform to the present regulatory requirements, since these are being incorporated at the early design stage. The safety assessment process provides a review of the applicants' written submissions assuring that the plant will meet the safety and security requirements of the regulations.

For additional details on the licensing process the reader is referred to relevant CNEN regulatory documents, including CNEN NE 1.04 [9] and CNEN NE 1.13 [10] which describe and consolidate the requirements and criteria used in the licensing process of nuclear facilities in general, and uranium mining and milling facilities in particular, respectively; CNEN NE 1.10 [11] which address the licensing process and regulatory requirements for tailings impoundment systems at uranium mining facilities; and CNEN NE 3.01 [12] which prescribes the principles of radiation protection, including a dose limitation system and radiation protection requirements.

### *Tailings management*

Systems for the management of wastes of these facilities are commissioned through the licensing process established for nuclear facilities. Information and supporting documentation required usually are provided with applications submitted by the proponent. The applicant should identify potential sites for disposal of tailings. The selection of a suitable site should be based upon an evaluation of design parameters and baseline environmental data.

Impoundment systems for the disposal of tailings arising from uranium mining and milling facilities are subject to regulatory control of CNEN. The regulatory standard CNEN NE 1.10 [11] address the regulatory requirements and outlines basic criteria to be applied in siting, designing, construction, operation and decommissioning of tailings impoundment systems. Radiation exposure and releases to the environment should be optimized taken into account the radiation protection requirements [12]. The proposed structure should be defined in sufficient detail to support a siting decision. The appropriate site selection and good operating procedures can ensure the safety of the general public and the environment.

The regulatory standard makes provision for the possible implementation of inspections, monitoring and maintenance if considered necessary. Further, the containment methods should be compatible with shut down procedures, namely stabilization of tailings and the containment structures. All construction should follow good engineering practices and must be conducted in accordance with the approved design. Finally, a final waste management plan detailing decommissioning, stabilization and rehabilitation programme must be developed and approved before the suspension of the licensed activity.

### *Decommissioning*

At the end of the production stage, the facilities should be decommissioned by the operator, according to the procedures approved by CNEN. Hence, it is essential to apply an interdisciplinary analysis methodology, which would allow understanding of the relationship between the environmental systems. At this time there is no specific Brazilian standard related to decommissioning of these facilities and site rehabilitation.

### *Radiation protection requirements*

The regulatory standard CNEN NE 3.01 [12] establishes radiation protection requirements, and includes a dose limitation system. The purpose of this regulatory standard is to achieve an appropriate level of protection for the workers and the general public against the hazards associated with the radiation exposure.

The dose limitation system, based on ICRP 26 Recommendations [13], states the following:
(a) Every practice involving radiation exposure shall be technically justified and produce a net positive effect (justification);
(b) All radiation exposures of the individuals and the population are to be kept as low as reasonably achievable (ALARA), social and economic factors being taken into account (optimization); and
(c) The individual exposure shall not exceed the established limits (limitation).

The radiation protection requirements can be summarized as follow:
(a) All unnecessary radiation exposure are to be avoided;
(b) Workers whose safety are directly affected by the conditions of the workplace have to know the situation;
(c) Workers should be trained for safe work practices;
(d) Requirements for radiation exposure should be observed during routine and accident conditions;
(e) Established limits of radiation exposure must be observed; and
(f) Radiation protection must be optimized, taken into account established limiting conditions.

The primary limits for the annual equivalent effective dose for persons occupationally exposed to radiation is 50 mSv and for public individuals is 1 mSv. In addition, the annual equivalent dose for workers' individual organs, tissues, skin, arms and legs is 500 mSv, except in the case of eye lens for which the limit is 150 mSv. These primary limits may also be expressed in terms of the secondary quantities of annual intakes and exposures, and derived working levels for use in the operational control of radiological hazards.

The regulatory standard also establishes technical and organizational requirements. A radiation protection plan must be proposed in such an extent that, during the operations, it will enable the verification of radiation limiting requirements, proving that radiation protection is optimized, and securing other requirements for safe operation. Establishment of action levels as a practical technical tool to achieve ALARA should be emphasized; the higher the action level, stronger corrective actions are required. This programme is developed by the licensee, reviewed by CNEN staff and modified if necessary. Once approved, it becomes a condition of the facility license. All the programmes approved should be periodically reviewed and updated.

### *Inspections and audits*

Nuclear facilities are inspected by CNEN. CNEN also certificates the radiation protection supervisor [14] of the facility and maintains an office near the mining site with resident inspectors.

Regulatory activities includes:
(a) Audits and surveillance of uranium mining and milling facilities;
(b) Conduction of compliance inspections;
(c) Review and assessment of monitoring procedures, carrying out of such programmes, and accumulated results;
(d) Establishment and conduction of check monitoring programmes to oversee the monitoring undertaken by the licensee; and
(e) Review and assessment of processes and procedures to ensure the continuity of safe practices.

The main function of the inspector is to ensure compliance with regulatory requirements and license conditions. Inspectors should verify that the approved operating practices and regulatory requirements are met, and that proper monitoring programmes are being conducted.

Compliance inspections can speed corrective actions if undesirable practices are observed. When any infringement of regulations or license condition occurs, the inspector can direct the licensee to take actions to remedy the infringement.

## 4. Discussion

Brazil has a federal system of government with a constitutional division of powers between Union and Federal States. There are also areas where federal and state governments share power.

Regulation of the nuclear industry in Brazil is a federal attribution for a number of reasons, including international safeguards control, strategic policies, limited supply of qualified and experienced personnel, uniformed regulations, radioactive waste disposal policies and implementation of international agreements and treaties related to nuclear safety.

One aspect to be considered is the governmental framework of regulators. No less than three federal regulatory bodies play an active role in regulating uranium mining operations, namely:

(a) Brazilian Nuclear Energy Commission (CNEN)
(b) Brazilian Environmental Institute (IBAMA)
(c) Brazilian Mineral Production Department (DNPM)

These organizations elaborate regulations according to their attributions and fields of competence and verify their implementation. As a consequence of the plurality of actors in Administration, legislative and regulatory framework is governed by many laws and decrees. With a profusion of statements it is not surprising that misunderstanding occasionally arises.

First DNPM is responsible for the concession of mining rights. Environmental regulatory responsibilities are fragmented among the Union and Federal States. The Brazilian Environmental Institute (IBAMA) is a federal agency responsible for the environmental licensing of nuclear facilities, and for issuing regulatory standards to address both radiological and no radiological hazards associated with mining and milling operations. IBAMA also plays a key role in overseeing closure of uranium mining and milling facilities.

IBAMA introduced an environmental impact assessment (EIA) process in the middle 1980s. It was designed to ensure that the environmental consequences of all project proposals were assessed for potential adverse effects early in the planning stage. The purpose is to identify environmental effects arising from the proposed facilities, to evaluate the significance of the predicted environmental impacts, and to identify measures needed to prevent or mitigate unacceptable impacts and ultimately judging the acceptability of the project. The proponent must prepare an environmental impact statement and make it available for public review.

Environmental license take into account that for many activities, even in a worst scenario, any possible safety and environmental effect will be localized. So regulation is primarily the constitutional responsibility of the state governments, as a result, Federal EIA process has paralleled the introduction of state regulations. For nuclear facilities, however, national regulatory standards are required, providing a framework for cooperation between federal and state agencies.

CNEN is the co-authority on matters related to radiation aspects of environmental licensing of nuclear facilities. The co-authority role means that a CNEN assessment and review has to be considered in the final decision by IBAMA. Finally CNEN has also a mandatory role concerning regulation of nuclear activities. Its licensing process will be discussed later.

The net effect of this overlapping has been a duplication of effort to a varying degree in a number of areas that directly affect uranium mining operations. This process requires a wide range of expertise. It is almost impossible for any regulatory agency to have this breadth of professionals. It is necessary further improvements in the dialogue between regulatory agencies. In view of the scarcity of nuclear expertise in Brazil, it is important to have an agreement to have a uniform set of regulations, inspections and reports.

### *Licensing process*

Brazilian uranium mines are classified as nuclear facilities by CNEN, becoming subject to a strict system of nuclear regulation. As a result, license for mining and milling of uranium is regulated by two regulatory standards [9,10]. One of them is the same that applies to reactors. While CNEN certainly has flexibility in interpreting these regulatory requirements, it must be done in a carefully thought out and legally supportable way. There is no guideline to assist licensees and even technicians in interpreting and implementing the requirements of the regulatory standards. Interpretation can generated misunderstood, resulting in unnecessary requirements. Almost everything has been formally approved by CNEN, leading to an unwelcome involvement of the regulator in the operator's management functions. Communication between the operator and the regulatory authority has been a frequent practice to make regulations clearer.

A number of regulatory standards applied to the uranium mining and milling facilities today in Brazil have their origins in regulatory interpretations that were developed by CNEN staff two decades ago, upon a period of nuclear development devoted to the establishment of an entire nuclear fuel cycle system and when the standards for uranium milling operations, including the disposal of uranium mill tailings, were being conceived. As a result, some of the positions that may have seemed reasonable at that time, appear inappropriate today. Regulations of uranium mining and milling need a different approach.

The occupational and environmental hazards resulting from these facilities vary widely. The effectiveness of the regulatory system must be reviewed. These regulatory standards could be based on actual risk that can be estimated. A necessary adjunct to regulatory standards is the preparation of guidelines. The development of safety culture for the operator is also necessary and should be implemented. A practical model is needed to avoid unnecessary delays and additional costs.

### *Waste management*

In Brazil there is no specific standard for waste management of mining and milling facilities. For these facilities a waste management system should include: management of surface water and groundwater, handling and treatment of mine water, management of waste rock, containment of tailings and treatment of liquid wastes, management of waste from ore stockpiles and management of particulate and gaseous contaminants. This guide should consider site-specific factors. Where radioactive effluents are released in a controlled manner, discharge limits must be set. Releases of radioactive material, which cannot be controlled in this way (e.g. seepage from tailings dams) must be assessed and minimized by the use of best practicable technology.

In the early years of world uranium mining, insufficient attention was paid to the potential environmental consequences of tailings disposal methods. There have been substantial improvements on practices. Many of these improvements however require continuing intervention and can only be considered reliable during the operating phase of the facility or during an extended period of surveillance. Improvements that would ensure long term environmental acceptability have been studied.

A guide to the establishment of criteria for long term management of uranium mill tailings will be provided by the IAEA [15]. This study seeks to examine the evaluation of alternative options for managing uranium tailings in order to achieve optimum radiological protection in the long term and to formulate criteria for tailings retention systems, and methods for assessing the performance of tailings management techniques. CNEN has been participating in this study. The international experience will be helpful to the establishment of Brazilian guides.

The Brazilian regulatory standard for licensing of tailings impoundment systems [11] involves review of dam design, methods of disposal of the tailings, restriction for releases of potentially hazardous constituents and closeout procedures. Revision of this regulatory standard should taken into account advances in engineering practices for disposal of tailings.

### *Decommissioning*

There is no specific standard for decommissioning in Brazil. In the framework of national regulations it is necessary the development of a strategy to acquire the necessary technical knowledge in order to define the criteria for decommissioning of these facilities, and develop the necessary regulatory standard.

The establishment of decommissioning plans and implementation of remedial actions during the life of operation is necessary. New regulations avoid the very costly environmental restoration, considering the decommissioning planning during the operational phase. The final goal is to establish and implement the policies and procedures, which will allow the proper management of hazards within the limits imposed by the radiological and non radiological regulatory authorities. It is important to note that impacts due to mill wastes are not restricted to radiological hazards.

Any technical plan of decommissioning should contain at least information about the current status and description of changes at the given site due to facilities operation, a long term safety analyses, environmental impact assessment, description of plans and procedures for decommissioning, methods of dismantling, decontamination, conditioning, transport, storage and elimination of parts of installation contaminated and radioactive waste management, including its disposal. The final goal is the stabilization of potential pollutant areas, reintegrating them, preferably, into their original landforms.

As a government-controlled operation and because of the limited number of mines in Brazil, beginning restoration should employ a risk based approach. Risk assessments should be based on the current situation and take into account hypothetical, but realistic, changes in scenario.

### *Radiation protection*

The current radiation protection requirements are based on ICRP 26 recommendations [13], but new regulations, based on 1990s recommendations of the ICRP [16] are in draft.

The Brazilian radiation protection regulatory standard [12] establishes the requirements for controlling radiation exposure caused only by practices. The concept of intervention is not taken into account. Fernandes and Franklin [17] discussed the need of put intervention criteria in its scope to achieve dose reduction.

We also believe that safety in the workplace is achieved by the combination of good workplace conditions, safe work practices, and safe attitudes. Worker plays a fundamental role in his own safety and CNEN have reinforced his role by ensuring he has training, information and input to control his workplace. Lack of knowledge and appreciation of the problems of radiation protection is a prevalent cause of infringements observed on compliance inspections. Guidelines for employee training programmes are desirable. Ways of educating the worker to use safe work practices should be emphasized.

### *Public perception*

Concern for health, safety and the environment has grown fast during the past decades. There is an increasing public concern about nuclear energy and its regulation, reflected in demands for more information on the licensing process and the safety performance of nuclear facilities.

Uranium mining projects have been subject to a level of scrutiny that goes far beyond what can be justified by their potential for environmental damage. It is quite often, however, that a great number of these concerns are based on subjective misinformation.

Often CNEN answers questions from the public and authorities, mainly the Public Ministry, about uranium mines and fuel cycle facilities operation and their environmental impact. The Public Ministry is a state or federal authority created to guarantee the access of the general public to its rights. Action of Public Ministry provides a valuable focus on aspects that need to be addressed by proponents and regulators. It shows that the issues are quite often social rather than technical. The public perception of radiation risks should be addressed, because this is often the driving force for Public Ministry.

Traditional reluctance of nuclear companies to talk openly to the public has resulted in the loss of credibility of the uranium mining industries. The general population is subject to well publicized critics and activist groups of the nuclear industry that capitalize mistakes and minimize benefits. The media generally takes widespread interest in events with strong emotional considerations. A long and difficulty process of complete openness of regulatory agencies in giving the public total and true information is desirable.

We recognize that political and social pressures may combine to render difficulties for operation of the uranium mining industry. Scientific arguments are not enough against social and political matters. Social considerations will probably result in requirements, which cannot be otherwise justified.

## 5. Conclusions

A strong regulatory framework is important to the credibility of the uranium mining industry. The multiplicity of regulators and the necessary infrastructure to support them causes confusion, misunderstanding, duplication, competition and even omission. Rather than more regulations, better regulations are needed, in particular clearer ones. It is important to have an agreement to use available human and material resources most effectively and to have a uniform set of regulations.

There is a need to have a more rational and uniform regulatory model to regulating mining activities that will assure safety to the workers, the public and the environment and at the same time not impede the mineral exploration. Regulatory standards should be based on actual risk that can be estimated.

The impact of these regulations should assure better planning of operations, improvement in mine and plant design and a more efficient tailings management. This approach could be proposed in the drafting of new regulatory standards, as constituting a better alternative to nuclear regulation of mines.

A necessary adjunct to regulatory standards is the development of guidelines to assist licensees and even technicians in interpreting and implementing the requirements of the regulatory standards.

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# ISL MINING

# Smith Ranch ISL uranium facility: The wellfield management programme

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**Abstract.** The Smith Ranch Project is a uranium In-Situ leach (ISL) mining operation located in eastern Wyoming about 40 kilometres (km) northwest of Douglas, Wyoming and about 80 km northeast of Casper, Wyoming. The Smith Ranch Project utilizes alkaline ISL (In Situ Leaching) technology to extract uranium from permeable uranium bearing sandstones located at depths ranging from 140 to 325 metres. Once extracted, the uranium is recovered by ion exchange. Periodically, the ion exchange resin becomes saturated with uranium. Uranium is removed from the resin by contact with a salt water solution. The ion exchange resin, stripped of uranium, is recycled to recover additional uranium. The eluted uranium is precipitated, washed to remove impurities, dried, and packaged for shipment. The Smith Ranch facility was constructed by Rio Algom Mining Corp. in 1996-1998 at a cost of $42 million. It has a demonstrated production capacity in excess of 770 tonnes U per year and operating flow capacity of 380 litres per second (L/s) through two ion exchange plants. In mid-2002, the project was acquired by Cameco Corporation, which continues to operate the facility through its wholly owned subsidiary, Power Resources, Inc. (PRI).

## 1. Introduction

### *Production and reserves*

Commercial production was initiated in late 1997 and the facility achieved its design production rate in early 1999. Production was cut back to 430 tonnes U in 2000 and 2001 due to the soft uranium market and the decision to only sell into its existing contracts. By the end of 2001, Smith Ranch had produced nearly 2,000 tonnes U and 850 tonnes of recoverable U remain in existing wellfields under well patterns. Smith Ranch resources at December 31, 2001 were 15,000 tonnes U with reserves of 10,300 tonnes. The property adjoining Smith Ranch on the north, Reynolds Ranch, contains an additional 6,900 tonnes U of resources.

### *Production capacity*

Although Smith Ranch was originally designed and licensed as a 380 L/s – 770 tonnes per year facility, it was conservatively designed and constructed such that with additional wellfields it is believed that flow rates through existing ion exchange facilities could be increased to 510 L/s or more and that with minor modifications and a small capital expenditure, the Central Processing Plant production capacity could be increased to 1,150 tonnes per year. This in-place capacity together with existing resources will allow PRI to respond quickly to increasing market requirements.

With a view to this potential, the recent NRC license renewal increased Smith Ranch's licensed capacity to 760 L/s and 1,348 tonnes U per year. To utilize all of this additional authorized capacity, PRI will build another ion exchange plant and expand the central processing plant elution facilities in addition to installing new wellfields.

### *Wellfields*

In 1996 and early 1997 the first commercial wellfield was installed and production has been continuous since June 20, 1997. The wellfields consist of arrays of monitor wells, recovery wells and injection wells, which form patterns and flow systems to measure and control flows of lixiviate and gaseous oxygen. The basic pattern for the Smith Ranch wellfields has been a square pattern (5-spot) with a 22 metre spacing between injectors and producers.

Wellfield have been installed as individual "Mine Units", also referred to as "monitor well rings." Each monitor well ring surrounds groups of production patterns, including the mining zones and aquifers immediately above and below the mining zone. The injection and recovery wells are installed to effectively cover the ore bodies such that flows from injectors to recovery wells traverse ore deposits and produce high concentrations of uranium in the production fluid. Table I lists the mining units that have been installed at Smith Ranch and their status as of 3 April 2001.

Table I. List of mining units.

| Mine unit | Year installed | Monitor wells | Recovery wells | Injection wells | Klbs. $U_30_8$[*] Produced | Klbs. $U_30_8$[**] Remaining Rec. |
|---|---|---|---|---|---|---|
| 1 | 1997 | 49 | 114 | 216 | 954 | 19 |
| 3 | 1998 | 46 | 151 | 249 | 1,885 | 740 |
| 4 | 1999/2000 | 43 | 124 | 218 | 1,041 | 546 |
| 4A | 2000/2001 | 47 | 101 | 172 | 107 | 973 |
| | | 185 | 490 | 855 | 3,987 | 2,278 |

* Cumulative eluted production on 30 April 2001.
** Includes secondary completions.

In groups of approximately 20 patterns, all the recovery and injection wells are connected with piping and a piping manifold into a common field meter and flow control station, or a "Header House". Each Header House contains flow measurement devices and throttling valves for each well, motor starters for each submersible pump, oxygen mixing/injection devices, and shutdown (fail safe) instrumentation for lixiviate and oxygen trunk lines. Gaseous oxygen is fed to each Header House from one of two liquid oxygen storage tanks and fluid flows to and from the IX Facility are in large polyethylene flow lines, which connect with either one or both of the IX Facilities.

## 2. Wellfield management

Wellfield management for commercial In-Situ leaching (ISL) operations is a complex task that begins at the onset of planning for the project and ends only when restoration and reclamation of the final wellfield are completed.

### *Wellfield mining unit concept*

The wellfield areas are divided into mining units for scheduling development and for establishing baseline data, monitoring requirements, and restoration criteria. Each mining unit or wellfield consists of a reserve block in the range from 8 to 24 hectares. Approximately twenty such units will be developed. Two to three wellfields are in production at any one time with additional units in various states of development and restoration. A mining unit is dedicated to only one production zone and typically has a flow rate in the 190 L/s range. Aquifer restoration of a mining unit will begin as soon as practicable after mining in the unit is complete. If a mined out unit is adjacent to a unit being mined, restoration of a portion of the unit may be deferred to minimize interference with the operating unit. The size and location of each mining unit is defined based on final delineation of the ore deposits, performance of the area, and development requirements.

### *Wellfield design concepts*

The wellfield pattern is the five-spot pattern. However, it is selectively modified to fit the shape of the orebody. The cell dimensions will vary depending on the formation and the characteristics of the orebody. The injection wells will be spaced from 23 to 46 metres apart. All wells are constructed to serve as either injection or recovery wells. This allows flow directions to easily be changed to optimize uranium recovery and groundwater restoration.

In each mine unit, more lixiviate is produced than injected. This creates a localized hydrological cone of depression or pressure sink. This pressure gradient provides containment of the lixiviate by causing natural ground water movement from the surrounding area toward the mine unit. It is expected that the over production or bleed rates will be a nominal 0.5% of the production rate for the Q sand mining units, and a nominal 1.5% for the O sand mining units.

Production zone monitor wells are located approximately 150 metres beyond the mining unit perimeter with a maximum spacing of 150 metres between wells. Monitor wells are also completed in the aquifers directly overlying and underlying the production zone. Such monitor wells are uniformly distributed within the mining unit area with one overlying and one underlying monitor well for each 1.6 hectares of wellfield. A plain view of a typical wellfield layout is illustrated in Figure 1.

Each injection and recovery well is connected to the respective injection or recovery manifold in a header building. The manifolds route the leaching solutions to pipelines, which carry the solutions to and from the ion exchange facility. Flow metres, control valves, and pressure gauges are installed in the individual well lines to monitor and control the individual well flow rates. Wellfield piping is high density polyethylene pipe, PVC and steel. The individual well lines and the trunk lines to the recovery plant are buried to prevent freezing. The use of field header buildings and buried lines is a proven method of protecting pipelines. The Smith Ranch pilot programmes employed this method and operated continuously through the winters without freeze-ups or other significant weather related problems.

### *Well completion*

Monitor, production, and injection wells are drilled to the top of the target completion interval with a truck mounted rotary drilling unit using native mud and a small amount of commercial viscosity control additive. The well is cased and cemented to isolate the completion interval from all overlying aquifers. The cement is placed by pumping it down the casing and forcing it out the bottom of the casing and back up the casing-drill hole annulus.

The well casing is SDR-17 PVC, which is available in 6 metre joints. Typical casing will have a 127 mm nominal diameter with a minimum wall thickness of 6.55 mm and a pressure rating of 1480 kPa.

Three casing centralizers located approximately 10, 30, and 45 metres above the casing shoe are placed on the casing to ensure it is centered in the drill hole and that an effective cement seal results.

The cement volume for each well is 110% of the calculated volume required to fill the annulus and return cement to the surface. The excess is to ensure that cement returns to the surface. Occasionally the drilling may result in a larger annulus volume than anticipated and cement may not return to the surface. In this situation the upper portion of the annulus is cemented from the surface.

After the cement has cured, the plug is drilled out and the well completed. The well is then air lifted to remove any remaining drilling mud and cuttings. A small submersible pump is used for final cleanup and sampling. If sand production or hole stability problems are expected, Johnson wire wrapped screen or a similar device may be installed across the completion interval. Typical well completions are illustrated in Figure 2.

### *Well casing integrity*

After a well is completed and before it is operational a Mechanical Integrity Test (MIT) of the well casing is conducted. In the MIT, the bottom of the casing adjacent to or below the confining layer is sealed with a downhole packer, or other suitable device. The top of the casing is then sealed and a pressure gauge is installed inside the casing. The pressure in the sealed casing is increased to a minimum of 20% above the maximum anticipated operating pressure, the well is closed, and all fittings are checked for leaks. After the pressure is stabilized, pressure readings are recorded at two minute intervals for ten minutes.

If a well casing does not meet the MIT, the casing will be repaired and retested. If a repaired well passes the MIT, it will be employed in its intended service. Also, if a well defect occurs at depth, the well may be plugged back and recompleted for use in a shallower zone provided it passes a subsequent MIT. If an acceptable MIT cannot be obtained after repairs, the well will be plugged. A new well casing integrity test will be conducted after any well repair using a downhole drill bit or under reaming tool.

Monitor wells are drilled and constructed in the same manner as production and injection wells and all three types of wells must pass MIT.

### *Commercial development*

Designing the initial commercial wellfield can be a highly uncertain process because of the absence of sufficient large scale test data. This was not the case at Smith Ranch where two back to back pilot wellfields were operated beginning in 1980 and continuing until 1991. Both used mild alkaline lixiviants and uranium recovery via ion (anion) exchange resins. Test objectives were (1) to obtain hydro-metallurgical information for economic analysis of ISL and (2) to satisfy Wyoming Department of Environmental Quality requirements of commercial licensing. The results of these multi-pattern tests were the basis for developing the production model which became the basis for the commercial wellfield operations. The production history for the first of these pilots is shown in Figure 3.

### *Production schedule*

The key step in planning development of a commercial ISL facility is to establish the desired production schedule for the first several years. This combined with the life expectancy of the wells, becomes the basis for determining the wellfield installation schedule as well as the needs for wellfield development and ore delineation drilling. Ultimately the project life and the corporate production goals will establish the basis for additional uranium exploration.

The original production forecast anticipated a staged development of the Project with an initial installed ion exchange capacity of 190 L/s available on April 1, 1997. Installation of a second, identical unit in the first half of 1998 provides for the availability of full capacity (380 L/s) on July 1, 1998. Planned annual production for the first five years was:

| | |
|---|---|
| 1997 | 380 tonnes U |
| 1998 | 578 tonnes U |
| 1999 | 770 tonnes U |
| 2000 | 770 tonnes U |
| 2001 | 770 tonnes U |

Subject to prevailing market conditions, it was anticipated that the 770 tonnes per year rate would be sustained until reserves are exhausted. Geological studies placed the recoverable resource above 11,550 tonnes. This would support full production through the year 2112 for a productive project life of 16 years.

Given the annual production schedule, a generic wellfield development schedule and production plan was formulated based on the following assumptions:

(a) Fluid production rates will be 1.26 L/s per production well.
(b) Initial production will be from the "Q" sand at an average depth of 167 metres. Recoverable reserves approximate 462 tonnes U.
(c) Subsequent production targets will be the "O" sand and other zones at a depth of 230 metres to 325 metres.
(d) Economic recovery will be 80% of the 0.15 GT (% - metre) cutoff ore with a minimum thickness of 1 metre.
(e) Average pattern "Mineable Reserves" will be 4.44 tonnes U.
(f) Average recovery per pattern will be 3.55 tonnes U (80% of 4.44 tonnes U).

Based on percent recovery per pore volume of produced fluid, a generalized wellfield production model or decline curve was developed for typical five-spot patterns, Figure 4. No single pattern may agree with the model. In fact, significant individual deviations from the model predictions will be observed. However, groups of wells or mining units will tend to match the model's predictions extremely well. It's origins are empirical having derived from history matching production performance of numerous Texas and Wyoming ISL mining units. It was the basis for initial wellfield planning at the Highland Project and was verified by the Highland performance. The model is also consistent with the performance of the two pilot tests at Smith Ranch.

The fact that a model derived from Texas ore bodies is applicable to Wyoming ore reflects the fact that the overall similarities in geochemical origins of roll front deposits outweighs the differences. In addition, the model is integral rather than differential which requires a less precise match to create predictive capability (i.e., the model does not predict instantaneous uranium concentrations versus time but rather forecasts cumulative recovery versus volumetric production).

The model as applied to the development of Smith Ranch is shown below:

GENERALIZED RECOVERY VERSUS TIME MODEL
(% Recovery as f(pore volume recovery))

| Operating Month | % of In-Place Reserves Recovered this Month |
|---|---|
| 1 | 14. |
| 2 | 14. |
| 3 | 9.5 |
| 4 | 7.5 |
| 5 | 6.5 |
| 6 | 5.3 |
| 7 | 4.5 |
| 8 | 3.6 |
| 9 | 3.1 |
| 10 | 2.7 |
| 11 | 2.5 |
| 12 | 2.1 |
| 13 | 1.8 |
| 14 | 1.6 |
| 15 | 1.3 |
|  | 80.0 |

For 1.26 L/s and 2.55 tonnes U recoverable, the net uranium concentration from a pattern will average 85.2 mg/L over its life, Figure 5. To raise this average, either the pattern reserves must be increased or its life shortened.

From this production profile, the startup schedule of recovery wells to meet the annual production goals was established. At a nominal 190 L/s operating capacity, each IX unit can accommodate 150 recovery wells producing an average of 1.26 L/s. For careful management of the startup of individual recovery wells, blocks of wells no larger than 20 are started on any given month. In the case of the first IX unit, new wells were regularly added during the first nine operating months until full flow capacity was achieved.

Even though substantial detail is created with such forecasts, they are only guides which serve a valuable role as a planning tool. The scheduled startup of wells may be adjusted either up or down to meet the production goal for a given month or year.

The key is that these forecasts serve as a guide to developing a cased well installation schedule which insures that sufficient wells are always available to meet the production goal. The installation schedule in turn becomes the basis for budgeting drilling expenditures and guides the geologists in their ore delineation and wellfield development efforts.

The key factors and assumptions in establishing the schedules are:

(a) Patterns are installed in blocks no larger than 20.
(b) Drilling and completion of a block of patterns requires one month - this sets rig requirements.
(c) Installation of downhole piping and interconnecting surface piping of a block of wells is completed one month later - this sets piping and electrical crew size.

(d) The wellfield construction will be a continuous, steady activity eleven months per year (one month deleted for poor weather conditions). This assures the use of company trained employees, which provides maximum economy, efficiency, and control.

(e) At all times, at least one block of operable patterns is held in inventory. This assures a response capability to any unforeseen production shortfall.

(f) Monitor wells are installed in blocks of 70 to surround a nominal 77- tonnes of recoverable reserves (a mining unit).

(g) Monitor wells are installed at least six months in advance of startup of a mining unit to insure sufficient time for requisite baseline water sampling, hydrology testing, and approval by the Wyoming Department of Environmental Quality (WDEQ).

The drilling plan for 1996 began promptly in January with installation of monitor wells for the first production areas. Baseline sampling and testing of these wells were completed during the spring and the results submitted to the WDEQ for review and approval. During the summer and fall, four drilling rigs were employed to install operating wells for over 385 tonnes of recoverable reserves.

This campaign positioned the project for the steady, ongoing phase of wellfield construction, which accompanies commercial operation. Cased well drilling in support of the second ion exchange facility begins in late 1997 with installation of initial monitor wells. At full production (770 tonnes U) and an average recovery of 3.55 tonnes per pattern, the annual consumption of cased wells is the equivalent of 217 patterns. Replacement of depleted reserves requires installation of 20 new patterns per month (11 working months per year) and 70 new monitor wells per year. At least nine full-time drilling rigs were employed at all times to meet this need.

Additional drilling rigs were required to sustain the wellfield development and ore delineation programmes which serve to identify commercial sized ore deposits and provide the detailed geologic data necessary for planning the layout of well patterns for future wellfields.

The narrow sinuous shape of the uranium role fronts at Smith Ranch increase the drilling density requirements for both ore delineation and wellfield development. Since 1996, as many as four drilling rigs have been assigned to ore delineation programmes with an additional four drill rigs committed to wellfield development. Further, much of the lands within the Smith Ranch Project and adjoining Reynolds Ranch project had not been fully explored. Aggressive exploration programmes were conducted on both properties from mid-1997 into early 2000. During this period, the total drilling rig count at the site averaged more than 20 and reached as high as 26.

The basis for this massive drilling effort was driven by the planned production rate, the production model, and the resulting depletion of wellfield areas. This situation is typical for the larger ISL operations in the U.S. where well patterns are relatively quickly depleted of uranium. To plan, coordinate, and administer four different drilling programmes (exploration, delineation, development, and well installation) in the midst of an operating ISL facility with ongoing installation of wellfield flow lines requires close coordination between geologists, engineers, logging operators, casing and piping crews, and operations personnel.

### *Wellfield operations*

Once commercial wellfield operations began in June, 1997, the wellfield management effort was expanded to encompass a new phase. While installation of additional wells continued, efforts turned to maximizing the productivity of wells now operating. This effort was two fold: (1) maximize the value of the sunk wellfield investment, and (2) identify improvements for applications to future wells and wellfields.

Economical operation of an ISL project is dependent upon the ability to maintain both the flow of uranium bearing fluids and the concentration of uranium in these fluids as they enter the uranium recovery facility (a high efficiency recovery facility is equally essential and beyond the scope of this presentation). At the same time, recovery of the uranium resources must be, within defined limits, maximized.

Grade control for an ISL operation is maintaining, at desired levels, the uranium concentration in the pregnant lixiviant which feeds into the uranium recovery facility. This differs from grade control in conventional mining in that ISL grade control is imposed subsequent to rather than prior to leaching. ISL grade control decisions are, of necessity, made without the advantage of direct observation and control possible in conventional mining.

Grade control is a multi-disciplined endeavor which involves both development and production geologists, wellfield drilling and installation teams, engineers, and operations personnel. It begins with designing the initial wellfield, continues with maintaining productively these first wells and extends through planning and operation of all subsequent wellfields which compensate for depletion of existing wells and, perhaps, changing production targets. During each phase of the project the objective is to optimize the performance of the current phase while ensuring that we are developing all information necessary to optimize future phases. Throughout this task, we remain cognizant of the fact that successful wellfield management results from an appreciation as well as an understanding of the complex geologic and operational parameters associated with the particular uranium deposits.

A list of significant geological factors must include, at a minimum, the following (Table II):

Table II. Geologic factors.

- Host formation mineralogy
- Uranium mineralogy
- Uranium disequilibrium
- Host formation strategraphy
- Permeability
- Depth of water table
- Ore quality (grade and thickness)

Our concerns are not limited to average or typical characteristics. A knowledge of the interactions among these factors as well as localized variations are important in designing, operating, and reclaiming ISL wellfields. For example, an ore body may display a desirable average permeability only to have its high grade ore confined to regions with extremely low permeabilities. These types of characteristics must be identified early in the development process such that commercial development, if justified, adequately anticipates such geologic limitations.

Similarly, the fundamentals operating parameters for a wellfield include those items which enable us to distribute the lixiviant within the ore bearing host, the chemistry to dissolve the uranium minerals, and the means to recovery the uranium bearing solutions. A minimum list of such factors includes (Table III):

Table III. Wellfield parameters.

- Wellfield completion design
- Well efficiency
- Well pattern configuration
- Well pattern size and shape
- Oxidant/pH/ chelating agent

It is here that we began to expand our understanding of the complexities of the particular ore deposit. We asked a series of questions:

1. Is each pattern performing as expected?
    - Uranium concentrations?
    - Fluid flow?

2. For wells with low fluid flow,
    - Is there evidence of well bore damage?
    - Is the completion interval set in sandstone?

3. For patterns with low uranium concentrations,
    - Are the attributed ore reserves confirmed by logging data?
    - Are the completion intervals of Injection and Recovery wells in communication?
    - Are completion intervals in the ore bearing sand?
    - Would the ore contact be improved by changing the well configuration?

A systematic evaluation and testing programme was undertaken to identify poorly performing wells and patterns. Basically this was a programme of management by exception, identify the poorest performing wells, work to identify and eliminate the causes, and improve their performance. The process is then repeated for those wells which remain or have become the poorest performers. The iteration continues as does the associated learning. In the case of the first wellfield at Smith Ranch, the predominate problem was a loss of injectivity which resulted from the production of extremely fine, clay sized sediments which passed through the primary filtration and were re-injected. As seen in Figure 6, the effects of this well plugging became evident in January, 1997. Swabbing proved to be an effective means of removing these fines from the wells and restoring injectivity. However, the well plugging was brought under control only after secondary filtration was added at each wellfield metering station. At each station a set of 5 micros bag filters was installed on the injection stream. Full production was restored by mid – 1997.

As is often the case, several well patterns failed to yield the anticipated high concentrations of uranium. Downhole logging data for these areas was reviewed in a search for causes. In key areas, core holes were drilled to confirm the quantity and quality of the ore. These studies also addressed the relative permeability of the high grade ore intervals with that of adjacent low grade or barren horizons. In some instances, relative permeability appeared to be a factor in the poor performance. In other cases, a single cause was not evident. What did emerge was a general consensus that (1) gravel packed completions were preferable to conventional screened or open hole completions: (2) relatively narrow completion interval, 6 meters, or less, were preferable to wide, 10-15 meter, completions; injection wells along the wellfield perimeter were preferable to perimeter recovery wells; and five-spot patterns were far more effective than either four-spot or six-spot patterns.

The benefits of this wellfield management programme became apparent when the relative productivity of each of the four wellfield that have operated is examined, Figures 7 and 8. Each succeeding wellfield has outperformed the preceding one. Unit flow rates, liters per second per meter of screen, peak uranium concentrations, uranium productivity, kg./day, and all other performance measures have increased with each new wellfield.

During the production phase of a wellfield's life, the key objective is to maximize the rate of uranium production from each recovery well in service. However, an environmental consideration, the loss of lixiviant into surrounding aquifers, must be avoided. An escape of lixiviant or excursion into unauthorized aquifers requires immediate attention and, if not promptly remediated, can result in a shut down of the facility by regulatory authorities.

As a result, wellfield management at Smith Ranch emphasized the importance of flow balancing. At no time was the injection rate allowed to exceed the recovery rate in any individual well pattern or a wellfield as a whole. Balancing on a pattern by pattern basis can be difficult when the injectivity of some wells markedly decreases. Maintenance of individual well flows is an important aspect of day-to-day wellfield management. A separate work crew and supervisor are dedicated to this task at Smith Ranch. Swabbing accompanied by air lifting has been very successful in restoring well injectivity and enabling pattern flow balancing. No acidizing of wells has been employed during commercial operations at Smith Ranch and no excursions of lixiviant have occurred.

### *Wellfield restoration*

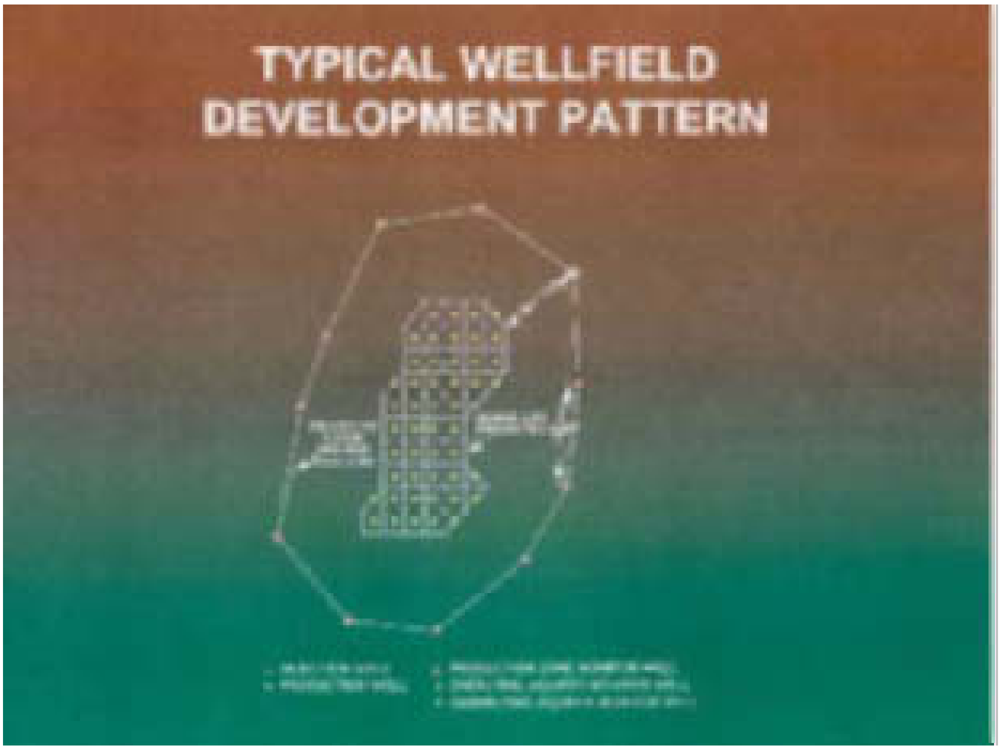
The decision to discontinue leaching of a particular pattern or wellfield at Smith Ranch has been based on the general mine plan. If the ion exchange facilities are operating at maximum fluid flow capacity, older, low productivity wells are shut-in to create flow capacity to accommodate new patterns and wellfields. A simple criterion to cease leaching is reached when the value of uranium produced from a pattern or wellfield is less than its direct operating cost. In many cases, marginal production can temporarily be sustained in a depleted wellfield area by rearrange wells within the area to redirect fluids through areas containing residual ore. As shown in Figure 9, this rearrangement programme was successful in both pilot and commercial wellfields at Smith Ranch. Such a programme does require a dedicated effort by wellfield operating personnel to understand the operating history and ore reserve distribution within the subject area.

The final phase of an effective wellfield management programme is that associated with the ground water restoration of a depleted wellfield. The Smith Ranch team is now moving into this phase. The techniques and methodologies employed during the production phase can be brought to bear on the management of the ground water restoration effort.

Because of anisotropic reservoir properties such a highly directional permeabilities, bedding plane discontinuities, and uranium roll front characteristics, it is not readily possible to fully displace the nature lixiviant with a second, clean fluid. (Nor is it possible to recover 100% of the uranium). Isolated pockets of lixiviant will remain even after restoration. Much like the production phase, a restoration programme should aim to maximize the removal of contaminates in the minimum time. Building on the knowledge gained during production, an intensive management programme will include frequent monitoring of water quality and flow rates, numerous well flow reversals to maximize contaminate removal, and addition of a strong reductant to reduce and reprecipitate dissolved metals.

## 3. Conclusion

Only when ground water restoration is finished and surface reclamation completed is the wellfield management task at an end. Not only is wellfield management the key to a successful ISL project, it is the most challenging and satisfying aspect of ISL. The uranium deposits of an ISL project are never seen in their entirety. Only glimpses are seen from logs, well performance, and cores. The challenge of wellfield management is to take these small pieces of information and to interpret them so as to maximize the economic recovery of the uranium mineral. Like a detective, when one can put these pieces of the ISL puzzle together and see positive results, there is great satisfaction.



TYPICAL WELLFIELD DEVELOPMENT PATTERN

*FIG. 1. Typical Wellfield development pattern.*

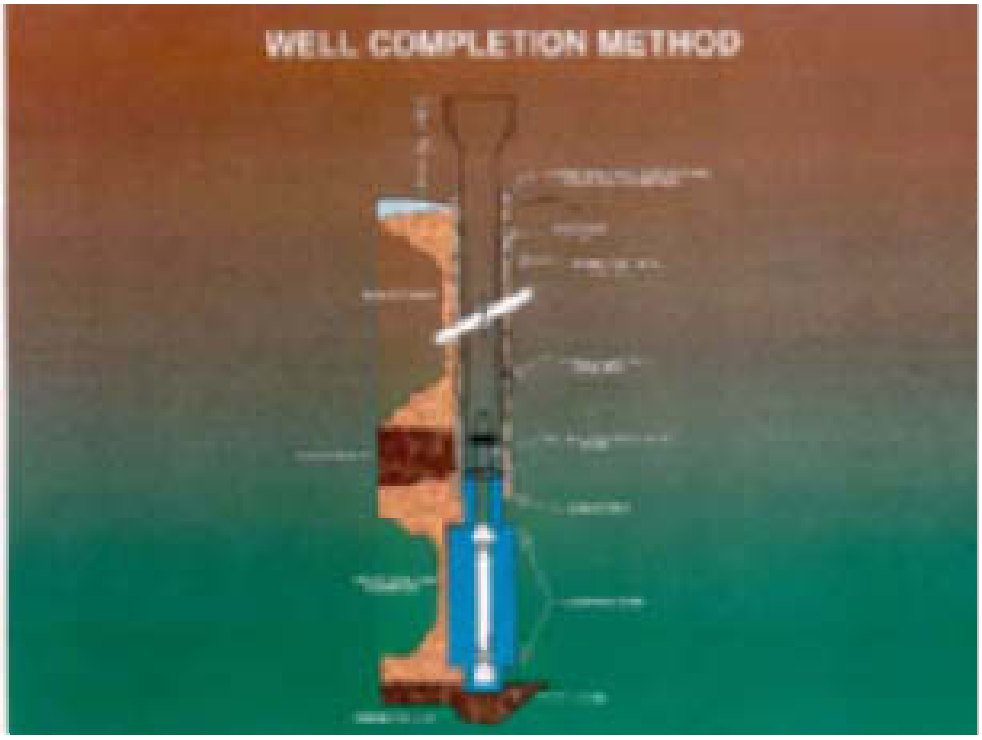


FIG. 2. Well completion method.

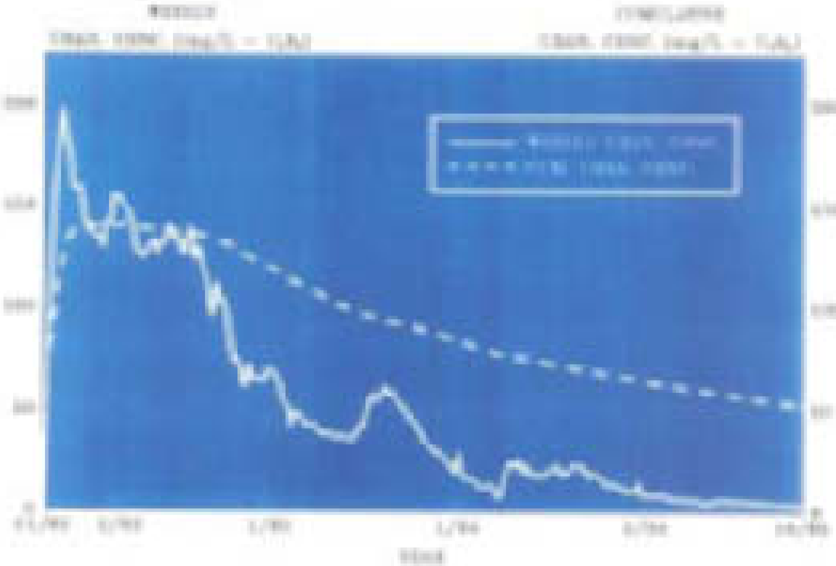


FIG. 3. Q-Sand production history.

FIG. 4. Generalized uranium recovery model.

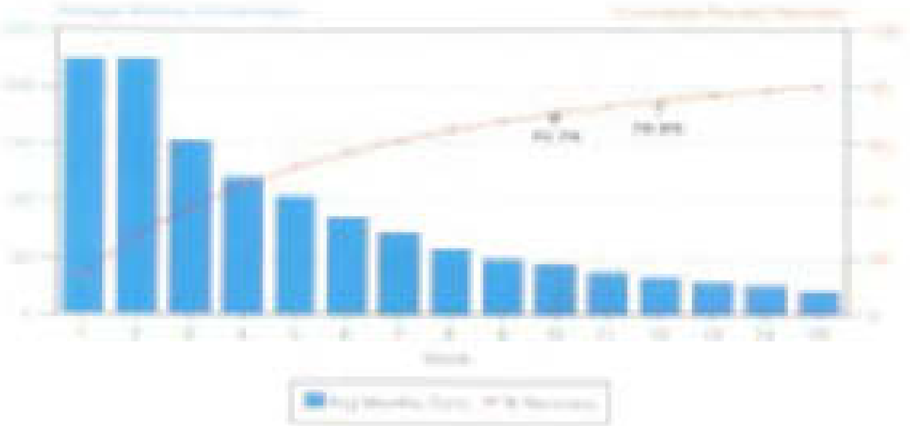


FIG. 5. Uranium recovery model**.**

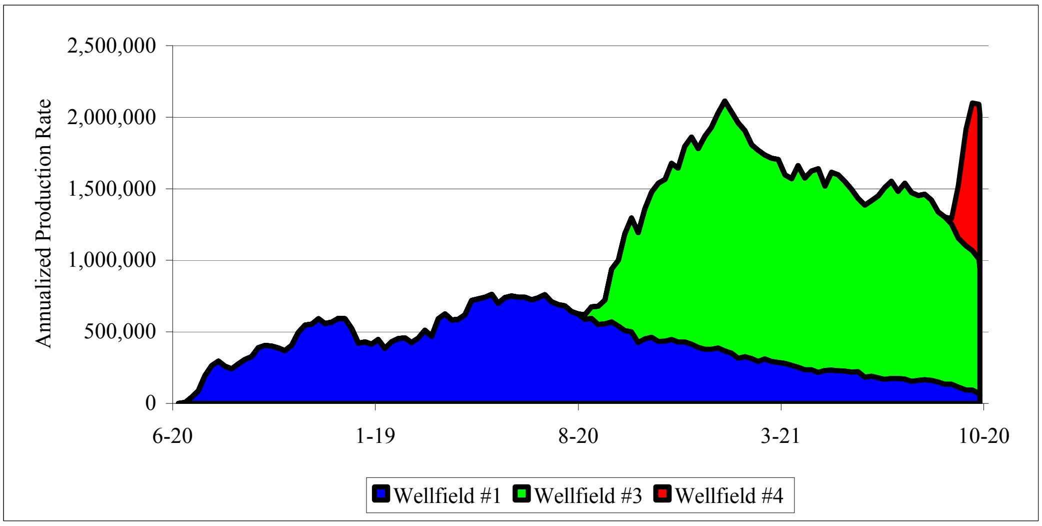


*FIG. 6. Smith Ranch production.*

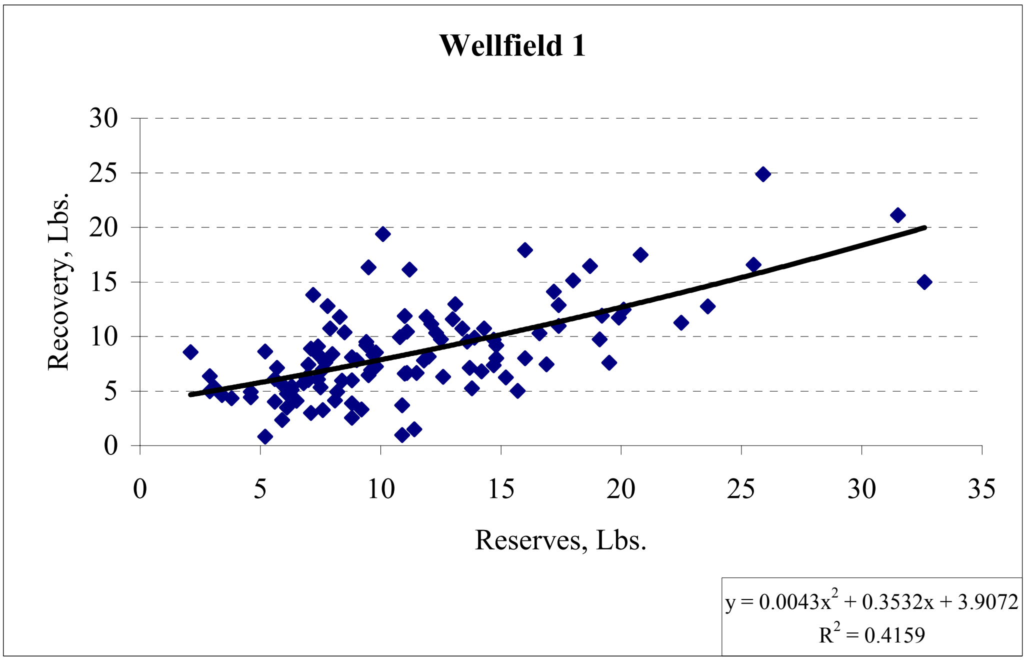


*FIG. 7 Wellfield 1.*

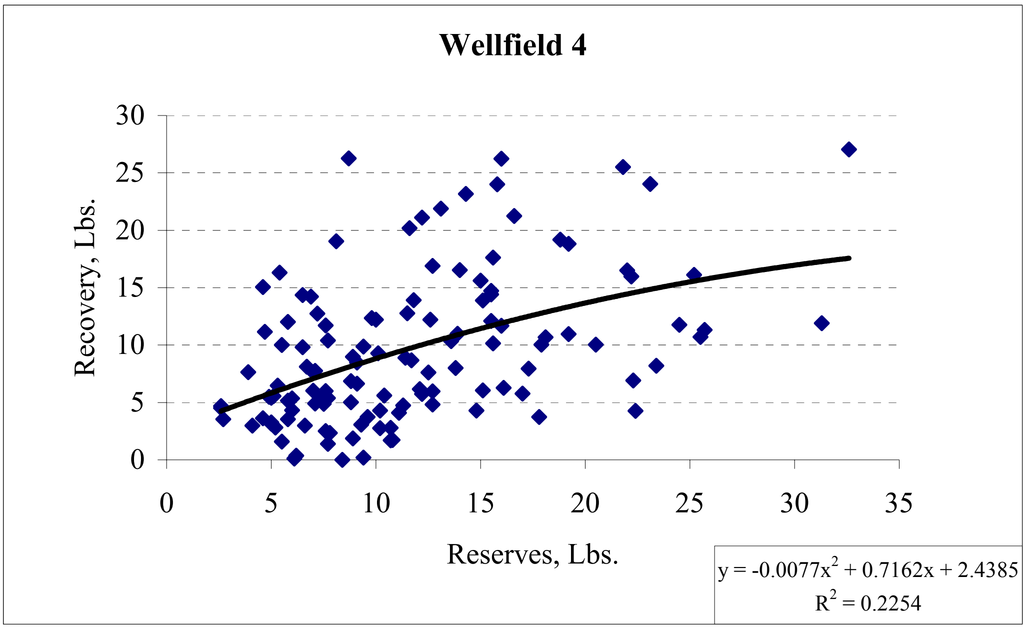


*FIG. 8. Wellfield 4.*

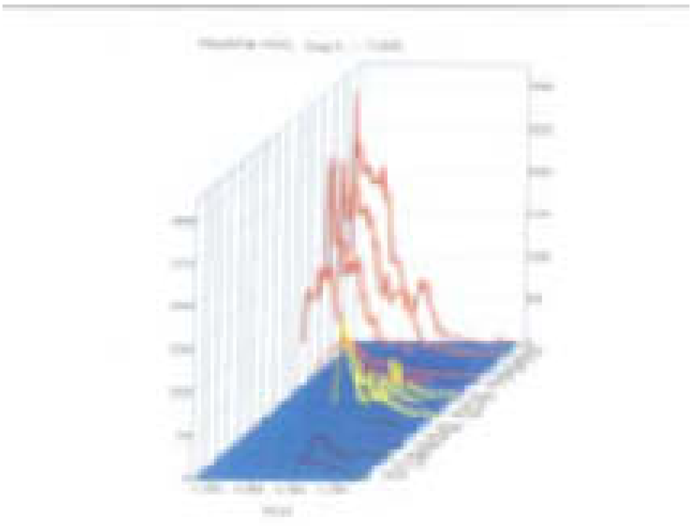


*FIG. 9. Q-Sand production history individual well data.*

# Field test of ISL uranium mining at Shihongtan Deposit in Xinjiang, China

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**Abstract.** Shihongtan deposit, located in Tuha basin of Xinjiang, is one of new uranium discoveries recent year. This sandstone type uranium occurs in weak permeable confined aquifer. Preliminary works for the possibility of ISL was begun in 2000, including lab tests and field tests. It is indicated from lab test that 87.2-95.8% of uranium could be leached by $H_2SO_4$ and 67.5-89.2% by $NH_4HCO_3$. The field tests, however, are unpleasant by acid leaching using 2-10g/l $H_2SO_4$ and 0.15-0.3g/l $H_2O_2$. During field test, the scaling in ore horizon, the decline of pumping/injection rate, the corrosion of equipment and the lower uranium content in pregnant solution are brought about. These are caused by complexity of formation construct, high content of $CO_2$ in ore as well as TDS, $Cl^-$, $Ca^{2+}$ in groundwater. Therefore, the third field test is going to be conducted by $NH_4HCO_3$. The geology and hydrogeology of the deposit, test results and some viewpoints obtained from test are proposed and discussed in the paper.

## 1. Introduction

The Shihongtan deposit, located in the end of southwest Tuha basin at an elevation of 118-315m, is a newly discovered uranium deposit. The rolling plains topography is typical desert land-scope covered by growl and windy-sand of Quaternary period. The climate of region, 16.6mm annual average precipitation and 3000mm annual average evaporation, is continental droughty, and the highest temperature is +48ºC in summer and lowest –35°C in winter.

After further exploration in 1997, thousands tons of uranium reserve was estimated. Test works for the possibility of ISL method was begun in 2000, and the satisfactory results from Lab leaching test of core samples showed that the ore of Shihongtan deposit was leached easily with accepted recovery rate and high uranium concentration in pregnant solution by acid and alkaline. Field tests were carried out twice in different blocks of orebody to determine technical and economical feasibility of applying in situ leaching. Due to condition of deposit and scaling encountered in ore horizon during tests, the field test results are not acceptable by acid leaching technique. The third field test is undergoing by $NH_4HCO_3$.

## 2. Geology

In the whole area, carboniferous basement and Mesozoic overlay are observed under exploration. Formations of Mesozoic are half-baked and composed of Jurassic, Tertiary and Quaternary. Quaternary formations are windy gravel 5–50m thick. Tertiary formations are mixed with red clay-sand of diluvium. The Jurassic system is coal measure rock of riverbed, and consists of medium-to-coarse sandstone, clay and coal. Carboniferous basement consists of shale, tuff and granite.

Shihongtan deposit is located in the east of nasal apophasis of Shihongtan. The mineralized zone, located in Xishanyao Group of middle Jurassic system, extends 20km length. It is confined above and below by mudstone or silt clay stone which is stable and continuous. The shape of orebody, controlled by interbedding zone of oxidation, is plate and roll type, dipping at 3~8 degrees. The depth of orebody ranges 81.6~350.0m. The grade of ore is 0.012~0.193% with an average of 0.030% uranium, and the thickness of orebody is 0.9~20.9m with an average of 7.16m. The uranium occupied per square meter ranges from 1.05kg/m$^2$ to 17.63kg/m$^2$, mainly about 3.22kg/m$^2$.

The mineralized zone is loose or hypo-loose sandstone, mainly consisting of gray sandstone, gravel sandstone, fine sandstone, mudstone and calcrete. More than 95% of the mineral components are acid insoluble or refractory to leaching, such as debris, feldspar, quartz, kaolinite, etc. Acid soluble minerals, e.g., carbonates, account for less than 5%, as shown in Table I.

Table I. Mineral composition of ore based on solubility in sulphuric acid (%)

| | | |
|---|---|---|
| Insoluble | Quartz, quartzite, silicate and siliceous conglomerate | 58.30 |
| | Minor minerals | <1 |
| | Subtotal | 59.30 |
| Refractory | Feldspar | 13.90 |
| | Mica | 2.85 |
| | Kaolinite | 10.05 |
| | Illite | 2.11 |
| | Montmorillonite | 2.46 |
| | Organic | 0.23 |
| | Subtotal | 36.07 |
| Soluble | Uranium minerals | <0.1 |
| | Carbonate | 3.34 |
| | Ironstone | 1.0 |
| | Sulfides | 0.9 |
| | Chlorite | 1.29 |
| | Subtotal | 5.53 |

Most of uranium is adsorbed in cementing materials of sandstone and gravel sandstone. The uranium minerals are mainly pitchblende, coffinite and uranous Ti-Fe oxide. The main incidental elements with potential value in use are Mo, Re. The ore sand has high calcite content, and pyrite, ranges form 0.92 to 3.91% of $CO_2$ content with an average of 1.94%; CaO in 0.613~5.03%, average of 3.02%; $FeS_2$ in 0.42~1.40%, average of 0.86%.

## 3. Hydrology

There are 8 groups of aquifer in Jurassic system. The orebody is buried in 5th confined aquifer, which the water table is 39.95-42.62m from surface. The entire host sand sequence is hydrologically connected, ranging from 34.7~59.9m with an average of 44.7m in thickness, and some clay stone and calcrete bases are appeared in the mineralization. The continuous shale layers above and blow the host sand provide adequate confinement and preventing leaching solution from vertical excursion.

Numerous hydrologic tests have been done to establish hydrologic parameters of aquifer. The values of hydrologic parameters of aquifer can be charactered as follows: horizontal permeability gives 0.138~0.714m/d, transmissivity values is 2.2-4.5$m^2$/d, and unit flow rate of production well shows 0.01~0.04L/s·m.

The high salinity of the groundwater of the mineralized aquifer is hydrologically classified to chlorine sulphate natrium type, with 18-21°C in temperature, 8.49-9.02g/l in TDS, pH 7.10-7.33 with high concentration in $SO_4^{2-}$, $Cl^-$, $Ca^{2+}$(see Table II). The water head of drink and industry comes from the groundwater of Tertiary, 20km away from the mine.

Table II. Chemical analysis of groundwater (mg/L)

| Component | K | Na | Ca | Mg | Al | Mo | ΣFe | U |
|---|---|---|---|---|---|---|---|---|
| Content (%) | 21.17 | 2033.07 | 882 | 462 | <1 | 0.5 | <1 | 2.2 |
| Component | Cl | F | $SO_4^{2-}$ | $PO_4^{3-}$ | $HCO_3^-$ | $CO_3^{2-}$ | pH | TDS |
| Content (%) | 3390 | 0.62 | 3360 | none | 481 | none | 6.95 | 8.6 |

## 4. Assessment for in situ leaching

In view of the geologic and hydrogeologic conditions, favorable factors include shallow depth of orebody, gentle dips, medium grade, higher mineralized thickness, easy leaching of uranium, ore occurs blow water table and shallow water table from surface. However, poor permeability, existence of clay and calcrete in the mineralization, high calcite content in the ore and high $Cl^-$, $Ca^{2+}$ in the groundwater present unfavorable to ISL.

## 5. Laboratory test

### *5.1. Static leach test*

The test samples with original granularity are prepared by blending the cores taken from ore zones of some drill holes. The grade of the sample is 0.0514%, and $U^{4+}/U^{6+}$ in waxed cores is 3/2. $U^{4+}$ in the sample is amenable to be oxidized when the sample is exposed in air. The lixiviant is made up by groundwater, and the test results are presented in Table III and Table IV. These test results indicate that satisfactory uranium leaching rate can be achieved by $NaHCO_3$ and $H_2SO_4$, while using $H_2SO_4$ as leaching agent, the leaching rate of uranium is 10-20% higher than that of $NaHCO_3$. When leaching with weak acid and weak alkaline, 68.5~88.7% uranium extraction can be achieved with long leaching period and high liquid/solid ratio.

Table III. Result of static leach test by weak acid and weak alkaline

| Sample No. | | H-1 | H-2 | H-3 | H-4 |
|---|---|---|---|---|---|
| Lixiviant | $H_2SO_4$ (g/L) | 1 | 2 | | |
| | $NaHCO_3$ (g/L) | | | 1 | 2 |
| | $H_2O_2$ (g/L) | 1 | 1 | 1 | 1 |
| | PH | 1.70 | 1.51 | 7.78 | 7.75 |
| | Eh, mV | 492 | 494 | 209 | 215 |

| | | | | | |
|---|---|---|---|---|---|
| Stage 1 | L : S | 10:1 | 10:1 | 10:1 | 10:1 |
| | Duration (h) | 48 | 48 | 48 | 48 |
| | Ph | 5.62 | 2.18 | 8.03 | 7.66 |
| | Eh (mV) | 321 | 499 | 197 | 225 |
| | U (mg/L) | 9.02 | 41.66 | 17.17 | 34.85 |
| Stage 2 | L:S | 5:1 | 5:1 | 5:1 | 5:1 |
| | Duration (h) | 48 | 48 | 48 | 48 |
| | PH | 2.02 | 1.54 | 7.84 | 7.75 |
| | Eh (mV) | 406 | 419 | 195 | 195 |
| | U (mg/L) | 87.23 | 7.58 | 4.31 | 5.91 |
| Stage 3 | L : S | 5:1 | 5:1 | 5:1 | 5:1 |
| | Duration (h) | 24 | 24 | 24 | 24 |
| | Ph | 1.78 | 1.49 | 7.69 | 7.88 |
| | Eh (mV) | 470 | 467 | 243 | 241 |
| | U (mg/L) | 8.82 | 1.40 | 4.31 | 1.70 |
| Overall leaching rate (%) | | 87.0 | 88.7 | 68.5 | 77.0 |

Table IV. Result of static leach test by generic acid and generic alkaline

| Sample No. | | H-5 | H-6 | H-7 | H-8 |
|---|---|---|---|---|---|
| Lixiviant | $NaHCO_3$ (g/L) | | | 5 | 10 |
| | $H_2SO_4$ (g/L) | 10 | 20 | | |
| | $H_2O_2$ (g/L) | 0.3 | 0.3 | 0.3 | 0.3 |
| | pH | 0.83 | 0.60 | 8.17 | 8.15 |
| | Eh (mV) | 506 | 514 | 182 | 180 |
| Pregnant solution | L : S | 10:1 | 10:1 | 10:1 | 10:1 |
| | Duration (h) | 48 | 48 | 48 | 48 |
| | pH | 0.98 | 0.81 | 9.65 | 9.70 |
| | Eh (mV) | 552 | 559 | 121 | 104 |
| | U (mg/L) | 48.1 | 51.5 | 37.17 | 37.12 |
| Overall leaching rate (%) | | 91.4 | 93.2 | 80.9 | 67.5 |

### *5.2. Column leaching test*

The column leaching test has been carried out with PVC column, 30mm in diameter, 1000mm long. The gravel filtration is designed at the bottom of column. The lixiviant goes in from the bottom of columns, and pregnant solution comes out from the top of columns, 2m differences of fluid levels is controlled to determine the change of flow rate. The test results, shown in Table V and in Figures 1 to 5, demonstrate that when leaching with 2~10g/l $H_2SO_4$ or 2g/l $NH_4HCO_3$, the pregnant solution gives 50mg/l uranium concentration and more than 70% uranium leaching rate could be obtained. However, the lixiviant consumption is high. When leaching with 0.8g/l $H_2SO_4$, pregnant solution in pH 6~8 and 0.3~1.0g/l $HCO_3^-$ concentration illustrated that uranium was leached by $HCO_3^-$. Ore bed blocking caused by the scaling of $CaCO_3$, $CaSO_4$ was observed during the column test.

Table V. Results of column leaching test

| Column No. | T-1 | T-2 | T-3 | T-4 | T-5 |
|---|---|---|---|---|---|
| Lixiviant | $H_2SO_4$ | $H_2SO_4$ | $H_2SO_4$ | $H_2SO_4$ | $NH_4HCO_3$ |
| Lixiviant concentration (g/L) | 0.8 | 10 | 2 | 5 | 2 |
| $H_2O_2$ (g/L) | 1 | 1 | 1 | 1 | 1 |

| | | | | | |
|---|---|---|---|---|---|
| L:S | 7.98 | 5.28 | 7.58 | 7.21 | 5.27 |
| Average uranium concentration (mg/L) | 41.5 | 73.7 | 56.2 | 50.9 | 61.1 |
| Highest uranium concentration (mg/L) | 193 | 708 | 521 | 667 | 600 |
| Average $HCO_3^-$ concentration (mg/L) | 394.5 | -- | 665.1 | -- | 875.3 |
| Acid consumption (kg/t ore) | 5.34 | 46.2 | 35.4 | 35.2 | -- |
| Leaching rate (%) | 65.01 | 75.66 | 95.78 | 71.34 | 72.96 |

## 6. Field test

### *6.1. Test I*

Two acid leaching field tests have been completed in two different blocks of orebody to determine the technical feasibility of in situ leaching to the deposit; the alkaline leaching field tests is undergoing.

Test I is conducted in the south of orebody in 5-spot well pattern, and an exploration hydrology hole, 50m away, was used as monitoring well. Some information about the test is listed in Table VI. Test I of the orebody is incised by 2-6 non-permeable layers with maximum thickness 8.3m. 2g/l $H_2SO_4$ is initially injected for acidizing. When pH of the pregnant solution decreased to 3.5~4.5, the lixiviant is injected at 10-15g/l $H_2SO_4$+0.3g/l $H_2O_2$. The test lasted for 72days, 7579.24m$^3$ of lixiviant is injected and 6613.98m$^3$ of pregnant solution in 2-8mg/l of uranium concentration is pumped. Liquid/Solid ratio is 0.55 and acid consumption is 5.53kg/t ore. The changes between baseline concentration in the natural groundwater and the concentration of the same element in the pregnant solution are shown in Table VII.

Table VI. Well field design parameters for test I

| | | | |
|---|---|---|---|
| Well pattern | 5 spot | Depth of orebody | 174.02m |
| No. of injection wells | 4 | Thickness of orebody | 8.7m |
| No. of recovery wells | 1 | Permeability | 0.153m/d |
| No. of monitor wells | 1 | Uranium content per square meter | 4.10kg/m$^2$ |
| Wells spacing | 15.0m | Ore grade | 0.0243% |
| Lifting of solution | Submersible pump | Original water table | 46.40m |

Table VII. Change of groundwater contents during leaching, mg/L

| Component | pH | Eh | U | ΣFe | $Fe^{3+}$ | $Ca^{2+}$ | $Mg^{2+}$ | $Al^{3+}$ | $SO_4^{2-}$ | $Cl^-$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Before leaching | 6.95 | 173mV | 0.7 | <1 | -- | 752 | 365 | -- | 3150 | 3370 |
| After leaching | 2.1 | 375mV | 5~8 | 1200 | 340 | 880 | 700 | 800 | 12400 | 3410 |

During test, the chemical scaling caused reduces flow rate of production well and injection well. The flow rate of production well dropped from 2.4m$^3$/h to 1.4 m$^3$/h, and returned to 1.54 m$^3$/h later. The flow rate of injection well dropped from 1.38 m$^3$/h to 0.513 m$^3$/h under the same injection pressure. Two submersible pumps are eroded during test due to high chlorine content in groundwater. Well cleaning is carried out by 35% HCl, then airlift pumping is used to clean sludge from well. Hydrofluoric acid is used only in case the HCl failed. The pH of pregnant solution is about 2.1 and most acid are consumed in host rock. The test results indicated that acid leaching is not an economically option for the deposits due to low uranium concentration of pregnant solution and high acid consumption. The initial purpose of field test I is not achieved.

### *6.2. Field test II*

Test II is conducted in the north of orebody, 320m away from Test I site. 4 drilling holes are arranged in triangle pattern. The purpose of test II was to determine the leach character of ore using weak sulphuric acid. Some information about the test II is listed in Table VIII. The mineralized zone of test II site is loose sandstone mainly consisting of medium to coarse sandstone, gravel, thin mudstone and coal. One calcrete zone is continuous with average 1.55m thick in mineralization.

During early stage, weak acid (1~2g/l $H_2SO_4$) is injected into orebody, and hydrogen peroxide is added at the rate of 1.0g/l. The stage lasted for 40 days. It is expected that bicarbonate could be produced by chemical reaction between weak acid and carbonate in ore, and uranium in ore could be leached by bicarbonate. The results of test II, however, don't appear the process of bicarbonate leaching as operated in the laboratory tests by weak acid. Reversibly, pH value and bicarbonate concentration of pregnant solution declined gradually, and calcium concentration was increasing from 0.61g/l to 0.92g/l.

Table VIII. Well field design parameters for test II

| | | | |
|---|---|---|---|
| Well pattern | 4 spot | depth of orebody | 175.4 m |
| No. of injection wells | 1 | Thickness of orebody | 11.29 m |
| No. of recovery wells | 3 | Permeability | 0.228 m/d |
| No. of monitor wells | 0 | Uranium content per square meter | 13.53 kg/m$^2$ |
| Wells spacing | 12.0m | Ore grade | 0.0655% |
| Lifting of solution | submersible pump | Original water table | 35.65 m |

The concentration of sulphuric acid is increased from 2g/l to 5~8g/l, up to 10~25g/l after 30 days. This period lasts for 160 days with 38mg/l of highest uranium concentration in pregnant solution. Sometimes, lixiviant is injected by adding HCl to reduce blocking of ore. It is effective to maintain calcium ions concentration 0.8~0.85g/l but $Cl^-$ increased. The chemicals variation in quantities of pregnant solution is given in Table IX.

During leaching, the precipitation of some calcium resulted in declination of the flow rate of well. Firstly, the injection rate reduced from 2.3 m$^3$/h to 0.64 m$^3$/h, subsequently, the pumping rate reduced from 4.9 m$^3$/h to 2.13 m$^3$/h. It demonstrated that the scaling of gypsum in the ore happened from injection well to production well. The effect of well cleaning by HCl and HF was very weak. Thus, the calcium of the raffinate stream from ion exchange columns was treated on surface by 2.0~2.5g/l $Na_2CO_3$ to reduce the scaling of ore. Calcium concentration of lixiviant solution reduced from 0.8g/l to 0.46~0.52g/l after treatment, below the level of groundwater's content.

Table IX. Chemical component of pregnant solution during leaching

| Leach time (d) | U (mg/L) | pH | Eh (mV) | TFe (mg/L) | Fe$^{3+}$ (mg/L) | Ca$^{2+}$ (mg/L) | Mg$^{2+}$ (mg/L) | Al$^{3+}$ (mg/L) | SO$_4^{2-}$ (g/L) | HCO$_3^-$ (mg/L) | Cl$^-$ (g/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Baseline | 1.24 | 6.41 | | 2.30 | | 607.87 | 242.60 | | 2.17 | 582.0 | |
| 20 | 1.30 | 6.36 | 270.67 | 40.25 | | 917.33 | 268.67 | | | 488.9 | 3.41 |
| 45 | 2.57 | 6.04 | 254.00 | 49.45 | 1 | 828.47 | 292.93 | | 3.35 | 378.3 | |
| 60 | 3.20 | 5.98 | 262.67 | 75.13 | 2.30 | 819.87 | 332.27 | | 3.25 | 349.2 | |
| 90 | 4.33 | 3.91 | 265.67 | 306.57 | 14.00 | 713.4 | 441.33 | 97.2 | 4.30 | 87.3 | 3.49 |
| 120 | 14.40 | 1.90 | 346.67 | 920.00 | 79.52 | 806.2 | 639.53 | 341.0 | 6.50 | | 5.08 |
| 150 | 15.60 | 1.53 | 373.00 | 998.40 | 156.03 | 858.13 | 660.67 | 363.0 | 7.40 | | 6.03 |
| 165 | 30.23 | 1.86 | 362.00 | 1232.4 | 127.87 | 823.60 | 571.93 | 570.2 | 7.90 | | 5.56 |

Later, the way of pregnant solution lifting was changed to airlift from injection well rather than from production well. The uranium concentration of pregnant solution from injection well went up as high as 600mg/l, and came down gradually after 20 days. The uranium concentration of pregnant solution, however, still maintained 30~38mg/l when normal pumping from production well was returned. Above phenomena demonstrated that the uranium in ore is amenable to be leached, the movement of solution from injection well to production well was hindered by formation of gypsum and leaded to lower uranium concentration.

## 7. Analysis and comments

Despite the fact that acid leaching of lab tests are successful, both field test I and field test II had met with the puzzle of lower uranium concentration and scaling of ore bed. The results of field tests demonstrate that the main factors influencing the application of ISL technique to Shihongtan deposit are as follow:

- High carbonate content of ore

General acid leaching is not economically option due to high carbonate content that raises acid consumption to uneconomic levels and causes deposition of gypsum in ore bed. The scaling of gypsum is permanent and hard to be removed; it decreases the flow rate of well. In addition, high carbonate content prolongs the acidification period and leaching time.

- High calcium concentration of groundwater

The calcium concentration of groundwater is almost the critical value to precipitation. When sulfuric acid or bicarbonate was injected into orebody, the precipitations of $CaSO_4$ or $CaCO_3$ could be happened. Therefore, the scaling of ore bed is too difficult to avoid by using general acid leaching or general alkaline leaching.

- High chloride concentration of groundwater

Because chloride ions in the pregnant solution will displace uranium ions from resin, the efficiency of recovery of uranium by resin ion exchange decreases markedly. In addition, the equipment and metal materials, e.g., submersible pump, processing column, injection pump, etc. are damaged easily and the life shortened under high chloride groundwater.

- Existence of non-permeable layers in orebody

Because the mineralized formation is incised into multiplayer by non-permeable layers, it is difficult to control lixiviant movement.

## 8. Conclusion

Acid leaching is widely used in commercial ISL uranium operations in china. Laboratory leaching tests of Shihongtan deposit showed that uranium was leached more rapidly with acid leaching than with alkaline leaching, and the overall recovery rate was greater. The time required to recover more than 80% of uranium by weak acid or weak alkaline was approximately 2~4 times of that required for general acid or general alkaline. The differences in uranium concentration between lab tests and field tests displayed that the operation of Shihongtan deposit by general acid leaching is uneconomical benefit at this deposit. Calcium is also one of the critical factors, which deposits in orebody settling around filter and reduces its conductivity. Therefore, the acceptable result of applying ISL techniques to Shihongtan may be obtained by using of feasible methods, which are required as follow:

- Permanent scaling is reduced at mostly,
- Economical uranium concentration of pregnant solution could be achieved with lower reagent consumption,
- Move than 65% of uranium extraction could be obtained.

It is quite necessary to do actively study on the technology of weak acid leaching and weak alkaline leaching. Field leaching test III by weak alkaline at pH value of 6-8 is under operation, and the good result will be expected.

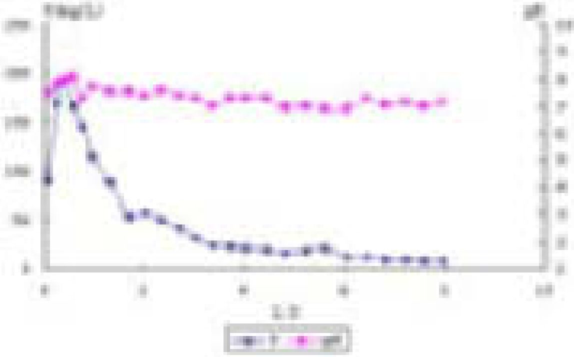

FIG. 1. Leaching history of column T-1.

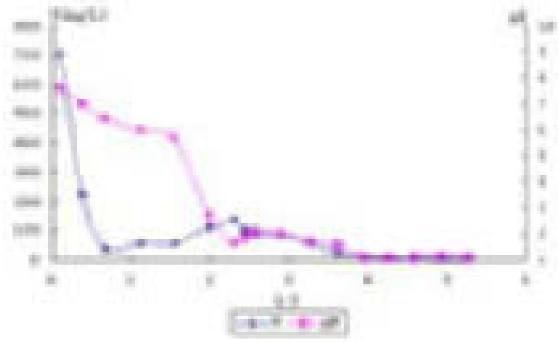

FIG. 2. Leaching history of column T-2.

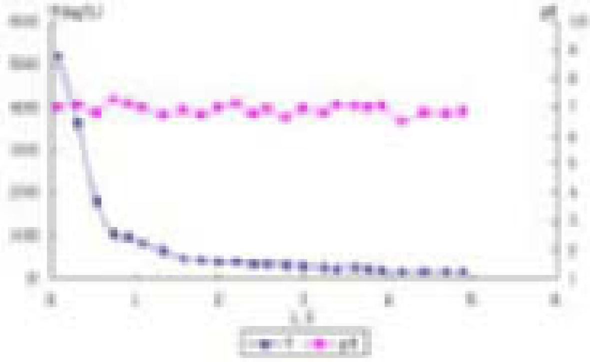

FIG. 3. Leaching history of column T-3.

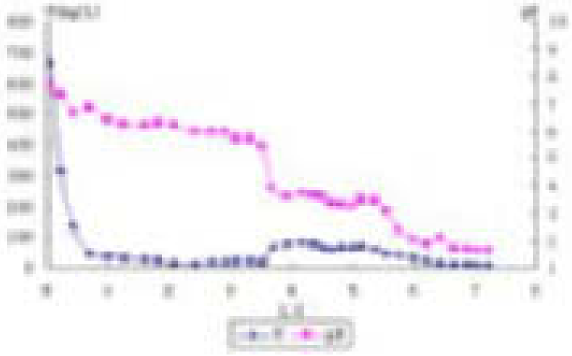

FIG. 4. Leaching history of column T-4.

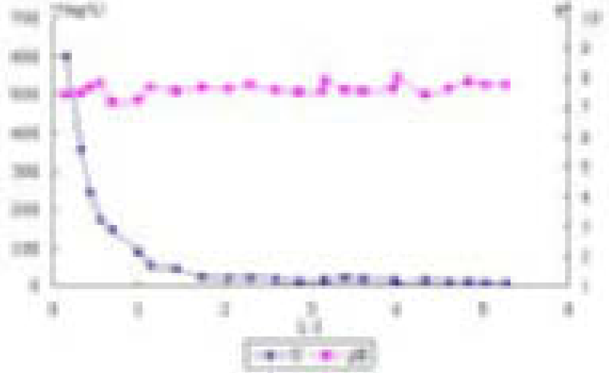

FIG. 5. Leaching history of column T-5.

# Downstream constraints on product specification and ISL mining methods

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**Abstract.** As uranium is more and more considered as a commodity, miners are producing natural uranium "as it comes out of the ground", forgetting sometimes that its isotopic composition can vary. Focusing on the 234U content of commercial concentrates coming from mining operations, it is reported that some batches are presenting difficulties. For these batches, ASTM C996 Standard specification requirements are not always met. It seems that this is only the case for certain uranium batches recovered through solution mining. Out of specification batches reaching the market now are more likely to cause problems than in the past. The main reason is that downstream from the front-end of the fuel cycle, the average U235 assay tends to increase significantly with the fuel burnups. And the economic ratio between uranium and SWUs prices is leading towards high tails assay. As ISL is increasing its output, it is important to understand the phenomenon at its roots and analyze the consequences of the problem. This paper is aimed at recalling the major facts explaining the U234 content variations and their potential consequences. To conclude, possible mitigation measures are discussed.

## 1. Introduction

Exploration Geologists are seeking for uranium as a metal, usually regardless of its isotopic composition, which is assumed constant everywhere on the planet at a human time scale. There has been so far a single but world famous exception: the Oklo Precambrian natural reactors area in Gabon.

Uranium Miners generally, mine uranium as a commodity. However, they are fully aware that some trace elements, if not sufficiently removed from the commercial concentrates, could incur the application of a penalty on the price of the product or even cause its rejection by the converters. Less focus has been made on the isotopic composition of uranium in the product, even if this point is also addressed by the ASTM specification for natural uranium commercial concentrates [Tables I and II].

Concerning the isotopic content, the ASTM specification itself was mainly aimed at discarding traces of irradiated uranium or other types of uranium having an artificially modified isotopic spectrum, through the application of threshold on the amounts of 232U, 234U and 236U. However, the main concern regarding 234U is its derived workers exposure during the fuel fabrication process.

In the past, almost all, if not all, fresh uranium produced at the mines seems to have satisfactorily complied with the isotopic specification [1].

Contrasting with the past situation, some uranium shipments in the recent years have shown excess content in 234U. All these shipments came from ISL operations, or from mine water recovery plants linked to remediation programs. It seems that amongst the anomalous mines, those using a sulfuric acid process are representing a very large share, if not all.

As ISL methods represent an increasing share of the global uranium production, and as ISL amenable resources already identified represent a very significant share of reported uranium resources, it appears very important to track, measure and understand fully this problem in order to solve it adequately.

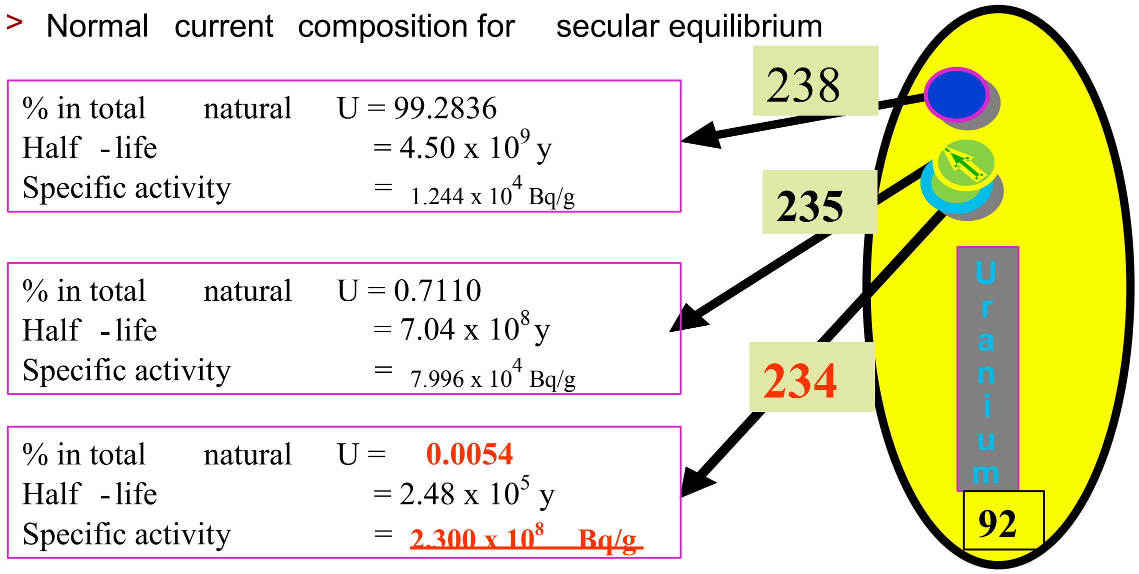
## 2. Recall of general data on 234U and natural uranium isotopic composition

### *2.1. The uranium decay series and the isotopic composition of natural uranium*

Geologists are more familiar with the starting point of the story as geochronology based upon uranium decay is a well-known geo-chronometer.

About 4.5 billions years ago, amongst other elements forming its total mass, our planet inherited from the stars dust an initial inventory of two uranium isotopes: 238U and a smaller quantity of 235U. Both of them are radioactive and decay through an alpha emission mode at different rates. Their half-life is respectively 4.5 × billions years for 238U (about the age of the Earth), and 0.70 billion years for 235U.

Now (at the geological time frame), the content of natural (total) uranium (Fig.1) is respectively of 99.284 grams of 238U per 100 grams of total U, 0.711 grams of 235U per 100 grams of total U, and 0.0058 grams of 234U per 100 grams of total U.



> Normal current composition for secular equilibrium

% in total natural U = 99.2836
Half -life = 4.50 x $10^9$ y
Specific activity = 1.244 x $10^4$ Bq/g

% in total natural U = 0.7110
Half -life = 7.04 x $10^8$ y
Specific activity = 7.996 x $10^4$ Bq/g

% in total natural U = **0.0054**
Half -life = 2.48 x $10^5$ y
Specific activity = **2.300 x $10^8$ Bq/g**

% as total U mass percentage or g per 100 g

*FIG. 1. Natural uranium isotopic composition.*

The content of 234U in natural uranium results from the decay of 238U, which follows two previous decay steps (Fig. 2). The first one yields 234 Thorium, a natural radioelement having a rather short half-life of 24.1 days, and the second one leads to an even shorter-lived isotope, 234 Protactinium, having a half-life of only 6.6 hours, and decaying to 234U. It should be noted than the two last steps are a beta mode decay.

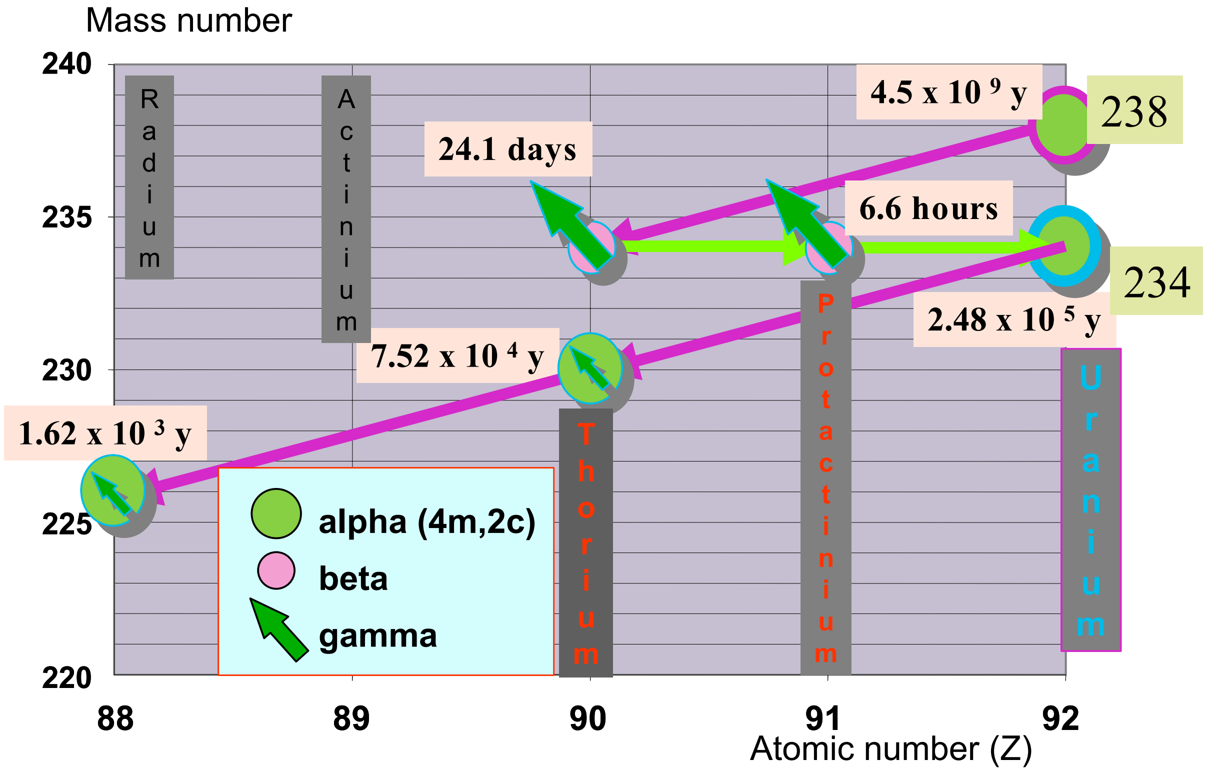


*FIG. 2. First steps of 238U decay chain.*

234U is the third and last member of the natural uranium isotopic spectrum. It decays through an alpha mode with a rather long half-life, 248 thousand years, in comparison with its precursors (234 Th and 234 Pa), but this half-life is very short by comparison with 238U. In its turn, 234U decays to 226 radium, a more familiar compound for geologists and environmentalists, as most of “natural uranium” radioactivity is linked to 226 Ra progeny.

Table I. Uranium composition under ASTM Standard Specification for commercial natural uranium hexafluoride for enrichment (ASTM C 787)

| Isotope | Content or Limit | Unit | Comment |
|---|---|---|---|
| 235U | C = 0.711 + –0.004 | g/100g total U | Natural isotope |
| 232U | L = 0.00001 | microgramme/g total U | Artificial isotope |
| 234U | L = 58.0 | idem | Natural isotope |
| 236U | L = 0.001 | idem | Artificial isotope |

Table II. 234U limits on uranium composition under ASTM Standard Specification for commercial grade uranium hexafluoride enriched to less than 5% 235U (ASTM C 996).

| Isotope | Limit | Unit | Comment |
|---|---|---|---|
| 234U | 10 000 | microgramme/g 235U | Standard limit |
| 234U | 11 000 | idem | Upper limit if agreed by commercial parties |

## 3. 234U content variability in natural uranium from mines

### *3.1. Variability in 234U content of natural uranium in ores and underground water* [Fig. 3]

In 1959, Rosholt was the first to publish data and analysis of uranium ore samples showing significant discrepancies with a reference isotopic content, including uranium isotopes and decay progeny.

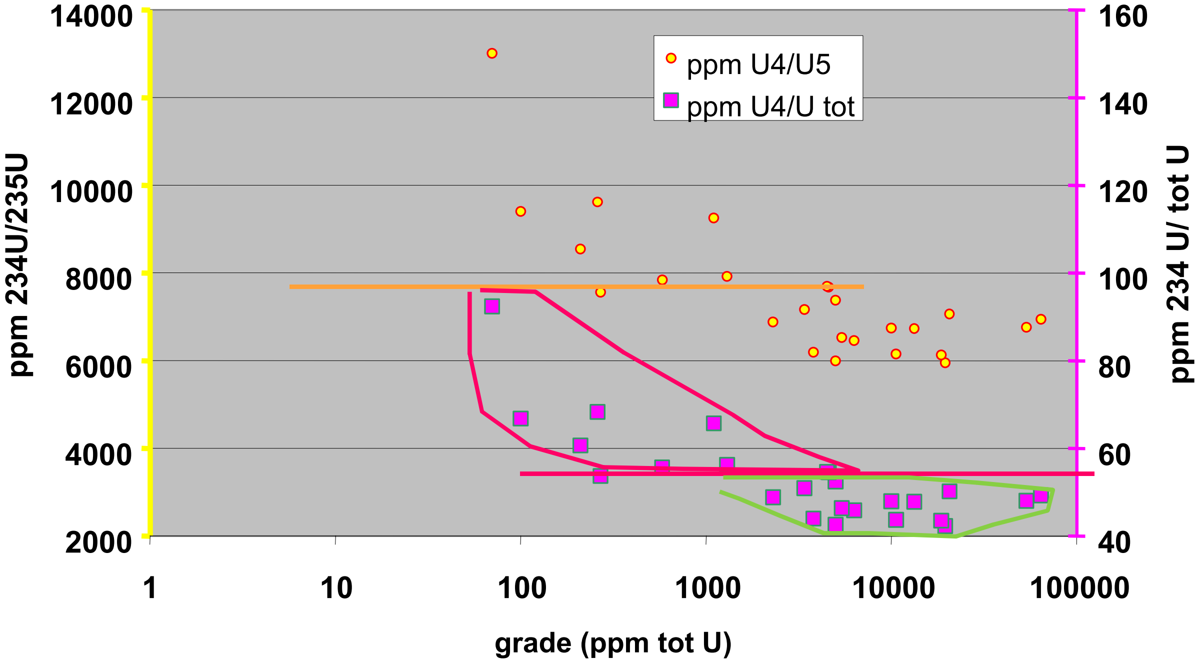


*FIG. 3. Variability in 234U content in ore samples (Shirley Basin, WY, USA).*

In 1964, [2] Rosholt et al. have shown that the so-called uranium roll type deposits in Wyoming are functioning in a way that could led to uranium "isotopic fractionation".

This fractionation was observed only for the 234U content, and the explanation was found within the decay chain of 238U, leading to 234U through short-lived compounds having a very different chemical behavior than U, and also by a possible selective leaching of 234U due to its special position in the crystal lattice or oxidation state, after 238U decays.

### *3.2. Causes of the 234U content variability*

Before discussing the causes, one can observe through various publications on the topic that almost all the circulating water on the planet, whether it is fresh water from streams and rivers, salt water from oceans, seas and oceanic currents, or underground water in aquifers, is more or less enriched in 234U by comparison with 238U, (Figure 4) [3].

This is obviously an explanation for relative enrichment in 234U when fresh mineralization is precipitated from this water content into uranium bearing minerals.

Of course, if the mineralization is "fossilized" and after about 10 times the 234U half-life (a few million years), this disequilibrium will vanish, but if the process continues, at least parts of the precipitation front will show high 234U content.

But one should understand why the water content is so often enriched in 234U, and if this can in some cases have consequences on solution mining operations.

The process is mainly due to the so-called alpha-recoil of 234 Th. When a 238 U nucleus decays, emitting an alpha particle, it receives an impetus corresponding to the energy of the alpha particle; a process very similar to the recoil of a gun.

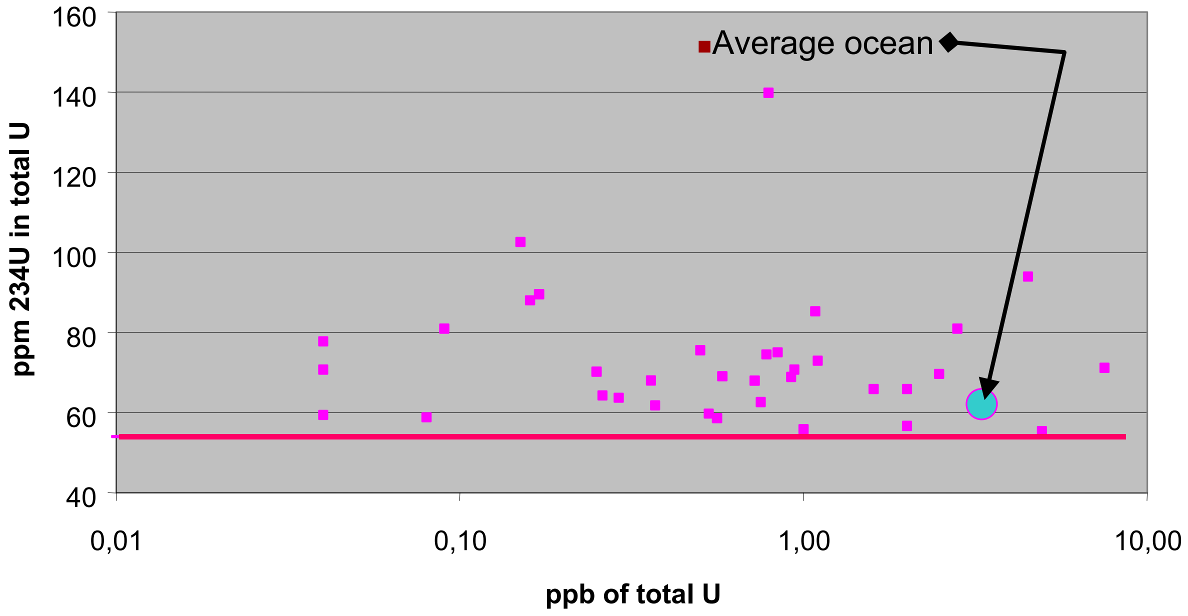


*FIG. 4. 234U content in surficial waters (rivers, oceanic water).*

The resulting 234 Th nucleus can be moved through its mineral-bearing lattice at a distance exceeding 500 angstroms. In some cases, when the decay occurs within this distance of the crystal surface, the 234 Th nucleus is expelled outside the crystal, possibly in the pore-water. The beta-decay mode of 234 Th and 234 Pa will help the resulting 234U nucleus to be part of an oxidized uranium atom [4,5].

In some cases, the alpha particle itself can create a channel in the crystal lattice, favoring the further leaching of 234U.

These elements are indicating that in the case of "sealed systems" isolated or fossilized for 2 millions years or more, the 234U/238U ratios will be the secular equilibrium. For open systems, this ratio will depart from this equilibrium.

One should ask a question: is solution mining opening somehow the system?

### *3.3. The ISL mining method and 234U variability in commercial concentrates*

*Solution mining: A completely different way of leaching uranium compounds*: During the leaching stages of the classical and widespread dynamic ore processing, the uranium bearing ore, previously crushed and milled is put in contact with extraction liquors in agitated tanks.

The size of the milled ore grains has been determined to optimize the extraction, and maximize the surface of uranium bearing minerals. The result is normally an almost complete dissolution of the uranium content, as shown by the very high rate of recovery (more than 80% and in many cases around 95%). In addition, the leaching-stage duration is typically a few hours. In such conditions, the isotopic composition is as close as possible to the isotopic composition of the in situ ore.

During the leaching stage of solution mining, water (not rock) is “mined”. The leaching solutions are replacing the normal water of the aquifer. The only changes are its chemical composition and its velocity in the open porosity. The uranium-bearing minerals are reached selectively, depending upon their position relative to the fluid pathway, and to their relative surface exposure. For example, a large uranium oxide crystal will be selectively less leached than a thin coating on sand grains. Thus, phenomena occurring at the surface of uranium bearing minerals are very likely to take an enhanced importance, especially through their dynamics during the leaching process. Contrasting with dynamic ore processing, in-situ leaching of a mineral grain has a typical duration of several days or even months.

*Solution mining: Only special types of ore bodies (called ISL amenable) are mined using this method*: Obviously, only permeable ore bodies are “ISL amenable”. This means that this kind of deposit shows intimate contacts between the uranium bearing minerals and pore water of the surrounding aquifer. This means also that ongoing interactions between the flowing aquifer and the uranium ore are likely to take place.

Furthermore, it has been shown [6] that in active roll-fronts, part of the ore-body is significantly departing from the secular equilibrium of 234U with 238U.

As a consequence, one might expect that, if a production wellfield is positioned on such a zone, batches of concentrates could have an excess content in 234U.

During the recent years, ISL has been represented a limited, but significant share of world production (Table III). Thus the problem must not be dismissed, even if the bulk of fresh uranium production shows a normal 234U content.

Table III. ISL share of world uranium production (data from OECD-IAEA Red Book 1999 & 2001).

| % of world production | 1995 | 1996 | 1997 | 1998 | 1999 | 2000 |
|---|---|---|---|---|---|---|
| ISL | | 13% | 13% | 13% | 17% | 15% |

## 4. Fuel-cycle problems caused by excess 234U

### *4.1. Reasons for the limit*

234U is a relatively active alpha emitter and as such represents a potential risk for internal contamination, especially by inhalation.

Its specific activity (bequerels per gram) is about 300 times the 235U figure and about 18 000 times the 238U specific activity.

Through existing isotopic enrichment processes (gaseous diffusion or centrifugation), 234U, an even lighter isotope than 235U, is concentrated in the product. For this reason, derived acceptable limits have been set under radioprotection regulations for the maximum content in enriched UO2 powder at fuel fabrication plants. The limit has been extended to enriched UF6 for acceptation by the fuel fabricators and for issuing transportation licenses. Derived limits for natural UF6 have been calculated and all these limits are part of the ASTM Standards (Tables I and II).

### *4.2. The enrichment process and 234U limits*

As mentioned above, the existing enrichment processes sort uranium isotopes by their atomic weight, and 234U reaches the head of the enrichment cascade faster than 235U does. For this reason, at a given tails assay, the content of the product in 234U relative to 235U increases with the product assay in 235U (Figure 5).

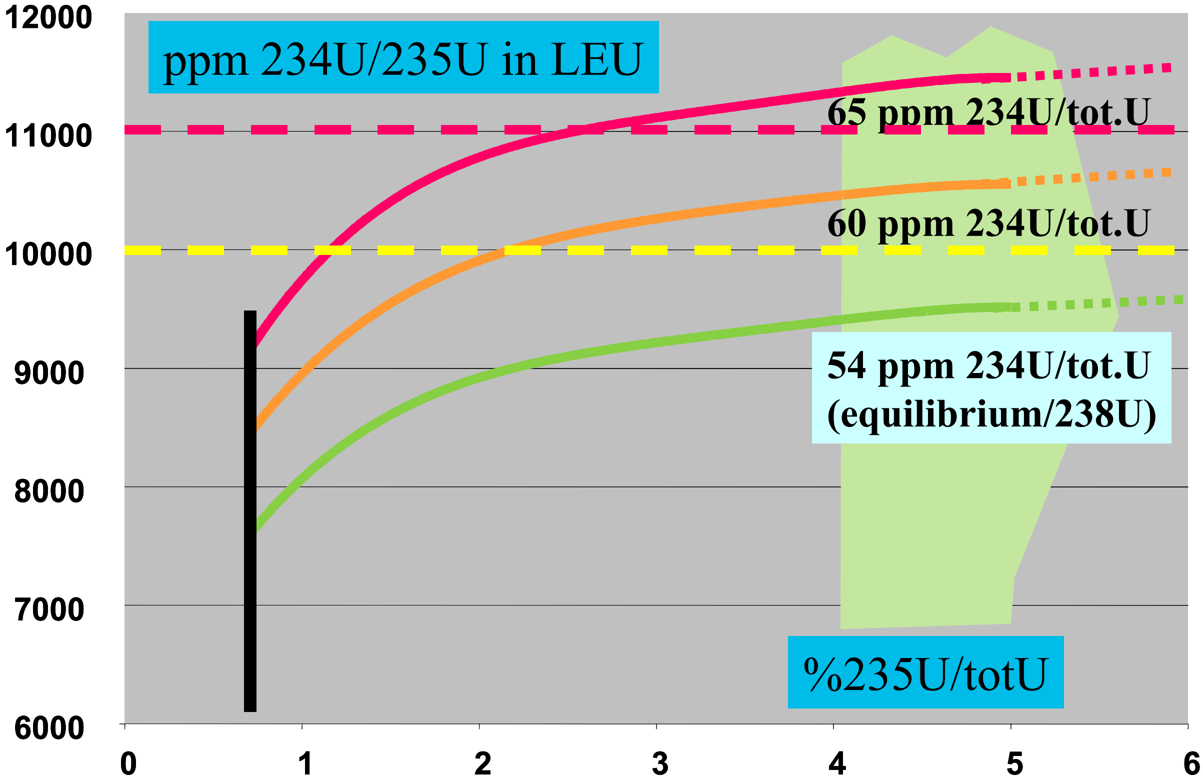


*FIG. 5. 234U ratio to 235U in LEU vs. 235 assay (at a given nw = 0.30% 235U).*

Obviously, should it be possible to reach a zero tails assay, the ratio of 234U to 235U in the product will be the same as in the feed material. It is thus understandable that this 234U to 235U ratio is declining with the tails assay, tending to the ratio of the feed when the tails assay tends to zero.

## 5. Conclusion

During the last decade, significant amounts of out of spec uranium concentrates have been shipped to conversion and enrichment plants. As 234U was not systematically measured before conversion, some enriched product batches where produced at higher than acceptable levels under the ASTM Standard, and had to be blended to overcome the problem, or even in some cases to be discarded and stored.

Now, enrichers and converters are alerted to the problem, and check the 234U content of shipments coming from mine sites or production areas having previously shown excess 234U content.

As ISL sources, mainly from Central Asia are becoming more and more important, and are likely to take a significant share of world production in the future, discussions have been launched during recent relevant ASTM meetings to try to increase the limits.

It seems that such an increase cannot be easily accepted by fuel fabricators, who have their own radioprotection constraints.

Various possible solutions are:

(a) Blending with in spec ores: not always possible for various commercial and safeguard regimes reasons
(b) Lower the tails assay: normally the choice of the tail assay is an economical optimization
(c) Try to find adaptations of the ISL mining methods to the problem.

The first two solutions are likely to initiate the implementation of 234U excess content financial penalties, as in the case for other undesirable elements.

The third solution is certainly promising, but implies a better knowledge of the solution mining intimate process, in order to plan several extraction fields in a timely manner, in order to produce a lower 234U content in the concentrates.

To date, this 234U problem can appear to be an issue of limited importance. However, this is likely to have an impact on the economic amount of ISL amenable reserves and resources.

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# HEAP LEACHING: IMPROVEMENT OF MILLING PROCESS

# Leaching method : Changes in Sierra Pintada Mine

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**Abstract.** Argentina has two Nuclear Power Plants (NPPs) working with natural and low enriched uranium, consuming nearly 120 tU/year. In the past CNEA exploited different uranium ore deposits in Argentina but now Sierra Pintada mine is the only one that remains opened. From 1979 to 1995 CNEA produced, by heap leaching, 1.000tU in yellowcake form in Sierra Pintada plant, to supply the fuel to Argentine NPPs. In the nineties due the lower price in the spot market and overvaluation of our currency, the uranium mine and yellowcake production plant were shut down. After the closure of the plant, the engineering group started to work on some different possibilities to lower the cost and improve leaching and waste treatment. At the beginning of 2002, Argentina currency was devaluated and this, reduced the domestic costs. Given this two conditions, nowadays we can produce yellowcake at a lower cost (nearly 20% less than the spot market) and at the same time treat the effluents to its final disposition.

## 1. Mineralogy

Quartz, Feldspar, Calcite, and Kaolinite are the most abundant minerals in the ore.The rock is formed by moderately well-sorted grains of quartz, feldspar, and rock fragments, all cemented by calcite with minor clay replacement.This mineral is a sandstone with high quantity of carbonates.

Uraninite, Brannerite and Coffinite were the only primary uranium minerals that have been clearly spotted. Uranophane and liebigite were the secondary uranium minerals found.

The usual sample of this mine contain the following elements:

| Element | % | Element | % |
|---|---|---|---|
| $U_30_8$ | 0.159 | P04 | 0.14 |
| Ca | 2.6 | $C0_3$ | 3.80 |
| Mg | 0.26 | Al | 4.22 |
| $Fe^{+2}$ | 1.4 | $V_2O_5$ | 0.02 |
| Fe(total) | 1.72 | Mo | <0.001 |
| S(total) | 0.017 | | |

## 2. Old mining parameters

Open pit with 0.025%U cut off.
8500tU reserves.
Waste /-mineral ratio: 10/1.
Average uranium contain: 0.076%.
Waste benches high: 10m.
Mineral benches high: 2.5m.

By now we have exploited:
13.400.000 $m^3$ of waste rock.
376.000t marginal mineral.
2.500.000t feeding plant mineral.

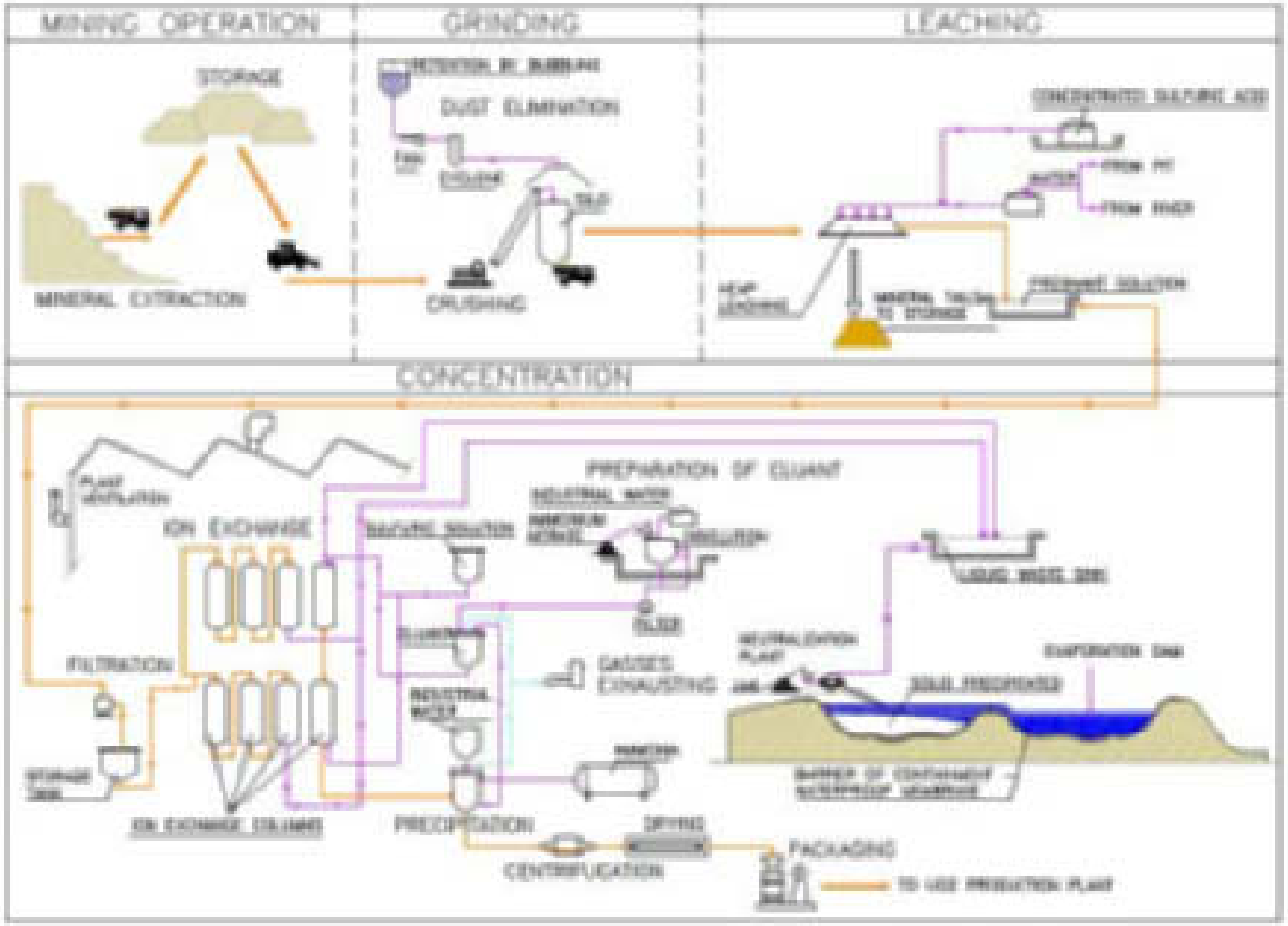

FIG. 1. Old concentration plant.

When the mineral arrived from the mine to the concentration plant, we had two different crushers with screens [Fig. 1]. The mineral flew from this stage with a maximum size of 50 mm. Afterwards, the acid was been used in heap leaching.

The uranium recovery was made by ion exchange in fixed bed columns. Then, we obtained the yellowcake with ammonia. This precipitated was hardened in a thickener and then centrifuged. After the centrifuging step, it was placed in a dryer with a steel belt and an electrical heater. At the end, this concentrated was packaged in 300Kg. drums to be sent to $UO_2$ plant, which is 700 Km far.

The liquid effluents were neutralized with lime and the slurry was set in natural dams. The clean liquids went to the evaporation dam, because we couldn't dump it to the river due to the high quantities of ammonium nitrates present in those liquids, while the solid effluents were put in temporary heaps.

In 1995 the plant was shut down. As a consequence to those changes which are mentioned at the beginning, we are now working in the next restart of the production. This restart is oriented basically to the environmental restitution during the operation.

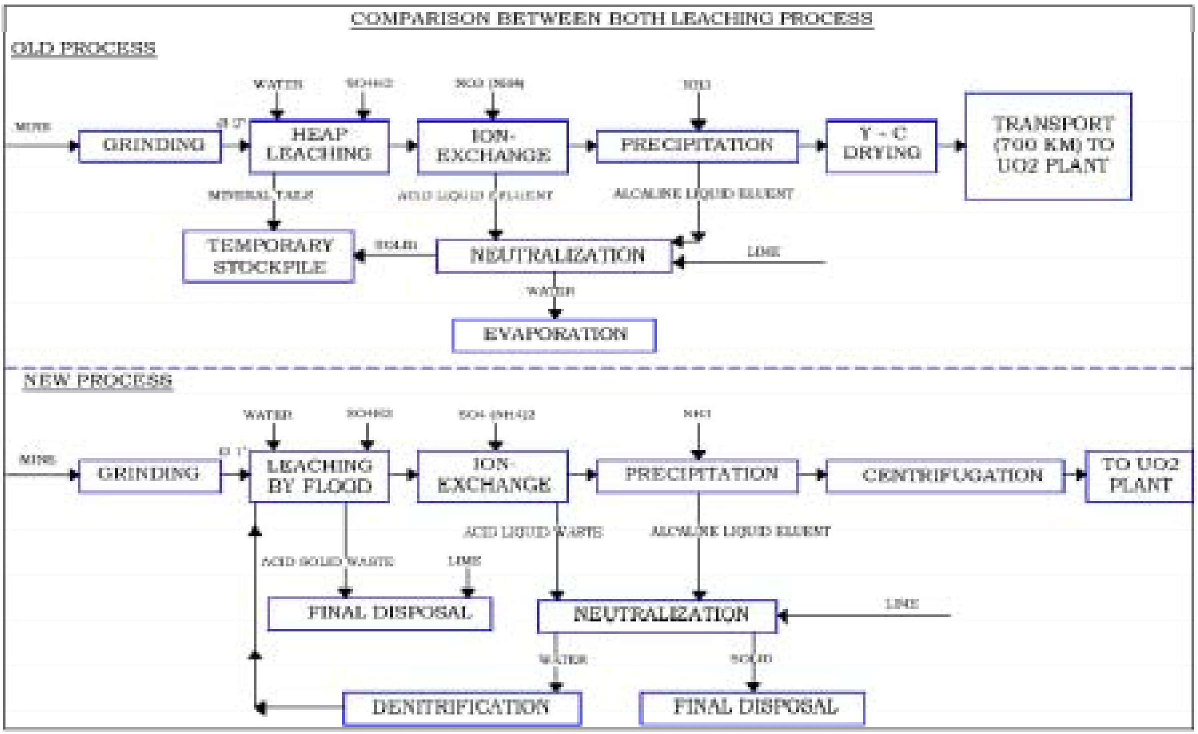

*FIG. 2. Changes in the process.*

## 3. **Ore processing** (Figs. 2 and 3)

In this new stage of production, the reserves were recalculated rising the cut-off and increasing the treatment plant feeding uranium contents from 0.9 to 1.8. kg U/t. With these new reserves, calculated in 2600 tU, this deposit can supply the two NPPs in operation during its entire life.

### *3.1. Size reducing*

In the past, the mineral that leaved the mine with a size of < 500mm was reduced in several stages until it was < 50mm to feed the heap leaching. This is the minimum size that the mineral can possibly reach without causing displacements in the slopes. In the new process, by flood, the size of mineral is reduced to a maximum of 25mm with which the time of leaching is reduced too.

### *3.2. Leaching*

Inside the plant, the main change was made in the leaching process. The new leaching will be by flooded mineral confined in sinks. The pilot plant assays show us very important advances in the new process. In order to reduce the investments we will have to excavate the old heap leaching places for the new flooded sinks. In this hole we will place a waterproof membrane and over this the mineral.

12 months of treatment were needed to reach an extraction of 80% with heap leaching. In the new process, the time of leaching is reduced by having the mineral confined in sinks, and by reducing the maximum size of particles. At the beginning of both process, the acid attack is made with sulfuric solutions between 30 and 50 grams per liter. Afterwards, the pH is maintained at 1.5. In the new process the redox potential is maintained with oxidation by air addition. In these conditions, within 3 months 90% of the extraction is obtained.

At the same time, we are making a lot of assays in bio-leaching with very good results. For example, it is possible to arrive to a 90% recovery in only two months, and also lessen the acid consumption.

Following these assumptions, at the beginning of 2003 we will begin a Technical Cooperation Project between IAEA and Atomic Energy Commission of Argentina. The goal of this project is to put in operation a bio-leaching pilot plant.

### *3.3. Ion exchange*

The purifying of uranium contained in the leached solutions is made in fixed bed columns. The fixed bed columns are grouped in two lines of three columns in series. In the past, with resin IRA400 (Rhom and Hass), the elution was made with ammonium nitrate. Now we change the resin by IRA 99, and the elution will be with ammonium sulfate. In this case we can reuse the water without problems.

In the past, the sterile effluent of the columns was neutralized with lime and then sent to the evaporation dam, where the hasty solid was deposited. In, the new process, the sterile effluent joins the rest of the liquids for neutralization and treatment. Afterwards it is reused in the plant.

### *3.4. Precipitation*

It is made with amonia in two stages. In the first one, ammonia is added to some part of the eluted until the pH rise to 7. In the second one, the process continues by adding eluted solution and $NH_3$ at constant pH = 7. This part of the process was not modified.

### *3.5. Centrifugation, drying and packaging*

The most part of this process has been eliminated. The centrifugation part remained to diminish the water that accompanies the yellowcake. This is possible, since the plant of $U0_2$ production will be placed next to the concentration plant. This allows us not to have to dry the concentrate, an important source of environmental contamination.

## 4. Solid waste and effluents management

In the past, the solid waste of the $U0_2$ plant was stored in drums inside the piles of old treated mineral. The solid wastes were stored in temporary stockpiles and the liquids were neutralized and evaporated. In the new project there are three different sections for wastes treatment (Fig. 4).

### *4.1. Solid remains of the $UO_2$ plant*

The solid remains originated by the neutralization of different liquid effluents in the $U0_2$ plant, are washed repeatedly with water to eliminate nitrates. Soon these remains are dissolved in sulfuric acid. This solution is then sent to the ion exchange columns in order to recover the uranium in it. The solid surpluses are managed with the solid effluents of leaching.

### *4.2. Treatment of the pit water*

The water that flows naturally from the open pit, and accumulates, is loaded with uranium and radio. In order to be able to use it, the water will be decontaminated in a series of ion exchange columns to diminish the amount of uranium and radio. Then it is possible to use it for irrigation of pastures and green curtains. This process implies an important positive environmental impact given that the mine is placed in a semi-arid zone.

### *4.3. Treatment of new and old wastes coming from the concentration plant*

The old mud, coming from the neutralization of acid liquid effluents, is hardened by stuffing it with the sterile stones obtained from the mining. Over this solid substrate, successive solid acid waste and lime layers are added and compacted to neutralize it. Then this is covered with a clay barrier to avoid the contact with the rainwater. The liquid effluents of the plant are neutralized with lime to eliminate sulphates and ammonium. The new precipitated sulfates will be accumulated over a waterproof surface above the phreatic level. Then they are stuffed with sterile rocks from the mine, and over this, new solid acid effluents with lime, are deposited and compacted. Afterwards it will be covered with clay. The overflow liquids will be reused in the plant.

See the following Figure 3, Uranium production, new flow-sheet.

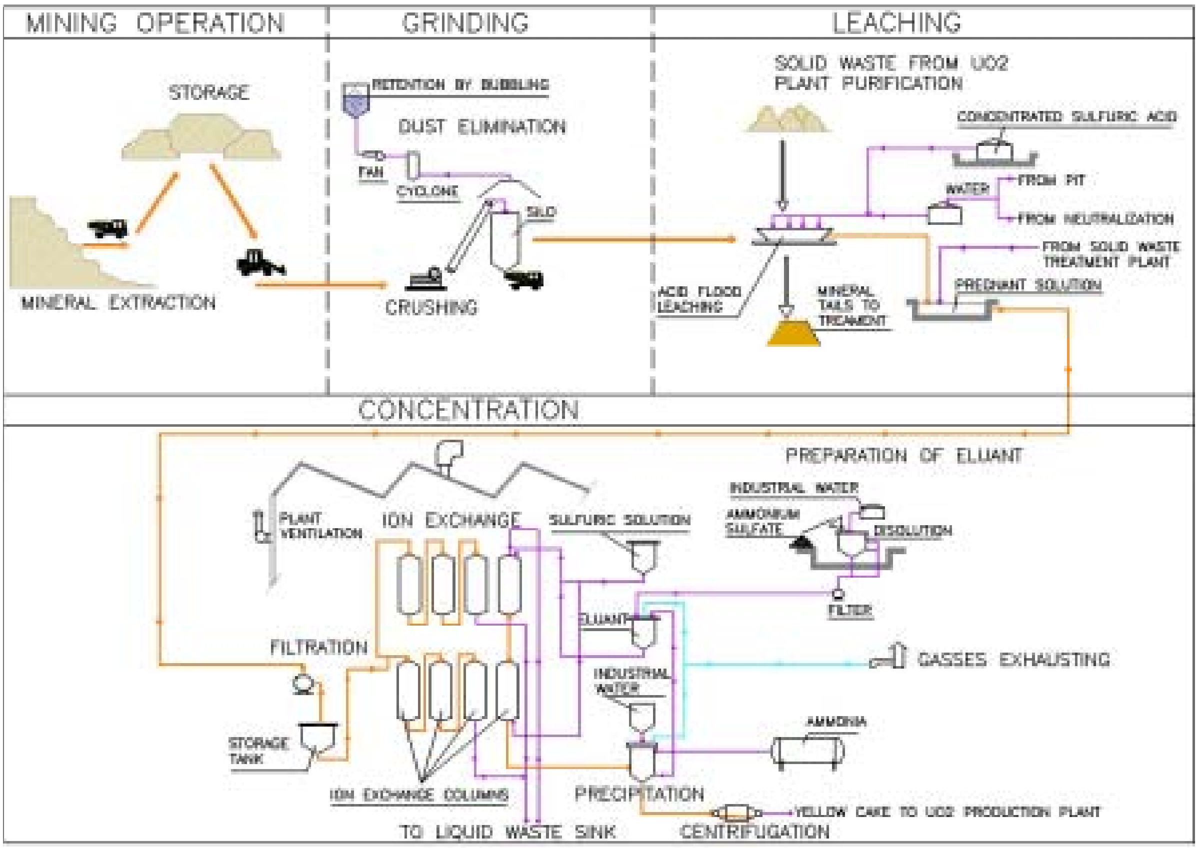

*FIG. 3. Uranium production, new flow-sheet.*

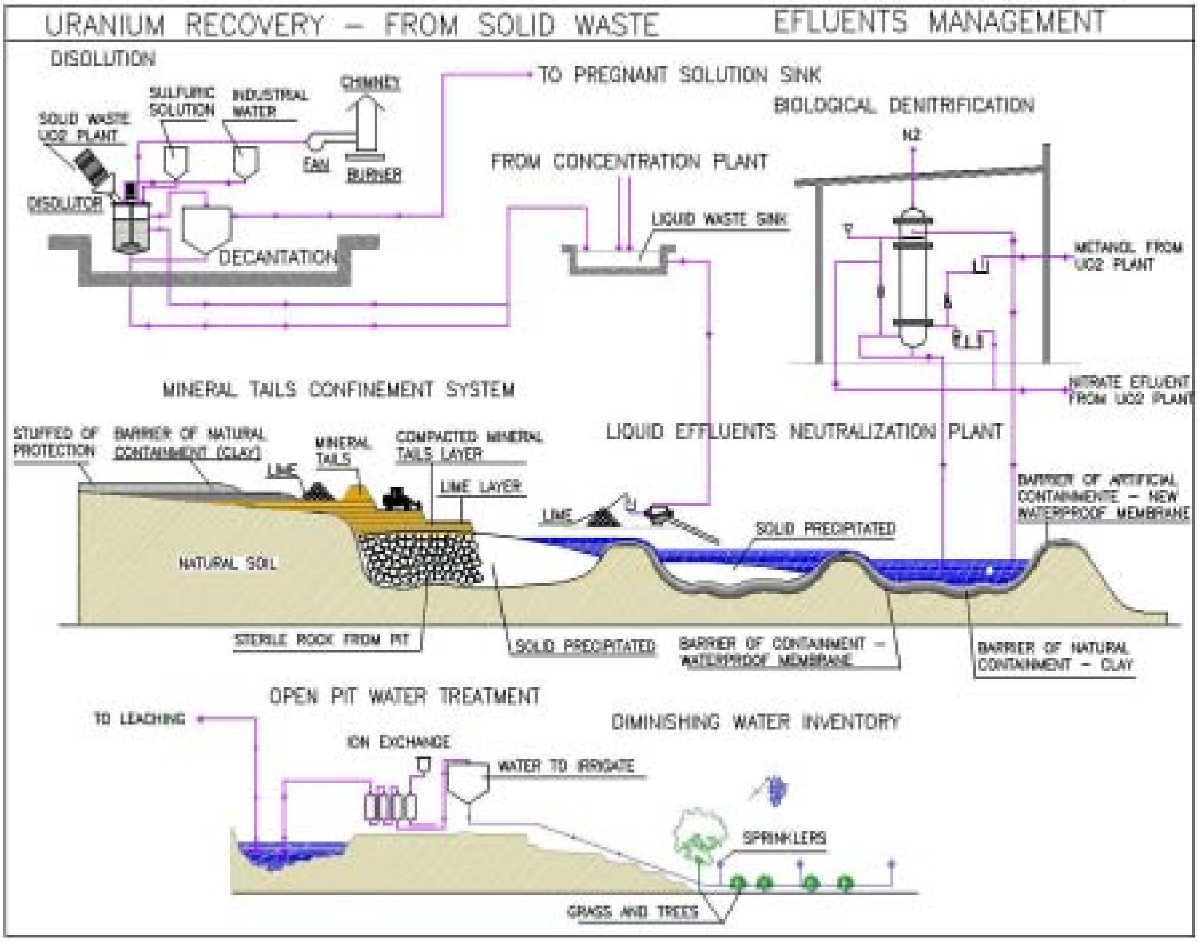

*FIG. 4. Solid waste and effluents management.*

# Influence of pelletization on uranium ores heap leaching

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**Abstract.** Experiments were conducted on two types of uranium ores to evaluate their processing by heap leach method. The ores were mineralogical and chemical characterized. The different uranium mineralogy and different matrices require different types of leaching agents, which, in these preliminary tests, were conventional acid and alkaline leach solution. The grain size analysis showed that both ores have a large amount (50-60%) of fines (<0,63mm) and, because the ores are friable, this percentage grows considerably after crushing. Tests of pelletization were performed using a lab pelletizer, in various conditions: amount of binder (soda-water glass, cement), water addition, mixing time and plate angle. Parallel experiments, simulating heap leaching, were conducted on columns filled with crushed ore and pelletized ore, by aspersing them with the leach aquifer. The solutions have been recycled, watching their uranium concentration in time, till a steady value. The experimental data shown in paper proved that pelletization aids the heap leach amenability, in these cases the ores leachability being increased by 10% when using pellets.

## 1. Introduction

Heap leaching is a method successfully used for values recovery, especially from low-grade ores, where it proved to be cost-efficient. In many cases, the ores characteristics do not allow direct heap leaching and some ore dressing methods were developed for a prior treatment, aiming to make the ore suitable. The pelletization process was theoretically founded by Tigerschiold in 1950, which stated that pellets are formed by congregating mineral particles around a center, while compressing. Under the cohesion forces of water molecules from particles surface, a strengthening occurs, along with the compression, resulting the so-called pellets. The factors that decide the success of pelletization process are: the ore characteristics (grain size, minerals, water content), the process parameters (stirring time, compression force applied) and the quality and amount of additives [1,2,3]. Samples of two types of uranium ores from Romania have been tested in order to settle their suitability to the heap leaching process.

## 2. Ores characterization

About 800 kg of ores were taken from the both mines. The samples were crushed in two steps using a jawbreaker and a roll crusher. Screen classifications were performed and average samples were analyzed from chemical and mineralogical viewpoint (Table I).

Table I. Chemical and mineralogical composition.

| Compound | Ore A | | Ore B | |
|---|---|---|---|---|
| | % | Minerals | % | Minerals |
| $SiO_2$ | 56.0 | Quartz, chlorite, garnets, biotite, feldspar | 56.0-75.0 | Quartzite, feldspar, biotite, chlorite, garnets, muscovite |
| $Al_2O_3$ | 14.0 | Feldspar, chlorite, biotite, muscovite | 3-12 | Feldspar, chlorite, biotite, muscovite |
| $Fe_2O_3$ | 1.6 | Pyrite, biotite, chlorite, garnet, apatite | 0.5-1.5 | Oxyhydroxide, pyrite, pyrotine, mispickel, biotite, chlorite, garnet, siderite |
| $P_2O_5$ | 0.2 | Apatite | -- | -- |
| S | 0.8 | Galena, blend, chalcopyrite, pyrite, sulfates | 0.5-1.6 | Pyrite, galena, blend, mispickel, sulfates |
| CaO | 7.6 | Carbonates | 3.0-6.5 | Calcite, sphen, apatite |
| MgO | -- | -- | 1.5-3.0 | Dolomite, chlorite, biotite, garnets |
| U | 0.4-0.5 | Pitchblende, bitumen | 0.10-0.15 | Uraninite, pitchblende |

Table II. Screen classification analyses.

| Grains size, mm | Ore A | | Ore B | |
|---|---|---|---|---|
| | V % | U % | V % | U % |
| +6.3 | 3 | 0.160 | 1 | 0.0305 |
| +2.0 | 19 | 0.605 | 23 | 0.024 |
| +1.6 | 12 | 0.712 | 9 | 0.133 |
| +0.8 | 17 | 0.802 | 23 | 0.097 |
| -0.8 | 49 | 0.419 | 44 | 0.092 |
| Total | 100 | 0.720 | 100 | 0.126 |

The difference between the uranium content of the rich ore is caused by the difficulty to obtain a real average sample. The large range of grain sizes and their different content of uranium (Table II) makes possible the radiometric classification followed by different processing methods, the in situ leaching of some sorts is to be tested as a part of a future flow-sheet.

## 3. Leaching tests

Preliminary tests of leaching of un-ground ores were conducted in stirring vessels with a 0.1 N solution of $H_2SO_4$ (Tables III and IV).

Table III. Leaching tests on grain classes (leaching time = 4 hours).

| Grain class, mm | U initial, % | U residual, % | Leaching yield, % |
|---|---|---|---|
| +20 | 0.03 | 0.02 | 33.3 |
| 10-20 | 0.05 | 0.03 | 40.0 |
| 6.3-10 | 0.35 | 0.20 | 42.9 |
| -6.3 | 0.40 | 0.20 | 50.0 |

Table IV. Leaching tests of –6.3 mm class.

| Leaching time, hours | U residual, % | Leaching yield, % |
|---|---|---|
| 4 | 0.20 | 50.0 |
| 6 | 0.13 | 67.5 |
| 18 | 0.095 | 76.2 |
| 24 | 0.090 | 77.5 |

## 4. Tests of pelletization

Both ores have a large content of fines (about 50-60% < 0.063 mm) that may render difficult the heap leaching process. That is why pellets are used in such cases to easy the flow of leaching agent and prevent the clogging.

For pelletizing tests a plate pelletizer was used. A successful pelletization (i.e. producing stable pellets resistant at compression but permeable in the same time) depends on material characteristics (minerals and grain sizes), amount of water and binders added and the pelletization parameters (in this case the duration of rolling and the plate angle). Table V shows the results obtained in different tests of pelletization of the crushed ore.

Table V. Pelletization tests on –6.3 mm class.

| Cement, kg/t | Aspersing solution | Plate angle, degrees | Pellets diameter, mm | Compressive strength, % broken |
|---|---|---|---|---|
| 10 | Water | 60 | 10 – 12 | 20 |
| 15 | Water | 60 | 30 – 40 | 40 |
| 100 | Soda water 5% | 80 | 10 – 15 | 0 |
| 150 | Soda water 5% | 80 | 10 – 15 | 0 |

The capacity of agglomeration and the characteristics of obtained pellets were watched during the experiments of pelletization using small quantities of binding material. Using 4–5 kg Portland cement or the same quantity of soda water conducted at pellets of poor quality. The chosen parameters of pelletization for obtaining the pellets for the leaching experiments were the following:

(a) Cement: 10 g/kg ore
(b) Soda water: 10 g/kg ore
(c) Water: 100 ml/kg ore
(d) Duration of homogenization: 3h/charge of 28-30 kg ore
(e) Duration of mixing in pelletizer: 5-7 minutes for cement and 8-10 minutes for soda water
(f) Plate angle: $46^\circ$
(g) Speed of rotation of plate: 20 – 25 rpm

The pellets obtained with Portland cement were more resistant from mechanical viewpoint (5–8% broken pellets) while with soda water this percentage rises to 12–15%. In the same time the pellets with cement have a good porosity. In both cases about 60% from the pellets have 6–10 mm diameter, 25% < 6 mm and 15% > 10 mm.

## 5. Heap leaching experiments

### *5.1. Acidic leaching*

Samples of crushed ore and pellets obtained as above-mentioned have been loaded in columns of 300 mm diameter and 1000 mm height for simulating the heap leaching conditions. The feeding with fresh solution and the recircuited ones was assured through the agency of 20 l reservoirs. Experiments of leaching were conducted discontinuously, in cycles of 5 hours/day, sampling of leach liquor after each 5 cycles. The ratio of ore (pellets) leaching solution was 3/1 and the aspersing flow = 285 $l/h.m^2$. The leach liquor was removed in three steps, figures 1 to 3 show the variation of uranium concentration during the leaching cycles. Uranium was recovered by direct precipitation as SDU and the ore and pellets washed, dried and analyzed.

*FIG. 1. Acidic leaching of ore A (step I )*

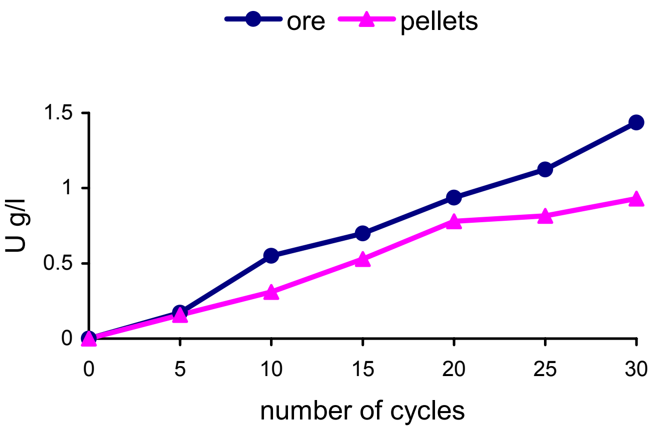


*FIG. 2. Acidic leaching of ore A (step II )*

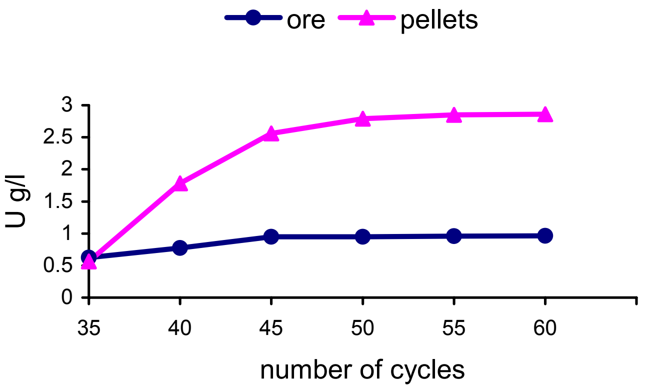
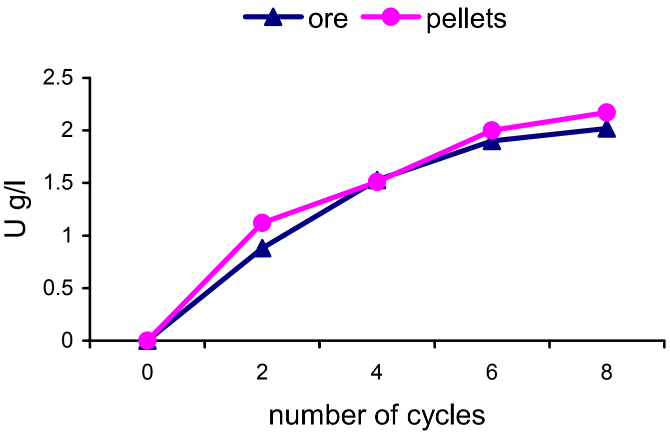


*FIG. 3. Acidic leaching of ore A (step III)*



### *5.2. Alkaline leaching*

The ore B has a significant content of carbonates and uranium is associated with sulfides, so the alkaline leaching is to be chosen.

Experiments of alkaline leaching were conducted in the same installation using pellets obtained in the following conditions:

(a) Uranium content in ore: 0.126%
(b) Cement: 100 g/kg ore
(c) Soda water: 120 ml solution 5%/kg ore
(d) Plate angle: 60°
(e) Pellets size: 10–30 mm

The leaching parameters were the following:

(a) Leaching solution: 10 g/l $Na_2CO_3$
(b) Aspersing flow: 5 l/h
(c) Duration of each cycle: 4 hours
(d) Ratio liquid/solid: 1/3
(e) Uranium concentration in leach liquor: 1g/l

Figures 4 to 6 show the variation of uranium content during the 3 steps of leaching.

*FIG.4. Alkaline leaching of ore B in pellets (step I)*

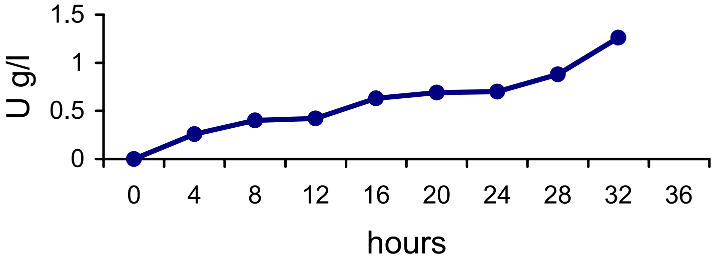
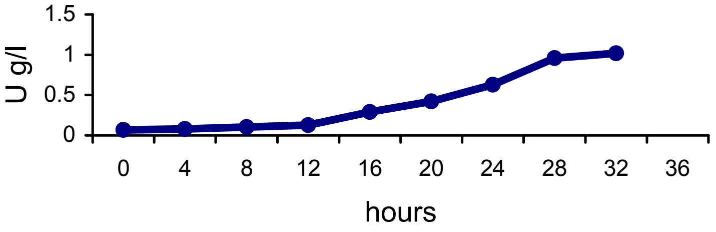


*FIG. 5. Alkaline leaching of ore B in pellets (step II)*



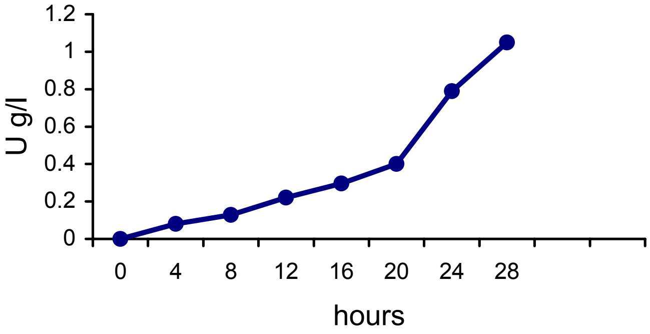


*FIG. 6. Alkaline leaching of ore B in pellets (step III)*

Uranium from the leach liquors was recovered by ion exchange on columns filled with resin. The leached pellets were washed, dried and analyzed.

## 6. Conclusions

(a) The large range of grain sizes of the tested ores allows the radiometric classification, this operation being of significance especially for the ore A.

(b) The major amount of uranium is included in fines (< 0.63mm), which represents more than half of ore quantity.

(c) For an in situ leaching method the large content of fines would hinder the leaching process and the pelletization proved to be a valuable method.

(d) The experiments showed that both ores can be processed by static leaching, the ore agglomeration by pelletization prior leaching showing several advantages as follows:

- Increases the recovery yield with 10-12%;
- Clearer solutions are obtained, which may be further processed without any other operations of settling or filtration;
- The residual content of uranium is smaller;
- The specific consumption of reagents is decreased.

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# An overview of technological progresses in China’s natural uranium industry

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**Abstract.** Due to the particular distribution of uranium resources in China, technological processes employed for natural uranium production in the country include four categories: in situ leaching (ISL), heap leaching, stope/block leaching and conventional leaching. In addition, a percolation-leaching project is being under construction. Although ISL has been given priority in China’s natural uranium strategy, the majority of natural uranium product comes from heap leaching of hard-rock uranium ores since mid-1980s. This paper summarizes the technical progresses and commercial application of the leaching processes and their supporting techniques, with emphasis placed on the research achievements and technical progresses in heap leaching of hard-rock uranium ores. In accordance with the actual status of uranium reserves in China, primary prediction and assessment are presented upon the developing perspective and applicable expectation of various uranium extraction technologies.

**Keywords:** China, uranium, heap leaching, in situ leaching, progress.

## 1. Introduction

China’s uranium mining and metallurgy industry, officially established in 1958, has been undertaking the responsibility to supply natural uranium for the country since. Its operation scopes involve uranium mining, uranium extraction and purification and uranium oxides production as well as associated work including uranium mine and mill design, mechanical processing, radioactive protection and environmental evaluation, mine and mill decommissioning, and so on. The main products at present are ammonium diuranate, ammonium uranyl tricarbonate, uranium peroxide, triuranium octoxide and uranium dioxide.

China has a wide distribution in uranium resources. Uranium deposits with commercial value have been discovered in almost all provinces and autonomous regions, able to meet the requirements for mid-term development of China’s nuclear industry. The uranium minerals explored so far in China, based on the host rocks, can be classified to following main categories: granite, volcanic rock, sandstone, moissanite mudstone, carbonate, quartzite and uranium-bearing coal types. Generally speaking, uranium minerals in China have the features of diversity in type, low grade and varied paragenetic elements. In the early stage of uranium hydrometallurgical history, all the uranium ores were processed by means of conventional process: ore grinding-agitated leaching-solid/liquid separation-enriching and purification. Because of the poor leaching selectivity and complicated flow-sheet with conventional process, which resulted in lower overall recovery upon uranium resources, high extraction cost and poor repayment, and for the sake of some deposits gradually being used up, authorities of China nuclear industry shut up in succession part of uranium mining and milling projects in the late 1980s and early 1990s.

Considering the uranium resources' actuality in China, Chinese technical personnel commenced the research and development on low investment and low cost uranium extraction methods like ISL and heap leaching (including in place stope leaching of blasted ores and percolation leaching) from 1970s. As a result of a few decades' effort, technical achievements in various aspects have been made, with most of them already well applied in commercial production. Up to now, China's uranium mining and metallurgy industry has developed to a new structural system in which in situ leaching and heap leaching (including stope leaching) dominate the uranium production while conventional process is on a subordinate place. Besides, a new-style percolation leaching project is under construction, which is expected to put into use within this year.

## 2. Technical achievements in uranium heap leaching

Of the proved uranium ore reserves in China, hard-rock minerals of low uranium grade, mainly located in southern China and suitable for heap leaching, take a relatively large proportion. Technological study on heap leaching of uranium ores has been emphasized in the past two decades and many academic breakthroughs have been made and already applied in production, bringing about significant benefit for the uranium mining and metallurgy industry in China. At present, heap leaching of uranium ores is the main technological process for natural uranium production.

### *2.1. Stope leaching of blasted ore*

For uranium deposits of low grade (e.g. U<0.1%) and not fit to in situ leach mining due to the hydrological and geological conditions, application of conventional underground mining and consequent surface treatment also would not be economical. Quan Aiguo, Li Yu, etc from Research Institute of Uranium Mining (RIUM) under CNNC have developed a technique of stope leaching of blasted ore through referring foreign experiences in the field of nonferrous metallurgy. Prior to applying this technique, an appropriate proportion of ore in an orebody must be mined out to surface to allow a compensating room. Then extrusive blasting is conducted, accomplishing the ore breaking and heap making at the same time as the ore is blasted down. This technique has been applied successfully in several low-grade ore deposits and in some residual orebodies of stoped mines. As most of the ore is treated underground, the production cost decreases greatly, and furthermore, radioactive contamination to the surface is alleviated.

### *2.2. Acid curing-ferric heap leaching*

Acid curing–ferric heap leaching, developed by Jin Suoqing and Xiang Qingfang, etc. from Beijing Research Institute of Chemical Engineering and Metallurgy (BRICEM), CNNC, is an intensified heap leaching technique. The ore is first crushed and pretreated through concentrate acid curing, converting most of the ferrous to ferric and uranium to soluble state. Then the cured ore is leached with water only. Data from years of commercial production show that the leaching period decreases to 60-100 days and uranium concentration in leach liquor reaches as high as 7-9g/L using this process.

### *2.3. Conglomerated heap leaching of poor permeable ores*

Conglomerated acid heap leaching of ores with low permeability has been a technically difficult problem in hydrometallurgical field. Zeng Yijun, Li Jianhua, Li Tieqiu, etc. from RIUM, through years of exploratory study and test work, have put forward a new concept for acid agglomeration describing that the strength of ball pellets can be kept stable by means of chemical binding. Accordingly, a series of new binders have been developed. These binders take a part in chemical reaction during pelletizing and leaching, forming a crystal structure net inside the pellets on the basis of crystal nucleus of formed hydrates so as to reinforce the operational strength of ore pellets. Acid agglomerated heap leaching has been successfully applied in commercial production for a clay-bearing uranium ore at Wenyuan Uranium Project in Guangdong. 95% of uranium extraction was achieved with this method. The leaching period can be reduced by 70% and uranium concentration in leach liquor increased by 50% while compared with direct heap leaching.

### *2.4. Heap leaching with small sized ores*

As an old hydrometallurgical technique, heap leaching has ever since been used as an auxiliary means for values recovery from low grade or even cut-off ores. Coarse sized ore leaching, long leaching duration and low recovery were considered inherent characteristics to heap leaching. Having conducted embedded studies on mass transfer mechanism and leaching behavior of heap leaching of uranium ores, Zhong Pingru, Li Cunkui and Li Shangyuan of RIUM developed a concept of small sized heap leaching, concluding that optimum particle sizes for heap leaching of various ores differ but are smaller than the employed decades since. And based on results of sufficient testing work, a math model was developed to decide the optimum economical size for particular ore heap leaching. Up to now, heap leaching with small sized ores has been employed by most of heap leaching projects in China.

### *2.5. Serial heap leaching*

In order to increase uranium strength of leach liquor and reduce reagent consumption, Chen Mingyang, Xiang Qiulin, Chen Xiangbiao, etc. from RIUM have conducted a systematic experimental study on serial countercurrent heap leaching, developing a theoretical model to enumerate operational parameters in different stages of serial heap leaching. It is shown from the operational results of some commercial projects applying this technique that the uranium concentration of leach liquor increases as much as 2-3 times and consumption of acid and oxidant in leaching stage and other reagents in recovery stage decrease by 20-30%.

### *2.6. Bacterial heap leaching*

In China, technological study on bacterial heap leaching of uranium ores started in 1960s. Ferrous thiobacillus was mainly used to oxidize the ferrous in pyrite or in barren solution into ferric which then converts quadrivalent uranium to soluble hexavalence. Deng Shunqin, Fan Baotuan, etc. of BRICEM have made some academic achievements in selection of bacteria species, acclimatization and continuous bio-membrane oxidizing device. A commercial test of bacterial heap leaching at Ganzhou Uranium Mine has been completed. The test results indicate that compared with the operation using normal chemical oxidant, the heap leaching with bacteria gives a drop in acid dosage by 12.5% and in leaching time by 32-45%, and a rise in uranium concentration of leach liquor by 88.2%.

### *2.7. Heap leaching of U/Mo paragenetic minerals*

Of the proved uranium reserves in China, a considerable part is uranium/molybdenum paragenetic minerals. Long leaching time, low molybdenum recovery and poor U/Mo separation are usually resulted from this type of minerals' heap leaching. Meng Jin, Niu Yuqing, etc. of BRICEM employed acid curing and activated leaching techniques in heap leaching of these minerals, resulting in a 50% of shrink in leaching time and 90% and 70% of uranium and molybdenum extractions respectively. Uranium and molybdenum in leach liquor are adsorbed simultaneously with a newly developed resin. Uranium and molybdenum in loaded resin are then fractionally stripped and the U/Mo separation coefficient reaches over 2000. This research fruit is now being prepared for commercial spread and application.

### *2.8. Percolation leaching of uranium ores*

Percolation leaching can be classified into heap leaching category in accordance with leaching mechanism. During heap leaching of uranium ores (e.g., volcanic rock type) containing iron, magnesium, calcium, aluminum, etc, the acidity of lixiviant is consumed rapidly as the leachant passing down the ore heap, and distinctive concentration gradients of uranium and other ions occur. This causes impurities like Fe, Mg, Ca, Al undergo repeatedly a process of migration-buildup-precipitation inside the heap, resulting in scaling and permeability drop. Because the liquid/solid contact mode in percolation leaching differs from that in heap leaching, the acidity of solution inside the ore pile remains comparatively stable and unique, and this can avoid from the formation of scaling. A commercial test of percolation leaching at Fuzhou Uranium Project has been fulfilled and the test results show that leaching time decreases from 300 days to 60 days and uranium extraction increases from 60% to 90% with the heap leaching being replaced by percolation leaching. Now a percolation leaching project with a capacity of 200 tons U/a is at the end stage of construction and is expected to put into production within this year.

## 3. Technical progresses in ISL

The research work on uranium ISL in China began in 1970. Long-term investigative tests were conducted respectively in southern and northeastern China early or late. A small-scale instructive ISL project was established in 1991. And the first commercial ISL project with capacity of 100 tons uranium per year was built at Yili, Xinjiang autonomous region in 1998.

In China, sandstone uranium deposits amenable to ISL have particular conditions at large, such as small deposit, low grade, poor permeability and complicated mineralogenetic environment. In their decades' exploratory research and test, Chinese engineers took the foreign advanced experiences in uranium ISL for reference and made some innovations. The use of outer annulus framework screen instead of formerly used net-wrapped screen prolonged the screen service life and boosted injection and drawing capacity. The innovation in screen installation manner led to the solution of screen clogging problem. The application of foam washing technique can deal with deep well washing. Technical progresses were also made in well drilling and sealing. Technical breakthroughs have been acquired in utilizing microorganism and nitrate in barren liquor as oxidizers, though hydrogen peroxide is still the main oxidant in ISL practice. The trial run results indicate that oxidant cost can be reduced significantly with nitrate in circulated raffinate or bacteria partly replacing $H_2O_2$ as ISL oxidizer. Remarkable work has also been accomplished in automatic monitoring and controlling of well field facilities. Flow-rate, pressure, pH and Eh of solution passing injection, compressed air and pumping pipes are measured and the start/close of submergible pumps is controlled automatically. Liquid levels of head tank, composite pond and make-up pond are also monitored offhand. These are fulfilled through the application of German-made automatic monitoring software Win CC and programmed controller. Practicality-oriented computer software mating the ISL technological development, such as leaching scope simulation system, expert system for in situ leach evaluation of uranium deposit information system of in situ leach technology, has been well developed and is playing an important role in commercial production.

Generally speaking, China’s ISL technology has been established on its particular uranium reserves. Up to the present, a complete technical system of uranium ISL with Chinese characteristics has been developed.

## 4. Some other progresses in uranium recovery

Along with the main technological processes, some efficient and practical new processes, techniques and materials have been developed and they are playing an important role in improving resources utilization, reducing production cost and alleviating radioactive impact to environment.

### *4.1. Heap leaching with zero discharge of process wastewater*

A uranium extraction technique with no process wastewater discharge has been developed by BRICEM. This technique is suited to acid heap leaching-ion exchange-precipitation circuit. Completely closed circulation of process solution is accomplished through alkaline elution and uranium precipitation, implementing the zero draining of process waste. This method brings about not only the pollution alleviation to the furthest extent and waste treatment cost reduction, but also the simplification of uranium precipitation circuit and improvement of uranium product quality.

### *4.2. Precipitating uranium directly from concentrated leach liquor*

Higher uranium concentration leach liquor can be obtained through serial heap leaching of uranium ores. For instance, around 6 g/L of uranium strength can be obtained in more than 70% of product leach liquor when ore with 0.2-0.3% of uranium grade is used. This kind of concentrated leach liquor needs not to be enriched and suits to direct precipitation. Zeng Yijun, Li Jianhua, Li Shangyuan, etc of RIUM have developed a novel fractional precipitation process to recover uranium from higher concentration leach liquor. Simplified flow-sheet, less reagent consumption and good product quality has been achieved with application of the technique.

### *4.3. Activated heap leaching technique*

Since 1994, BRICEM has conducted investigation on activated heap leaching technique, which could improve the ore and leachant surface physical properties and increase leaching efficiency, and developed an activator for exclusive use in heap leaching. This activator has many favorable features such as, well designed structure, easy to install, durable, power free and no need for specific service and is getting well applied. The leachant is activated as flowing pass the activator and its surface properties get improved, so as to boost the uranium leaching extraction and shorten leaching duration. The activator's commercial use shows that uranium extraction increases by around 10% and leaching duration decreases by 30% or more while compared with normal heap leaching.

### *4.4. New resin for uranium recovery from high chloride-bearing leach liquor*

SLD-225b resin is a particular chloride-resistant resin. It can effectively adsorb uranium from leach liquor with chloride strength up to 12 g/L, while comparatively high operational capacity and mechanical strength are ensured. This resin was once used in a pilot ISL test where the resin operational capacity achieved above 90 mg U/g (dry) upon conditions of chloride >3 g/L and total dissolved solid >10 g/L, with other property indexes kept satisfactory.

## 5. Development trends of uranium mining and metallurgy in China

It is not doubted that the development of ISL technology will be preferred in uranium mining and metallurgical industry in China, due to its low capital cost, low operating cost, as well as relatively slight pollution. Since 1980s, the focus in the field of uranium exploration has been put on the sandstone uranium deposits amenable to ISL, and great achievements have been attained. However, as a whole, the sandstone uranium deposits suiting for ISL are comparatively scant in China, and furthermore their developing conditions are unfavorable. Therefore, heap leaching of hard rock uranium ores will still stand a leading position in the production of uranium in the near future. The emphasis of study on ISL and heap leaching techniques in the coming years will be put on the following aspects, based on the present status of explored uranium reserves.

(a) Study on ISL for the deposits with poor permeability and/or thin thickness. For the sandstone uranium deposits occurred in ancient riverway, uranium mineral in the flank part of the deposit stands for a certain proportion to the full orebody. Comparing with the front-roll, the flank part usually presents small thickness, high content of clay near the lower base and poor permeability. Hence, they could not be profitably processed by conventional ISL technique. Up to the present, the front-rolls of some ISL deposits have been exploited over. That how to extract economically uranium in flank part and how to recover more uranium as possible is urgent task.

(b) Study on ISL for the deposits occurred in aquifer with high content of calcium and high mineralized degree. A new sandstone uranium deposit was lately discovered, where uranium reserves achieves thousands of tons, featured by high content of calcium and staunch mudstone layer. The total dissolved solid in the ground water is more than 10g/L, of which $Cl^-$, $SO_4^{2-}$, $Ca^{2+}$ etc present high strengths. That how to extract uranium from reserves in such a highly mineralized aquifer by ISL technique requires experimental work in-depth.

(c) Study on alkaline ISL and neutral ISL. A new sandstone uranium occurrence zone was recently found in China, and most of its deposits have high content of carbonate so as not to suit for acid ISL. The present alkaline ISL technique is also not applicable to the occurrence, due to its complicated geological and hydro-geological conditions. In order to make use of these uranium resources, researchers have to probe into new alkaline ISL and neutral ISL technologies.

(d) Study on alkaline heap leaching of carbonate uranium ores. Carbonate uranium reserves hold a definite proportion to the uranium reserves of hard rock type. These carbonate uranium ores were processed by conventional stirring leaching flow-sheet in the past, and now are laid off because of the shut-down of those conventional uranium mills. For the purpose of making full use of these uranium reserves, it is urgent to develop alkaline heap leaching technique.

(e) Following are the key research subjects in the future for uranium mining and metallurgical industry in China: bacterial ISL technique, restoration of ISL ground water, further automatization of practical operation, comprehensive use of the associated elements, micro-wave activated leaching technique, re-filling of heap leaching tailings, ISL for blasted orebody, a variety of new ion exchange resin and solvent extracting reagents, light movable apparatus mating with ISL and heap leaching.

# Application of agglomerated acid heap leaching of clay-bearing uranium ore in China

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**Abstract.** The permeability of ore mass has a great influence on the leaching period of heap leaching and the leaching efficiency, hence the uranium ores with high content of clay present a significant difficulty to acidic heap leaching. The Research Institute of Uranium Mining has engaged over years of studies on the cementing agents of acidic agglomeration, agglomeration method, as well as the curing measures of pelletted balls. On the basis of these studies, several types of clay-bearing ores have been tested with good results. The technique of agglomerated acid heap leaching has been successfully applied in a uranium mine. Since agglomeration has effectively increased the permeability of ore mass, its leaching period is decreased from 200 days to 60 days, the leaching efficiency from less than 40% up to 96%, comparing with direct heap leaching programme.

**Key words**: Permeability, uranium ore, acid heap leaching, agglomeration, application.

## 1. Introduction

The permeability of ore mass is usually poor for ores with high content of clay. Until the end of 1980s, specialists considered that these ores were not suited to be processed by acidic heap leaching. Therefore a great number of uranium presenting in clay-bearing ores has to be excluded for heap leaching.

There are many types of exploited uranium resources in China, of which the uranium reserves that could not be treated in direct heap leaching due to their high content of clay and low permeability stand 30%. These uranium ores were usually processed by conventional stirring technique, which lead to shortcomings such as complicated flow sheets, high consumption of energy and high consumption of materials, further bringing high operating cost to those uranium plant.

Agglomeration is one of the most effective measures to improve the permeability of ore mass. Through adding cementing agent and wetting solution, fine particles bind with skeleton particles by rolling movement and ball up, hence the physical characteristics of ores mass (such as density, porosity, appearance, size distribution and mechanic robustness), or their chemical characteristics (such as chemical composition, oxidation-reduction state), are changed. Pelleting raises not only the permeability of ore mass, but also prevents ore particles from segregating in the process of heap-building, latter makes the solution penetrating evenly different areas of the same heap. Intensive leaching approaches can be realized by adding lixiviant and/or oxidant when agglomerating, which will speed up leaching reaction, shorten down the leaching period, increase recovery rate, reduce consumption and operating cost.

The technical study work on agglomerated heap leaching was initiated by 1980s in China. At the beginning, it focused on alkaline heap leaching, and acquired success soon. Agglomerated alkaline heap leaching is widely used to extract gold from roasting tailings of sulfuric acid and clay-bearing copper oxide ores etc. By the end of 1980s, as a pioneer in China, The Research Institute of Uranium Mining (RIUM) began to study agglomerated heap leaching in acidic conditions. In agglomerated alkaline heap leaching, fine particles bind with their skeleton by physical forces, namely electrostatic attraction and Van-de-wael force. However, in agglomerated acid heap leaching, except the mentioned physical forces, the combination of ore particles is accomplished by chemical reactions. The cementing agent reacts with ores, produces hydrous compounds, and forms binding networks in single ball. These hydrous compounds networks enhance greatly the cementing strength of pelleted balls, so as not to break in the process of leaching.

By years experiment, The Research Institute of Uranium Mining has successfully developed series products of the cementing agent used in agglomerated acid heap leaching, held related technology and processing parameters in the field of pelleting, curing measures of ball, leaching operation. Up to now, the technique of agglomerated acid heap leaching has been successfully applied to treat 11 types of ores with poor permeability, including low grade nickel oxide ore, tailings of copper-cobalt ores, cracked granite uranium ore, uranium ore with flake mica, kaolin cementation uranium ore, slaty copper ore etc.

## 2. Conditional test

### *2.1. Experimental method*

Test on the characteristics of ores: it consists of sampling and preparing of ore samples, screen analysis, mineralogical determination, chemical analysis, as well as bench scale leaching experiment. Bench scale leaching experiment is performed in the conditions of room temperature and L/S 2.5-5.0 to 1, by stirring 70% > –200 mesh ores. Residual is detected after two times pulping and washing. Washing liquor is mixed with leaching liquor, measured its volume, then taken detection.

Conditional test of agglomeration: agglomeration of ores is carried out in a stainless balling disc which dip angle is adjustable, speed 40r/min, dimension Φ 500mm. It is important to determine the leaching strength of pelleting ball. The determination methods include: particle size (Φ 5~40mm) determination, water-adsorbing capacity (about 20%) determination, compression test (compressive strength > 3N), soaking detection (wet strength determination), pit permeability test. A kind of “three stages determination” is adopted in the agglomeration of ores, in terms of agglomerated acid heap leaching. Put the pelleted ball into a transparent column, measure the number of balls, leaching by fresh water, then 20~30g/L acidic solution, finally 50~100g/L acidic solution. After each leaching stage, measure the number of unbroken balls, compare each figure with the original number. The percentage of unbroken balls to the original number means the leaching strength of pelleting ball.

Column test: make scale-up leaching experiments in columns in the chosen conditions. Not only the leaching strength of pelleting ball, but also the leaching parameters, is investigated by the column test.

Checking test: on the basis of column test, conduct multi-stages series column test with scale-up capacity, usually 1~5 tons ores. It aims to obtain some necessary data for the pilot plant, except checking further the leaching strength of pelleting ball.

### *2.2. Results of test*

The results of agglomerated acid heap leaching test are list in Table I, for the cracked and clayed granite uranium ore, uranium ore with flake mica, kaolin cementation uranium ore.

Table I. The results of agglomerated acid heap leaching test.

| No | Ore | Characteristics | Results |
|---|---|---|---|
| 1 | Kaolin cementation uranium ore | The percentage of particles smaller than –0.5mm in ore samples is 45% to 75%, its permeability fails to meet the demand of direct heap leaching. | Agglomeration improves obviously the permeability of ore mass. Leaching efficiency 95%, uranium grade in the leaching residual less than 0.02%, leaching period less than 30 days in column test, and less than 40 days in the scale-up multi-columns test. |
| 2 | Uranium ore with flake mica. | Ores occur in flake and/or powder, contain clay and clayed powder host rock, easy to agrillizing and caking. –0.5mm particles stand 35%. When processing by direct heap leaching, its permeability less than 10L/m$^2$.h, leaching period more than 6 months, uranium grade in tailings present great variability. | Comparing with direct heap leaching, agglomerated heap leaching increases the permeability more than 10 times. No apparent changes for the appearance and number of the pelleted ball. Leaching period less than 60 days, uranium grade in tailing less than 0.03%. |
| 3 | Cracked and clayed granite uranium ore. | Ores contain a large amount of clayed oxide debris, –0.3mm particles in the ores samples is about 30%. Its permeability fails to meet the demand of direct heap leaching. | Through crushing, classification, –0.3mm particle fraction is separated from the coarse fraction, and used in agglomerated acid heap leaching. Leaching efficiency more than 96%, leaching period less than 60 days, uranium grade in tailing less than 0.03%. |

## 3. Application

This paper introduces the application of agglomerated acid heap leaching to a kind of clayed and cracked granite uranium ores in Guangdong province, China. The clayed and cracked granite uranium ores were processed by conventional stirring technique in the past. Due to high investment, complicated flow sheets, high consumption of energy and materials, its operating cost were high. Afterwards, direct heap leaching test was carried out with less than 40% leaching efficiency through 200 days. It is thought that the failure stems from the poor permeability of ore mass.

### 3.1. *Characteristics of ore*

The permeability of ore mass after crushing into -5mm is shown as Table II, its particles distribution as Table III.

Table II. The permeability of ore mass.

| No | 1 | 2 | 3 |
|---|---|---|---|
| Particle size, mm | -5 | -5~+0.3 | -0.3 |
| Permeability, $L/m^2.h$ | 13.2 | >500 | ~ 0 |

Table III. The results of screen analysis.

| No | Particle size, mm | Percent in weight, % |
|---|---|---|
| 1 | -5.0~+2.0 | 33.86 |
| 2 | -2.0~+1.0 | 21.82 |
| 3 | -1.0~+0.3 | 14.28 |
| 4 | -0.3~+0.15 | 12.72 |
| 5 | -0.15 | 17.32 |
| Total | | 100.0 |

### 3.2. *Processing flow-sheet*

In order to decrease the tons of agglomerated ores, the ores are crushed into –5mm, then sieved and classified. The 0.3~5mm fraction is treated by direct heap leaching, while the -0.3mm fraction is dehydrated, agglomerated, and cured for heap leaching, which processing flow-sheet is briefed in Figure 1.

### 3.3. *Results*

The application of agglomerated acid heap leaching gives the results in Table IV, the uranium grade in the tailings in Table V, the permeability of ore mass changes as Figure 2 in the course of heap leaching.

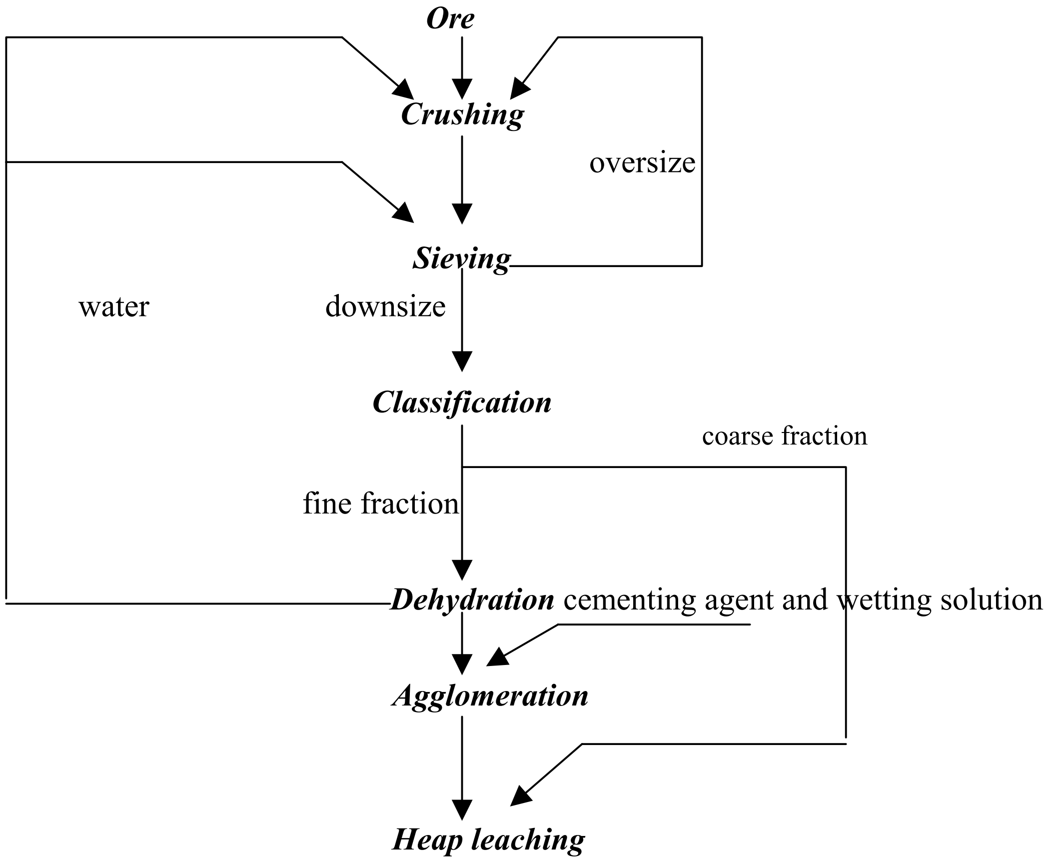

*FIG. 1. Processing flow-sheet.*

Table IV. Statistic results of agglomerated acid heap leaching.

| No | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|
| Leaching period, d | 53 | 56 | 55 | 58 | 53 |
| L/S | 2.27 | 2.25 | 2.28 | 2.27 | 2.26 |
| Uranium in pregnant solution, g/L | 8.30 | 8.05 | 9.70 | 9.52 | 9.30 |
| Acid consumption, Kg/t | | | 57.19 | | |
| Leaching efficiency (based on solution calculation), % | 99.80 | 99.79 | 99.83 | 99.84 | 99.83 |
| Uranium grade in tailing, % | 0.019 | 0.018 | 0.023 | 0.016 | 0.025 |
| Leaching efficiency (based on tailing calculation), % | 97.12 | 97.73 | 97.16 | 98.30 | 96.97 |

Table V. Uranium grade in tailing.

| No | | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| Upper heap | 1 | 0.012 | 0.011 | 0.017 | 0.012 | 0.015 |
| | 2 | 0.014 | 0.018 | 0.019 | 0.014 | 0.014 |
| | 3 | 0.020 | 0.019 | 0.015 | 0.018 | 0.022 |
| | 4 | 0.017 | 0.014 | 0.018 | 0.013 | 0.020 |
| | 5 | 0.016 | 0.018 | 0.016 | 0.013 | 0.023 |
| | Average | 0.016 | 0.016 | 0.017 | 0.014 | 0.019 |
| Middle heap | 1 | 0.015 | 0.014 | 0.027 | 0.020 | 0.035 |
| | 2 | 0.018 | 0.019 | 0.019 | 0.015 | 0.026 |
| | 3 | 0.023 | 0.021 | 0.022 | 0.011 | 0.025 |
| | 4 | 0.022 | 0.020 | 0.019 | 0.017 | 0.019 |
| | 5 | 0.018 | 0.016 | 0.028 | 0.017 | 0.030 |
| | Average | 0.019 | 0.018 | 0.023 | 0.016 | 0.027 |
| Under heap | 1 | 0.026 | 0.027 | 0.027 | 0.026 | 0.037 |
| | 2 | 0.017 | 0.014 | 0.036 | 0.020 | 0.035 |
| | 3 | 0.025 | 0.026 | 0.024 | 0.013 | 0.029 |
| | 4 | 0.016 | 0.020 | 0.033 | 0.018 | 0.022 |
| | 5 | 0.026 | 0.013 | 0.025 | 0.013 | 0.021 |
| | Average | 0.022 | 0.020 | 0.029 | 0.018 | 0.029 |
| Average | | 0.019 | 0.018 | 0.023 | 0.016 | 0.025 |

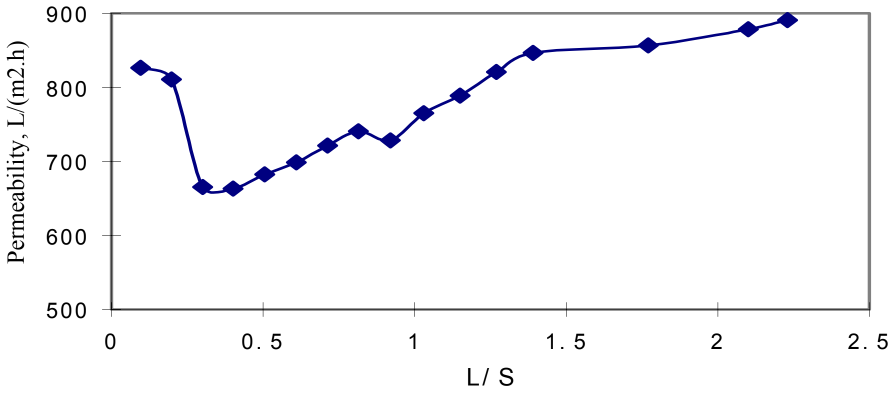

*FIG. 2. Change of the permeability of ore mass in the process of heap leaching.*

## 4. Conclusion

Heap leaching of poor permeability ores was ever a difficult technical problem in the field of hydrometallurgy. Through years test, the researchers of RIUM put forward a new idea on agglomeration. On the basis of physical combination, the pelleted particles are forcefully bound by chemical attraction. New series products of cementing agent for agglomerated acid heap leaching are developed. The cementing agent reacts with ores, produces hydrous compounds, and forms binding networks in single ball. These hydrous compounds networks enhance greatly the cementing strength of pelleted balls. The flow-sheet are offered, including the processing parameters in related to agglomeration, curing measures of the pelleted balls, leaching operation.

These achievements have been commercially used to handle clay-bearing uranium ores. It is demonstrated, by the practical application that agglomeration nor only improves the permeability of heap leaching, but also strengthens leaching reactions, raises profits. The permeability of agglomerated ore heap reaches above 600L/m$^2$.h. Comparing with direct heap leaching operation, the leaching period of agglomerated acid heap leaching is changed from 200 days to60 days, the average leaching efficiency from 40% to 96%. By agglomerated acid heap leaching, the uranium grade of the tailings is usually less than 0.03%. Therefore, this new technique is widely being spread in heap leaching of clay-bearing uranium ores in China.

# The new progress on heap leaching of hard rock uranium ore in China

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**Abstract.** The strengthened surface heap leaching technologies including comminuted ores granulating & curing with concentrated acid – heap leaching with ferric salts microorganism oxidization heap leaching, lixiviant activation heap leaching and the application of the permeating aid. Through these methods we can make better use of the resource, improve the efficiency of uranium extraction, cut short the heap-leaching period, reduce the consumption of regent, and decrease or eliminate environmental pollution. By amine solvent extraction method, process wastewater is realized closed cycle in uranium recovery process; with the high efficient compacted moving bed absorption column and new type ion exchange resin, uranium can be recovered from the lower concentration leaching effluent. With the new recovery technology for Uranium-molybdenum coexisting ore, uranium-molybdenum can be separated and recovered effectively and economically.

## 1. Introduction

When the conventional uranium hydrometallurgy method that is characterized by agitation leach become mature, the research on surface heap leaching of hard rock started. Beijing Research Institute of Chemical Engineering and Metallurgy CNNC (abbreviated “BRICEM” in the following) began research of the acid plugging & granulating, bacteria oxidation and activation heap leaching on granite and volcanic rock. Of 10 years, the strengthened heap leaching method has been applied to uranium deposits from the laboratory, and is making great contribution to the China’s uranium industry on the base of industrial production of high efficiency and benefit.

## 2. Characteristic of ore

### *2.1. 101-Deposit*

The deposit is located at the contact zone of granite and ancient stratum, and the majorities of mineral ore are associated to quartzite, associated granite and associated mica schist. The uranium mainly exists as the form of pitchblende. Associated minerals are pyrite, pyrrhotite, sphalerite and etc. Gangue minerals are quartz, feldspar, sericite, white mica, some chlorite and calcite. Chemical analysis of mineral sample illustrates in Table I.

Table I. Chemical analysis results of mineral sample %.

| U | $SiO_2$ | $Fe_2O_3$ | $Al_2O_3$ | CaO | MgO | $K_2O$ | $Na_2O$ | $TiO_2$ | S | $CO_2$ | P |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.331 | 77.58 | 2.14 | 10.96 | 1.54 | 0.86 | 0.40 | 4.77 | 0.32 | 2.21 | 1.06 | 0.028 |

### *2.2. 103-Deposit*

The ore type of 103-Deposit is volcanic rock, and the host rock is tuffaceous staglutenite. Main components of the ore are pitchblende, pyrite, organic substance, quartzite and calcite etc. The chemical analysis results are shown in Table II.

Table II. Chemical analysis results of 103-deposit %.

| U | CaO | MgO | Fe | Al | $SiO_2$ | K | S |
|---|---|---|---|---|---|---|---|
| 0.158 | 3.78 | 3.19 | 1.83 | 8.12 | 75.22 | 4.03 | 0.274 |

### *2.3. C-1-Deposit*

The ore type consists of granite, conglomerate, and andesite. The mineralization type is single uranium and uranium minerals mainly are pitchblende and coffinite. Gangue minerals are quartzite, potash feldspar, plagioclase, black mica, white mica, hydro mica, chlorite, fluorite, hematite, pyrite and calcite etc. The chemical analysis results are shown in Table III.

Table III. Chemical analysis results of C-1-deposit %.

| U | Ca | Mg | Al | $SiO_2$ | Fe | F | S | $CO_2$ | K | Na |
|---|---|---|---|---|---|---|---|---|---|---|
| 0.255 | 3.25 | 1.02 | 9.10 | 76.03 | 3.08 | 0.24 | 0.55 | 1.10 | 5.06 | 2.14 |

## 3. Heap leaching technology

### *3.1. Comminuted ores granulating & curing with concentrated acid – heap leaching with ferric salts*

Flaser leaching was put forward on the basis of combination of acid pugging and heap leaching overseas in the past. BRICEM developed comminuted ores granulating & curing with concentrated acid – heap leaching with ferric salts after recent 10 years of laboratorial study and industrial experiment. It intensifies leaching process with concentrated acid curing and ferric salts leaching by performing the remnant leaching reaction that can’t be fulfilled with flaser leaching. The aim of granulating is to decrease the content of fine muddy minerals in piles and to avoid block of leaching pad. And it doesn’t drain process wastewater by closed circulation of process effluent. Most of the leached residue is used as mine backfill, so it lowers environment pollution. Compared with conventional heap leaching, its prominent advantage is over 50% reduction of leaching period, over 5% improvement of leaching efficiency, about 15% saving of ore processing expense. So, production cost of yellow cake can be decreased on a large scale. The technology has already been employed in industrial process of 101-deposit, processing ore 30,000 tons/year. Process effluent solution is back to sprinkle or to make stripping agent and precipitator solution. Leaching period about 90days and leaching efficiency 92~94%. It achieved zero discharge of process wastewater in operational process and made the enterprise get higher economic effect and good environment results.

### *3.2. Activation heap leaching*

Activation heap leaching has good effect on high acid consumption of 103-deposoit. Its mechanism is to increase ion activation energy by activating treatment of lixiviant to make lixiviant penetrate into the inner of ores with higher rate. At the same time, for this method, migration rate of uranyl ion is enhanced, that is, mass transfer velocity is increased and this obviously improves kinetics of leaching process. As for impurities, it avoids enlarging of particles by virtue of increasing the possibilities of collision among ions and forming finer nucleus. Because finer nucleus is easy to be washed away by flowing lixivium and not form precipitation, as makes unwanted ions, such as aluminum, fluoride and calcium and so on, transfer orderly. So, uranium ore can't be enwrapped by $CaSO_4$ and leaching path not to be blocked by colloid formed by silicon and aluminum in leaching process. All of these are propitious to operation of leaching process, reduction of acid consumption, improvement of leaching efficiency (about 5~10%) and cutting down on leaching period by 30%. In recent years, BRICEM made a good deal of research about mechanism, device, technology and engineering of activation leaching, aiming at solving problems in heap leaching of hard-leached uranium ore and uranium & molybdenum coexisting ore. For example, for pilot plant research of 103-deposit, leaching efficiency exceeds 80% and sulfuric acid consumption is about 7~8%. Heap leaching in series can decrease operation period of single pile and make uranium concentration stand at a stable value. The key factor on industrialization of activation leaching lies in activating device. Based on the reason, BRICEM developed uniserial and multiple serial beehive style of activation devices whose special structures make sure of uniform activating field, simplified operation and good effect and efficiency.

### *3.3. Bacteria heap leaching process of C-1-deposit*

The technology of bacteria heap leaching is a comprehensive application of biology, chemistry and engineer to exert its special function of microorganism in the ore process. The technology of bacteria applied in uranium extraction can improve leaching kinetics and intensify leaching process. Within decades, BRICEM have made a lot of research about the technology of bacteria heap leaching and completed pilot and industrial experiments with different uranium ores in recent years. Compared with conventional heap leaching, it cut leaching period short by 50%, improves leaching efficiency by 10% and decreases acid consumption obviously. If processing uranium ore 30,000tons per year, plant investment is 52% of conventional leaching plant cost and operation expense is 50% of the latter. In addition, it makes less affection on to environment.

It is known, for bacteria heap leaching, the most difficult problems are longer oxidation period, lower production efficiency and limited adaptability for leaching process. The specialty of BRICEM's research achievements is the application of a new style of continuous biofilm oxidation device, which takes place of conventional beehive pipe or multiorifice as the carrier of bacteria. This new material radically changes key process of preparing bacteria solution and bacteria oxidizing regeneration of adsorbed effluent. After then scientific method is used to make bacteria habituate to greatly enhance capacity of bacteria's bearing chloride and fluoride, so it broadens the range of application of bacteria heap leaching.

The study and practice show that it is not only new way of uranium extraction for counter-flow heap leaching of bacteria regenerated solution, but also can be extended to other metals extraction, such as gold, copper and so on.

## 4. Uranium recovery

### *4.1 Ion exchange process*

In domestic uranium recovery plant, uranium concentration of leaching effluent is low. It is feasible to recover uranium from this solution with ion exchange process. Compacted moving bed column holding special structure developed by BRICEM is widely applied to recover uranium from in-situ and heap leaching effluent. Its void column linear velocity reaches

60m/h. In addition, it has high production efficiency, economical investment and simple operation. Serial style of resin D263 matched with the technology, whose particle-size distribution is in the range of 0.8~1.2mm and exchange capacity 4.06 mmole/g, shows outstanding kinetic performance of mass transfer. Sulfuric acid solution is employed to elute saturated resin. So, all hydrometallurgical process can be carried out in medium of sulfuric acid, which turns away $Cl^-$ erosion and pollution in eluting process with chloride and the disturbance in purification process of natural uranium. In addition, process wastewater can be utilized circularly, to decreases production cost and environment pollution.

### *4.2. Amine solvent extraction*

Uranium concentration is sometimes very high in serial heap leaching, such as granulating & curing with concentrated acid – heap leaching with ferric salts of 101-deposit, which uranium concentration reaches 5~10g/l. Tri-fatty amine is applied to recover uranium from solution, sodium carbonate to back extract and sodium hydrate to precipitate in recovery process to get sodium diuranate. The trait of the process is water phase of extraction back to leaching, precipitated liquor back to make stripping agent. By virtue of these, the whole operation reaches zero discharge of process wastewater. So, it is observed that the technology, granulating & curing of comminuted ores with concentrated acid – heap leaching with ferric salts – extraction with tri fatty amine – back extraction with sodium carbonate – precipitation with sodium hydrate, has become one of the main technology in new uranium plant.

## 5. Precipitation

Uranium recovery from acidic leaching effluent with two steps precipitation is feasible and convenient. It has advantages of low consumption of chemicals, low investment, non-introduction of impurities (such as organic matter, $NH_4^+$, $Cl^-$, $NO_3^-$ and so on) and direct recycle of process wastewater. As early as sixties of last century, BRICEM began to make research of multi-function precipitation tank, in 1990s it was developed successfully. It combines all services of precipitation to one device such as precipitation, aging, condensation, controlled filtration. For collide precipitation $Fe(OH)_3$, which generates in the first step of neutralization with sodium carbonate, it can be turn into amorphous precipitation. It makes volume of slurry decrease and improve strainability, with this device, the precipitation process has been improved obviously.

## 6. Conclusion

BRICEM's research achievements on heap leaching process have already been applied in uranium industry. They are changing technological structure of uranium industry. Promotion of production cannot but need development of technology. To meet the demand of heap leaching technologies applied to conventional grade of uranium deposit, staff of BRICEM is speeding up research on aid-penetration, permeating aid and other technologies to improve heap-leaching efficiency for different uranium mineral.

# Comparative procedures for uranium solubilization from ores using the leaching method

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**Abstract:** The activities related to uranium ore exploitation and milling are in charge of the state-owned National Uranium Company S.A., ensuring the uranium for the national nuclear power programme. The hydrometallurgical milling of uranium ores in Romania, using the alkaline leaching technology, commenced in 1978 at the Feldioara plant - Brasov county, where are processed the raw ores from the Apuseni Mountains, from the Banat mines and from the Eastern Carpathes mines. For the new uranium deposit located at Tulghes - Neamt county, the use of an acid leaching technology was studied. The criteria for choosing a leaching technology takes into consideration the carbonates content of raw ore, which is higher for the commonly leached Romanian ores, and lower for Tulghes ore. In present the $H_2SO_4$ price is lower, compared to the situation in 1978.
At the Feldioara plant the average output for the alkaline uranium leaching is 81% and for the Tulghes ores is foreseen the same output in case of alkaline leaching or 90% average output if using acid leaching in pachucas type vessels.

## 1. Introduction

Uranium ore exploitation commenced within the country since 1953, but during the 1953 - 1963 all the raw ore having a higher content was directly exported. Uranium production for the CANDU power plants are based on the ore exploited from three mines after 1963, two of these having almost depleted economic reserves [6,7]. The leaching method and the general milling technology has been chosen in past taken into consideration the features of the ore ensured by the three mines and of he ore in stock at the mine sites. Until present industrial leaching method used was the alkaline one, in autoclaves, at relatively high temperature and pressure levels.

## 2. Uranium leaching

The present milling of uranium ores is not subject to upgrading which can be used for the impurities separation from raw ore, such as sulphide flotation, iron magnetic removal, carbonates separation.

Only uranium ores radiometric sorting out is a specific method for such ores, which enables the removal of an important sterile ore percentage from the raw ore. The basic principle of radiometric sorting uses the gamma radiation measurement of the useful components, on basis of radiometric dose difference between sterile or low content rocks and uranium ore, for the boulders sorted from the raw material by a granulometric mechanical separation, usually material having more than 30 mm.

The wet processing methods for uranium ores are the main processing technologies within the uranium milling industry, enabling the uranium separation and concentration from a wide variety of existing deposits.

The two main milling methods for all the known uranium ores are the acidic technology and the alkaline one, having been used as a function of mineralurgical structure of the ores. Thus, for ores grading less than 12% carbonates are recommended an acid leaching technology and for ore with higher than 12% carbonates grade the chosen method is a sodic attack technology. The late one enables a smaller reagent consumption compared to acid need, generally sulphuric acid [1,2,3].

Although conventional milling of domestic ores gives acceptable uranium recovery rates, because of decreasing of average uranium content on some mines and because of the lack of major investment funding needed for conventional mine development, the alternative of Heap Leaching or Block Leaching was taken into consideration by the uranium mining company in Romania, but never used on industrial scale.

The first steps for feasibility assessment of the mentioned technologies had as aim the study of raw uranium ore leaching conditions.

Both acid leaching and sodic leaching were studied at a laboratory and pilot scale. The mineralurgical ore analysis found the following components:

(a) Carbonates: 19-39% (higher content for the Bihor ore)
(b) Alumina-silicates and silicates: 36-51% (higher for the Eastern Carpathian ores)
(c) Sulphides: 1-2.5%
(d) Iron minerals: 1.1-2.4%

The carbonates are represented mainly by ferodolomite (46-52%) and calcite (13-22%). The chemical analysis for a raw ore sample is presented in the following table.

TABLE I. CHEMICAL ANALYSIS OF RAW ORE.

| Element | Average content (%) | Element | Average content (%) |
|---|---|---|---|
| $SiO_2$ | 44.30 | $TiO_2$ | 0.660 |
| $Al_2O_3$ | 4.60 | Pb | 0.030 |
| $Fe_2O_3$ | 2.18 | MnO | 0.120 |
| FeO | 3.60 | $MoO_3$ | 0.005 |
| CaO | 21.20 | $V_2O_3$ | 0.003 |
| MgO | 12.70 | Cu | 0.075 |
| S | 1.12 | Zn | 0.010 |
| C (organic) | 0.040 | Calcination loss | 6.50 |

The main milling parameters for the Feldioara hydrometallurgical plant are:

(a) Milled ore granulometry: 95% passing 0.100 mm sieve
(b) Leaching temperature: 140°C
(c) Pressure in autoclaves: 15 atm
(d) Oxidation by compressed air
(e) Uranium solubilization output: maximum 85%, average 81%.

The alkaline leaching method using sodium-carbonate as reagent has two great advantages on the classical acid leaching: selectivity in uranium leaching and possibility of using the existing vessels.

## 3. Alkaline leaching for processing of domestic ores

The mineralurgical composition of ores, the difference between the prices for sulphuric acid and sodium bicarbonate during the seventies, the necessity to ensure a yellowcake with a minimum of impurities, were the factors that imposed the sodic leaching process at Feldioara plant [4,5]. The uranium leaching in leaching carbonate media is based on the feature of such solutions to dissolve the U (VI) from the raw ore. This is the reason that oxidation conditions must be ensured during the 6-8 hours of sodic leaching in autoclaves, compared to 56 hours of leaching in pachuchas, having pneumatic agitation, at low temperature and atmospheric pressure. The leaching process is carried up in 5-6 autoclaves, in series, each of them having mechanical stirring ensured by 4 electric engines with a power of 300 kw/autoclave (Figure 1).

## 4. The acid leaching method

The Tulghes new deposit, located within the Eastern Carpathes, is foreseen to be exploited in the nearest future. The ore have a structure with fine grained pitchblende intimately associated with bitumen or carbonates, being under the form of impregnated areas, small veins, thick lens. The gangue has a high clay content, reddish carbonates, breccia looking, from the dolomite - ankerite - calcite association. Very low-grade rocks can be partially removed during radiometric sorting, but under 50% of the ore is amenable to this type of operation. About 30% of the mineral mass can be removed and stored at the mine site, without transporting it on railway, at a 350 km distance. The chemical composition of a bulk sample from this raw ore is presented in the table below.

TABLE II. CHEMICAL ANALYSIS OF TULGHES ORE.

| Element | Average content (%) | Element | Average content (%) |
|---|---|---|---|
| $SiO_2$ | 60.71 | $TiO_2$ | 0.766 |
| $Al_2O_3$ | 13.35 | $K_2O$ | 3.071 |
| $Fe_2O_3$ | 1.78 | MnO | 0.115 |
| FeO | 3.67 | $MoO_3$ | 0.005 |
| CaO | 4.97 | $V_2O_5$ | 0.010 |
| MgO | 1.95 | Cu | 0.078 |
| S | 0.82 | Zn | 0.010 |
| $CO_2$ | 4.05 | Calcination loss | 5.900 |

For the hydrometallurgical processing of the mentioned new type of ore was set up a proposal for a new technology which presents the following features, compared to the existing alkaline leach technology at Feldioara:

(a) Upgrading of the uranium content by radiometrical sorting at the mine site of the rocks having over 30 mm;
(b) Flotation at the mine site or the milling plant, of the minerals with a higher uranium content, leaving a sterile mineral mass with less than 200 ppm uranium per tonne ore (similar to the present tailings, production within the mentioned mill) and a concentrate having about half of the milled ore mass; flotation efficiency and cost are still under assessment within laboratory and small pilot stages;
(c) Alkaline or acid leaching of the upgraded ore or of the raw ore;
(d) Uranium separation and concentration from filtered alkaline or acid solutions by ion-exchange, using strong anionic resins, in fixed bed filled columns.

The factors, which lead to the proposal for acid leaching of the Tulghes ore were the following:

(a) The mineralurgical structure of the uranium ore;
(b) The price ratio sodium carbonate / sulphuric acid which in present is favourable to the acid reagent;
(c) The higher average output recovery for uranium compared to alkaline leaching.

The oxidized U (VI) is relatively easy solubilized in sulphuric solutions, when the redox potential is up to 550 mV and the pH between 1.2-1.5.

Because the sulphuric acid concentration is largely higher than the stoichiometric quantity needed for the chemical reaction and uranium dissolution, the U (VI) is transferred in solution under the form of a mixture of uranium sulphates like $UO_2(SO_4)$. There is a mixture of complex anionic sulphates that are present due to the excess of sulphate in the aqueous system. Optimal pH value for the ion exchange process must be ensured after the filtration of the leached pulp. After the technological study was finalized, the following flow sheet resulted for the acid-leaching variant, presented in Figure 2.

The parameters for the leaching operation are the following:

(a) Leached pulp density: 1.37 t/$m^3$
(b) Leaching temperature: 60°C
(c) Leaching duration: minimum 4 hours
(d) Sulphuric acid consumption: 90-110 kg / tonne ore
(e) Oxidant $KClO_3$: 5 kg/ tonne ore
(f) Leaching pH = 1.2-1.5
(g) Average leaching output: 90%
(h) Maximum leaching output: 95%
(i) Liquid volume in pulp: 1.27 $m^3$/tonne ore
(j) Sterile U content: maximum 0.020% (200 ppm)

First filtration stage:

(a) Washing water filtration: 1.27 $m^3$/tonne
(b) Filtration water + washing water volume: 2.54 $m^3$/t ore
(c) Uranium concentration in filtered solution: 0.665 kg/$m^3$

Water/ore cake remixing (repulping) and leaching:

(a) Solution volume for mixing: 1.27 $m^3$/t
(b) Uranium content in the mixing solution: 0.200 kg/$m^3$
(c) Duration of second leaching stage: 2-4 hours

Second leaching stage for the raw ore cake (in the case when the first leaching gives cakes having over 400 ppm U/tonne):

Second pulp filtration and washing:

(a) Washing water volume: 1.27 $m^3$/t ore
(b) Second filtration solution volume: 2.54 $m^3$/t
(c) Uranium content in second filtrate: 0.096 kg/$m^3$

The necessity of a second stage for cake remixing / leaching / washing / filtration will be assessed on benefit / cost analysis of such operation, taken into consideration that phase separation is carried out on a second belt filter; raw ores with more than 0,40% U content can be subject to an acid leaching in two stages.

Neutralization of the acid tailings and removing the radium dissolved must provided, but the techniques are well known as a number of studies in the past dealed with these operations. Final separation of uranium traces from pond waters using ion exchange process is already available at the existing milling plant.

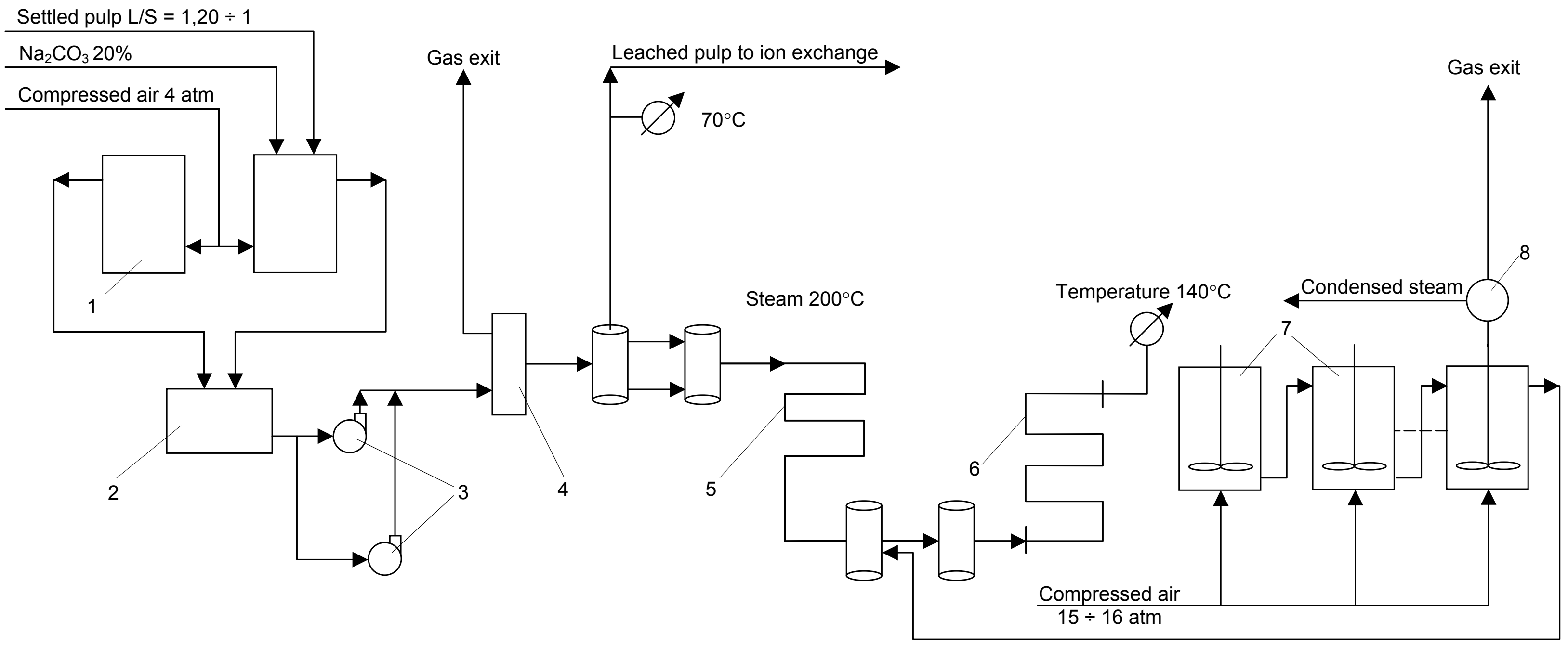
## 5. Conclusions

The alkaline autoclave leaching method, for processing the Romanian uranium ores was established as a function of the ratio carbonate content / silicate content in ores. The ores rich in carbonates, from Bihor and Banat, and also the ores from the Crucea mines, were processed only by alkaline leaching, within the Feldioara plant. The average output on a 24 years period was 81%.

Romanian uranium ores have a mineral composition that recommends the alkaline leaching method for the recovery of uranium.

Because of decreased carbonate content of the present milled ores, comparative studies were done to leach ores from a new ore deposit using the acid technology and the alkaline one. Acid leaching enables an output of 90% for the Tulghes type ores but involves the change of the present technological flow sheet.

Shorter duration of leaching, lower leaching temperature, electric energy and thermic energy savings, improved recovery output, are the main advantages of the method over the existing alkaline leaching. With the aim of decreasing acid consumption and transport costs, radiometric sorting is recommended at the mine site.



**CONTENT**

1. Pulp conditioning vessel.
2. Distribution vessel.
3. Pulp pumps.
4. Air compressor.
5. Heat recovery exchanger.
6. Heating device.
7. Vertical autoclaves.
8. Condensed steam vessel.

*FIG. 1. Alkaline leaching flow sheet presentation.*

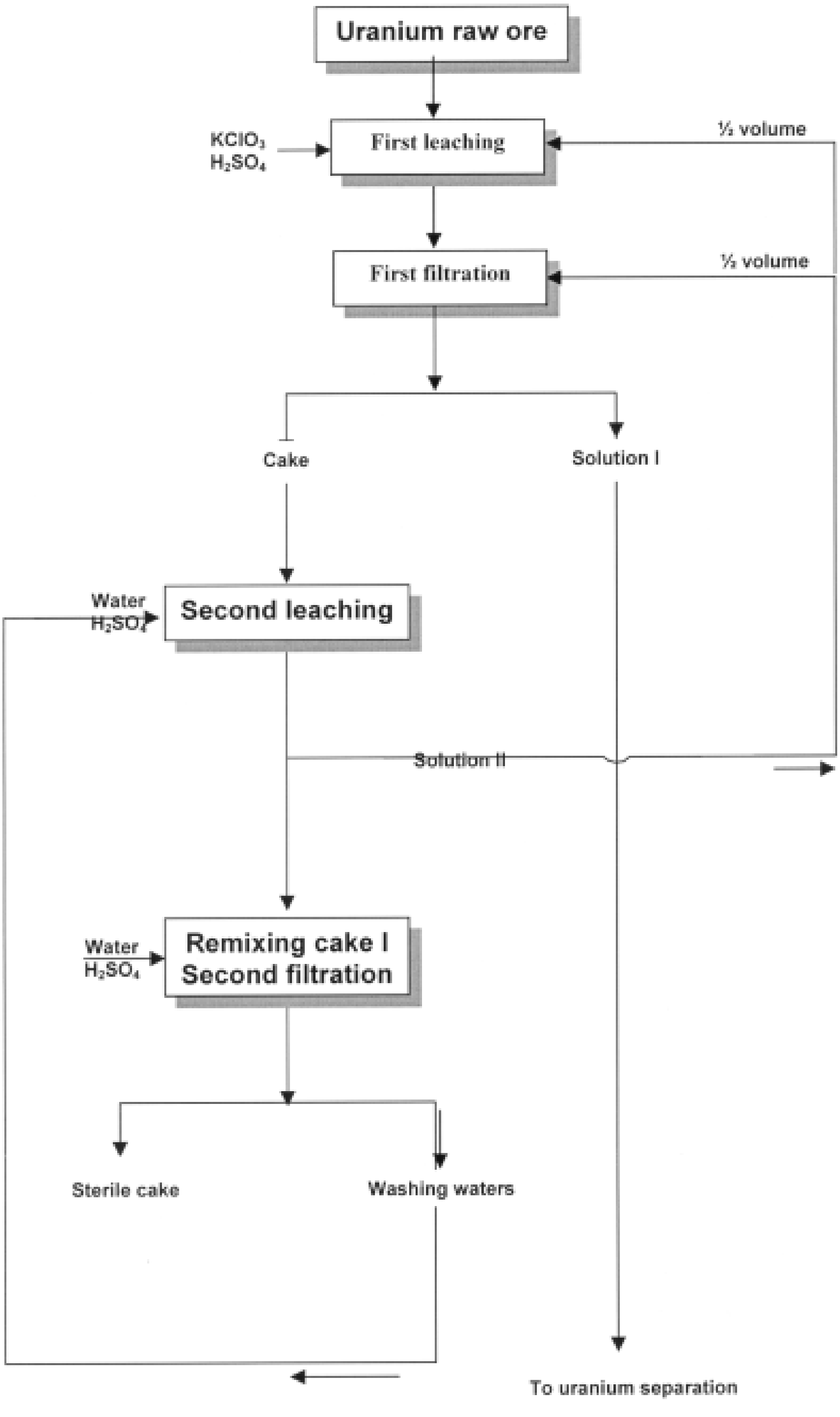


*FIG. 2. Sulphuric acid uranium leaching.*

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# Industrial-scale experiment on bacterial heap leaching of uranium ore

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**Abstract**: This paper presents the results of industrial-scale experiment on bacterial heap leaching of uranium ore in CaoTaoBei mining site, GanZhou uranium mine and summarizes the heap situation, installation of spraying and sprinkling device, bacterial domestication and operation of bioreactor. This experiment is carried out for 85 days and uranium recovered is 6.859 kg. The leaching rate is about 92% by tailings measurement. Acid consumption is 2.1% and total liquid-solid ratio is 2.9m$^3$/t. By compared with conventional acid heap-leaching, leaching period shortened about 75 days, acid consumption reduced by 0.35% and leaching rate improved by 2%. The results provide the basis of design and experience of operation for industrial application of bacterial heap leaching of uranium ore.

**Keywords:** Uranium ore, bacterial heap leaching, bioreactor.

## 1. Introduction

Heap leaching has become an important processing technique in uranium ore processing industry in China, due to the advantages such as lower capital expenditure, simpler techniques and shorter construction period [2,3]. The major task of mines, factories and institutes is to improve leaching rate, reduce acid consumption and shorten leaching period. At present, except for controlling strictly processing conditions, parameters and establishing quality guarantee system of every circuit, lots of practical techniques have been introduced into heap-leaching, in which, bioleaching has been applied and studied commonly in main counties of producing uranium. The introduction of bioleaching into heap leaching can exert fully the particular role of microorganisms, strengthen leaching procedure, amend leaching kinetics, shorten leaching period dramatically, improve leaching rate and reduce cost. In1960s in China the works on bioleaching were carried out. Especially in recent decades, further research on bacterial heap leaching of different types of uranium ores and refractory gold ores were done, and perfect experimental system is established [1]. Works on bacterial screening and domestication, combination of process flow, as well as bioreactor have made great progress. Through pilot test and industrial experiment on different uranium ore, the technique of bacterial heap leaching is more perfected, the tolerance to toxic elements and adaptability to variable environment of bacteria are tested, the production capacity of bioreactor and possible engineering and technical problems in operation are reviewed, experience on operation management of barren solution' regeneration are gained and the basis for industrial application of bacterial heap leaching of uranium ore is founded.

CaoTaoBei mining site is the earliest project, which applied conventional acid heap leaching in uranium ore processing industry in China [4]. Because of the usage of new technique, new equipments and new material, many economic and technical norms of heap-leaching are in the leading status in uranium industry. It is easy to leach the uranium ore consuming lower acid, but using leaching agent regenerated by bioreactor, leaching procedure can be strengthened, leaching period shorts greatly, as well as leaching rate and acid consumption can be amended significantly.

## 2. Preparation for the experiment

### *2.1. Composition of the uranium ore and heap situation*

The ore studied is familiar with that of conventional acid heap leaching, most of which is from CaoTaoBei mining site, the other is from other sites of GanZhou mine. The origins are different but all belong to GanNan area controlled by HuaXia Construction and volcanic collapse configuration of Xiangshan becken. The uranium deposit is of middle-low temperature hydrothermal fluid. The ore types are Breccia, Granite and Andesite. The commensal combinations with ore are uranium-hematite, uranium-pyrite, uranium-fluorite, uranium-calcite and uranium-chlorite. The ores contain uranium is in the range of 0.14% and 0.31%, in which the content of hexavalent uranium is more than 40% usually.

Mixed in storage tank and crushed, the ore with the particle size is less than 10mm is delivered by truck to the leaching site to make a heap. The surface of heap becomes smooth using bulldozer, then the compactive ore is loosened by digger, the total ore quantity is 3904.8t, physic grade is 0.177%. The dimension of heap is 28m by 26m, and the height is 3.7m. Twenty samples were gained, and the average uranium grade of ore id 0.189%. Analysis of particle size and uranium grade is shown in Table I, and component of ore is listed in Table II.

Table I. Analysis of particle size and uranium grade

| Particle size/mm | Percent of the total % | Uranium grade % | Percent distribution % |
|---|---|---|---|
| > 10 | 19.02 | 0.16 | 15.12 |
| < 10 ~ >8 | 5.19 | 0.18 | 4.62 |
| < 8 ~ >6 | 9.68 | 0.13 | 6.21 |
| < 6 ~ >4 | 9.96 | 0.21 | 10.00 |
| < 4 ~ >2 | 23.97 | 0.23 | 27.41 |
| < 2 | 32.15 | 0.23 | 36.67 |

Table II. Component of ore

| Component | U | K | Na | Ca | Mg | Al | Fe | P | $CO_2$ | F | $SiO_2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Content, % | 0.189 | 5.06 | 2.14 | 3.25 | 1.02 | 9.1 | 3.08 | 0.515 | 1.1 | 0.24 | 76.03 |

### *2.2. Installation of spraying and sprinkling device*

Spraying and sprinkling device that is cheaper is employed in this experiment. Such device is installed and replaced easily, of which, the tube wall is flimsy and the pore is bigger that not easy to be blocked. Liquid sprayed disperses to minor droplet and not to form fog. The valve of main tube controls spraying intensity. In the surface of heap thirty-six tubes with the length of 28~32m were used, and the distance between tubes is 60cm. In each tube there is a double of Φ 10mm pores every 25cm, liquid sprayed from two pores can form 120° included angle. There are total 8680 spraying pores to make sure the uniform spraying to the heap.

### 2.3. *Composition of bioreactor and bacterial domestication*

#### 2.3.1. *Bioreactor*

Bioreactor is comprised of three parts: (1) oxidizing tank of biofilm with packing material; (2) blower through which air is supplied, lots of diffusers with fine pores; (3) confected tank used to supply bacterial nutrients, pipeline through which barren solution is passed.

Two 30m$^3$ tanks were revised to form the oxidizing tank of biofilm. Lots of elastic packing material, the diameter of which is 150mm are used in oxidizing tank. Many air diffusers and tubes with fine pores are placed in the bottom of the tank. A low-noise blower is used to supply air and airflow rate is 3m per min. Two 1m$^3$-plastic tanks are confected tanks of ferrous sulfate and ammonium sulfate. The total solution is passed by gravity flow. Schematic of bioreactor is shown in Figure 1.

#### 2.3.2. *Bacterial screening and domestication*

In the procedure of bacterial heap leaching, it is important to screen suitable strains according to the type of ore. At present, the strain used mostly is Thiobacillus ferrooxidans (t.f). The strains employed in this experiment are domesticated in barren solution for long time through expand test and pilot plant done by microorganism group of Beijing research institute of chemical engineering and metallurgy. Due to high adaptability to toxic elements and varied environment, the strains can oxidize ferrous ion to its oxidized ferric ion form in the solution with higher concentration of salt, fluorion (F$^-$), chlorion (Cl$^-$) and lower pH value.

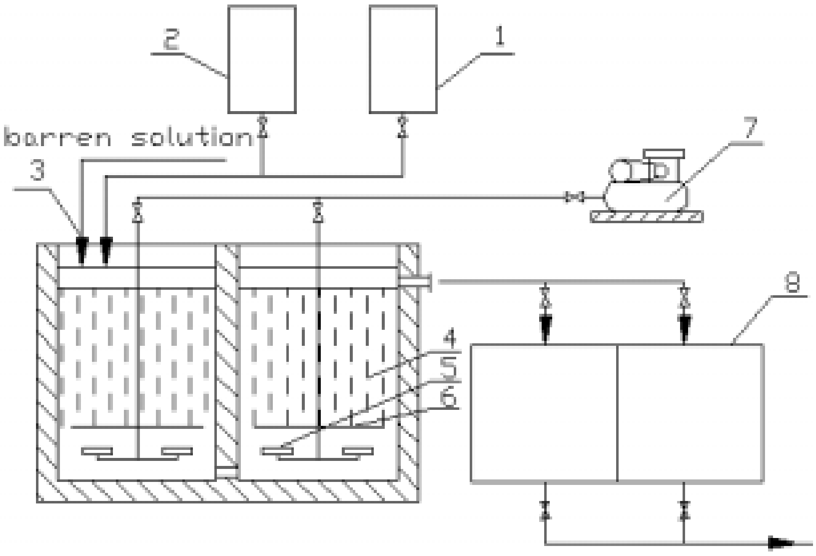

*FIG. 1. Schematic of bioreactor.*

*1) Confected tank of ferrous sulfate, 2) Confected tank of ammonia sulfate, 3) Barren solution, 4) YDT packing material, 5) KBB air diffuser, 6) Packing material supporter, 7) Blower, 8) Storage tank of leaching agent regenerated.*

## 3. Flow sheet, parameter and equipment

### *3.1. Flow sheet*

The flow sheet of this experiment is familiar with that of conventional acid heap leaching. Part of leaching agent of this experiment is the solution with higher redox potential, regenerated by bioreactor. Because ion exchange system is used to treat the total leaching solution of overall heaps in the mining site, the solution regenerated by bioreactor is a part of mixed barren solution. Figure 2 shows the detailed flow sheet.

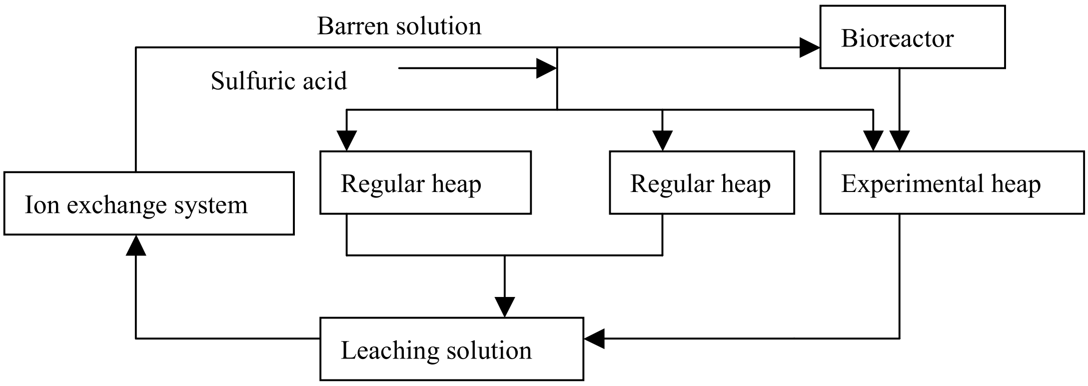

*FIG. 2. Schematic of flow sheet of bacterial heap leaching.*

### *3.2. Parameter*

a) Experimental heap: See 2.1.

b) Leaching agent: The acidity of leaching agent is determined by the acidity of leaching solution, which is about 1g/L to 3g/L usually. The acidity of leaching agent is varied with leaching time as following:

| | |
|---|---|
| 1~5d | $\rho\ (H_2SO_4) = 50\sim30\,g/L$ |
| 6~12d | $\rho\ (H_2SO_4) = 20\sim10\,g/L$ |
| Regular leaching time | $\rho\ (H_2SO_4) = 5\sim3\,g/L$ |

c) High redox potential leaching agent with large quantity cells

$\rho\ (\Sigma Fe) = 3\sim4.5\,g/L$ pH : 1.5~2.0
Eh : 450~610mv

d) Spraying intensity: $8\sim12\,L/m^2.h$

Spraying quantity: $120\sim160\,m^3/d$.heap, everyday four shifts, one shift is $30\sim40\,m^3$

e) Barren solution: $\rho\ (H_2SO_4) = 2\sim3\,g/L$ $\rho\ (\Sigma Fe) = 3\sim4.5\,g/L$
$\rho\ (Fe^{2+}) = 2\sim3\,g/L$ Eh : 300~400mv
pH : 1.0~1.8 $\rho\ (u) = 5\sim100\,mg/L$
$\rho\ (F^-) = 0.3\sim1.8\,g/L$ $\rho\ (Cl^-) = 2\sim4\,g/L$

### *3.3. Equipment*

Since flow sheet and parameter of this experiment are familiar with that of conventional acid heap leaching. The regular manufacture of the site is not affected. In order to meet the demand of this experiment, some pipelines and equipments are revised. The image of equipments of bacterial heap leaching is displayed in Figure 3.

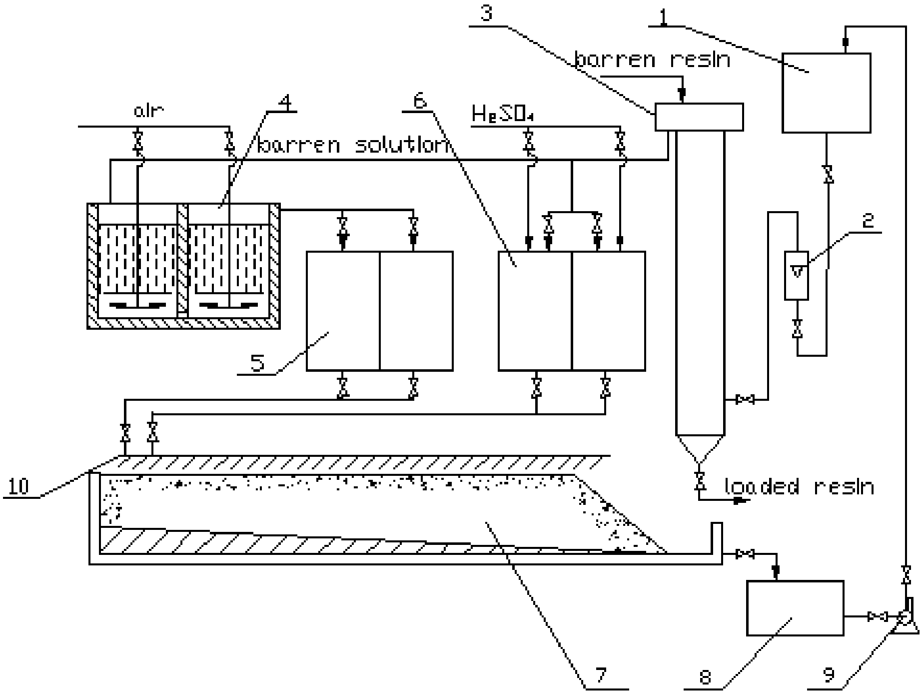

*FIG. 3. Image of equipments of bacterial heap leaching.*

*1) Storage tank of leaching solution, 2) Flowmeter, 3) Adsorption column, 4) Bioreactor, 5) Storage tank of leaching agent regenerated, 6) Confected tank of leaching agent, 7) Heap, 8) Collective tank of leaching solution, 9) Infusion pump, 10) Spraying and sprinkling device.*

## 4. Operation and Results of industrial experiment

### *4.1. Operation of bioreactor*

Bioreactor is key equipment, which supply high redox potential leaching agent to heap. The quantity of leaching agent regenerated by bioreactor is related to the success of bacterial heap leaching. The oxidization of ferrous ion by bacteria is influenced by a series of different factors, one of which is the characteristic of bacteria. In addition, it is necessary to have an environment suitable for bacteria to grow and harvest, established according to the feature and demand of biology. Disadvantageous conditions should be avoided.

Firstly, nutrients and carbon resource must be supplied to bacteria. Except for nitrogen element, in most ore leached and barren solution there are majority of nutrients such as ferrous, phosphorus, kalium, calcium, magnesium and sulfate, which can meet the need of bacteria. A certain quantity of oxygen and carbon dioxide in the solution can be maintained by aeration. Everyday ammonium sulfate and ammonium bicarbonate ($NH_4HCO_3$) should be added to bioreactor as nitrogen resource.

Secondly, the accumulation of toxic material, especially fluorion ($F^-$), chlorion ($Cl^-$) in barren solution should be avoided. When the concentration of fluorion ($F^-$) and chlorion ($Cl^-$) is over the tolerance, growth of bacteria is influenced adversely. Except for domestication used to improve the tolerance to toxic materials, it is more important to discharge periodically part of barren solution with high content of fluorion ($F^-$) and chlorion ($Cl^-$), but ferrous sulfate solution should be added into bioreactor to supply the reduction of concentration of ferrous ion caused by the addition of water.

Finally, physical and chemical condition for bacteria to grow should be met. Emergency action must be taken when lots of cells are dead caused by accident. The optimal pH value and temperature for bacteria to grow must be controlled strictly, and uniform feed rate should be maintained. Since a series of measurement are taken, bioreactor run smoothly during the period of experiment. Although pH value of barren solution and the content of fluorion ($F^-$) and chlorion ($Cl^-$) varied significantly, everyday about 60~80m$^3$ regenerated leaching agent with high redox potential (450~610mv) can be supplied, in which the concentration of ferrous ion is in the range of 3.5~4.5g/L. 2t of ferrous sulfate and 0.6t ammonia sulfate are consumed in this experiment, leaching agent regenerated is 2967m$^3$ and meet the need of this experiment.

### *4.2. Experimental procedure and results*

The leaching period is 85d. The total quantity of regenerated leaching agent is 2967m$^3$, industrial sulfuric acid consumed is 82t, leaching solution collected is 11320m$^3$ and uranium leached from ore is 6859kg. The grade of tailings is about 0.0154%, leaching rate is 92% and 93% respectively by tailings and liquid measurement. Acid consumption is 2.1% and total liquid-solid ratio is 2.9 m$^3$/t. Variation of uranium concentration with time is summarized in Figure 4. Comparisons of leaching rate of bacterial heap leaching and conventional acid heap leaching are shown in Figure 5, and Analysis of particle size of tailings is provided in Table III.

Table III. Analysis of particle size of tailings.

| Particle size (mm) | Percent of the total weight % | Grade % | Leaching rate % |
|---|---|---|---|
| >10 | 15.90 | 0.021 | 86.87 |
| <10~>8 | 5.48 | 0.019 | 93.44 |
| <8~>6 | 10.96 | 0.015 | 88.46 |
| <6~>4 | 34.32 | 0.013 | 93.80 |
| <4 | 33.33 | 0.012 | 94.78 |

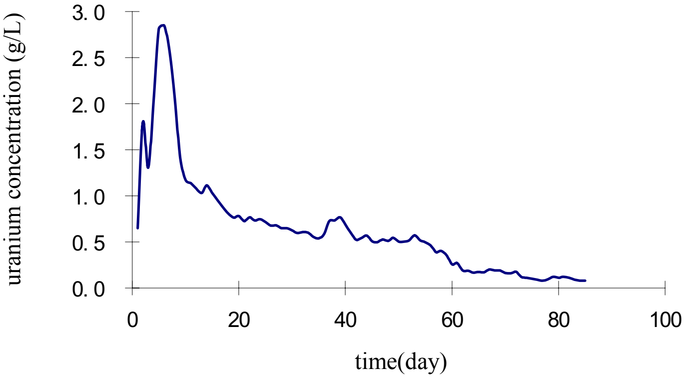

*FIG. 4. Variation of uranium concentration of bio-heap-leaching.*

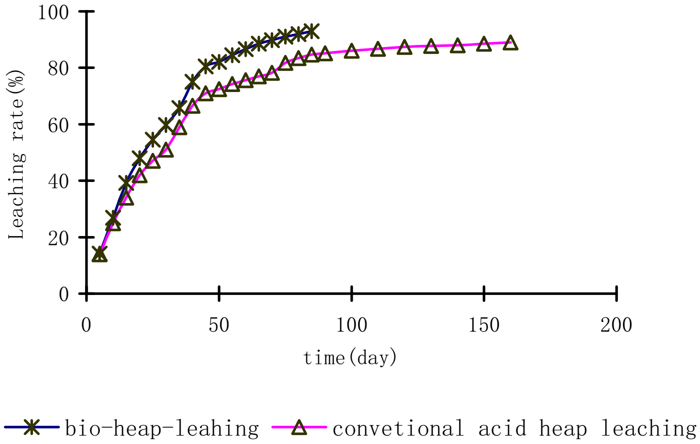

*FIG. 5. Variation of leaching rate with time.*

From the results it is demonstrated that lots of economic and technical norms are better than that of conventional acid heap leaching. The uranium concentration is over 0.5g/L for 55d; this phenomenon is never seen in the past. The analysis of particle size of tailings show that it is advantageous to improve leaching rate by reducing the ratio of ore with bigger particle size under the condition of perfect penetrability of heap.

## 5. Economics of bacterial heap leaching

### *5.1. Comparison of main economic and technical norms of bacterial heap leaching with that of conventional acid heap leaching*

Leaching results of six heaps with fine particle size are summarized in Table IV. It showed that in the defined period, leaching rate of bacterial heap leaching increased by 2 percent, acid consumption decreased by 0.35% and total liquid-solid ratio dropped by 1.57, compared with conventional acid heap leaching. The improvement of such economic and technical norms can bring great economic benefits.

Table IV. Results of bacterial heap leaching and conventional acid heap leaching

| Serial number | Acid heap leaching 1 | Acid heap leaching 2 | Acid heap leaching 3 | Acid heap leaching 4 | Acid heap leaching 5 | Bio- heap leaching |
|---|---|---|---|---|---|---|
| Grade of crude, % | 0.158 | 0.181 | 0.143 | 0.142 | 0.136 | 0.189 |
| Grade of tailings, % | 0.013 | 0.0185 | 0.0148 | 0.0147 | 0.0152 | 0.0154 |
| Leaching rate by liquid, % | 89.39 | 87.16 | 90.16 | 90.48 | 88.61 | 92.95 |
| Leaching rate by tailings, % | 91.77 | 89.78 | 89.65 | 89.65 | 88.82 | 91.88 |
| Average uranium concentration, g/L | 0.327 | 0.495 | 0.264 | 0.294 | 0.232 | 0.606 |
| Spraying time, d | >150 | 125 | >150 | >150 | >150 | 85 |
| Acid consumption, % | 2.52 | 2.35 | 2.40 | 2.45 | 2.51 | 2.10 |
| Liquid-solid ratio | 4.32 | 3.46 | 4.88 | 4.47 | 5.33 | 2.9 |

### *5.2. Analysis of economic benefits*

(a) The leaching rate is higher about 2% than that of conventional acid heap-leaching, and the quantity of uranium leached from ore increased 148 kg,

(b) Acid consumption reduced almost 0.35%, and about 14t of sulfuric acid is saved,

(c) The total liquid-solid ratio dropped 1.57, almost 6130m$^3$ of leaching solution is decreased,

(d) Since the leaching period is shortened, the productive task is finished, 2.5 months earlier against the past. About 1×10$^6$ kw power, 30t coal, 25t lime and 2400 working days are spared. 9000 samples analyzed are dropped. If the production is carried out during 2.5 months, about 10t uranium can be gained.

## 6. Discussions

(a) Because of the limited conditions, everyday the quantity of regenerated leaching agent accounts for 35~50% of the total, the other part is the acidic barren solution adjusted with sulfuric acid, and desire results are gained. If the total leaching agent is regenerated, better results can also be reached. From other hand, the results show that bioleaching of some type of ores, leaching agent do not to be regenerated totally, the quantity can be determined by test.

(b) Oxidant is needed to improve leaching rate. The common oxidants are manganese dioxide ($MnO_2$), sodium chlorite ($NaClO_3$), hydrogen ($H_2O_2$), and ferric sulfate. They are expensive and some can cause environmental pollution, as well as not reused. Since ferrous ion in barren solution can be oxidized by bacteria to ferric ion, which is an oxidant, ferrous ion can be recalled economically.

(c) The leaching rate and leaching period are influenced by many different factors. According to the ore type and heap conditions, particle size, spraying system and intensity, and acidity of leaching agent are all determined suitably. Perfect penetrability and uniform spraying should be maintained during the overall period of leaching.

(d) When uranium concentration reduced significantly after several days of leaching, the heap should be loosened by digger, as a result, the ore of the bottom is transferred to the top, the ore in the edge is delivered to the midst, and ore can be leached fully. This makes it advantageous to improve leaching rate, fasten leaching velocity and the growth of bacteria in heap.

## 7. Conclusions

(a) By compared with conventional acid heap-leaching, the leaching rate increased about 2%, the acid consumption reduced 0.35%, the leaching period shortened 75d and the total liquid-solid ratio dropped 1.57, economic benefits and social benefits are distinct. The technique of bacterial heap leaching is an optimal plan to improve economic benefits of the mine.

(b) The strains employed in this experiment, by domestication in barren solution, have higher tolerance to fluorion ($F^-$) and chlorion ($Cl^-$), and in the solution with low pH and high content of salt, can oxidize ferrous ion to ferric ion.

(c) Bioreactor and YDT packing material can meet the need of the production. The biofilm has higher tolerance to toxic material and adaptability to varied environment. By a series of measurement taken and experience gained, the technique of regenerating leaching agent is perfected; the wide application of bacterial heap leaching can be realized soon.

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# RESTORATION: ENVIRONMENTAL ISSUES

# Perspective of exploitation of new sandstone type deposits by ISL method and environmental impact from uranium deposits mined out by in situ leaching in Ukraine

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**Abstract.** In Ukraine, two uranium deposits, Devladivske and Bratske, were mined using acid in-situ leach method during the seventies-eighties. No restoration of the affected aquifer was made after mining. More than ten years after the end of mining, no displacement of the contaminated aquifer has been observed. In contrast, a process of self-restoration has been observed, with a significant decrease of U, Th, Ra, sulphates content. pH increased from 3.9 to 6.2. Self-restoration of the aquifer may be attributed to significant content in coal and clay minerals in the leached formation, that promote self-neutralization of the affected aquifer.

Presently thirteen uranium deposits of exogenic infiltration genesis type (sandstone type) have been discovered within the Dniprovskyi brown coal basin in Cenozoic sedimentary cover of the Ukrainian shield. The deposits were formed as a result of geochemical processes on the Ukrainian shield, on the boundaries between zones of bed oxidation and Paleogene unoxidized coaly terrigenous rocks filling depressions in the basement. The majority of deposits are located in river and transitional river to lagoon-liman sediments. These are small to middle-sized deposits with uranium resources from 500 up to 3600 tonnes of U and content of metal in ore from 0.01 up to 0.08% U.

As it is known, in situ leaching (ISL) is safer than underground mining concerning environmental impact. The main advantage of the ISL method, in comparison with traditional underground mining, is its high economic efficiency. For this reason, now a majority of uranium mining countries in the world is focusing prospecting and exploration on this type of deposits.

Two deposits of this type, Devladivske and Bratske, were effectively mined out by ISL method using sulfuric acid solution. Three deposits, Safonivske, Surske and Sadove, were transferred to the Skhidnyi Mining and Concentration Combine (SMCC). Field tests conducted earlier on the Safonivske deposit have shown sufficient efficiency of uranium extraction by ISL method. Examination of a possibility to apply to remaining deposits this method is a task of further work in this direction. Besides this, the replacement of sulfuric acid by more ecological pure reactant, particularly by carbonate-oxygen reactant is actual. In this connection the proper research is also conducted.

Mined out Devladovskoe and Bratskoe deposits were reclaimed according to the legislation existing in that period. Alienated ground was recultivated and transferred to primary land user. Recultivation of Bratskoe mine site is being finished. As a result of mining, underground waters of productive horizon were polluted by natural radionuclides in a higher degree than prior to the beginning of mining. During the exploitation of deposits a network of monitoring wells was created. At present, the supervision of chemical composition and level of underground waters is conducted by the specially created hydrogeological group of the VostGok Mill.

The general area of Dneprobas where uranium deposits suitable for mining by ISL method have been discovered makes about 100 000 km$^2$ and uranium resources are estimated at a level of 70 000 tons.

The essence of the ISL method is that bedded deposit located in water-bearing horizon, which are combined to non-tight sediments, are drilled from surface by wells with installation of filters within ore intervals. Some wells (injector) are used for underground injection of leaching solution containing reagent. Other wells (producer) are used for pregnant solution pumping. Pregnant solution is the result of the interaction between leaching solution and ore minerals during its movement through ore body from injector to producer wells.

Extracted solution is moved to the main pipeline using system of modular pipelines and further to the processing plant, where useful component is being extracted by sorption on ionite. Reagent is added to the solution which has stayed after an extraction up to the necessary concentration. The received solution through injector wells again moves underground. The sulfuric acid with concentration from several grams up to 50 grams per liter is usually used as reagent.

## 1. Devladovskoe deposit

Devladovskoe deposit is situated in the Dnepropetrovsk area in the upper part of Devladovsko-Ternovskay paleovalley. It is located in Buchak sediments of Paleogene. The formation of Buchak sediments occurred within the limits of an ancient river valley, which was formed in a basement depression located within the limits of deposit at depths of 32-95 meters from surface (Figure 1).

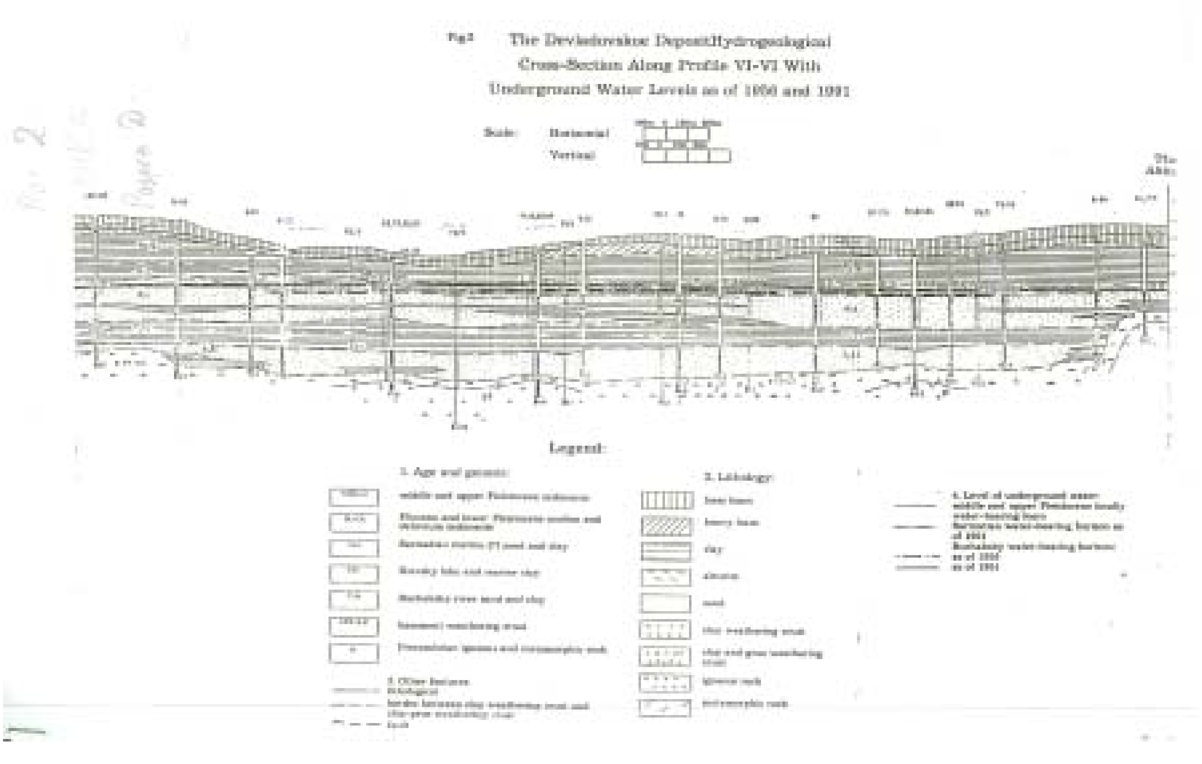

*FIG. 1. The Devladovskoe deposit: Hydrogeological cross-section along profile VI-VI with underground water levels as of 1956 and 1991.*

Uranium mineralization has been found in more than 20 ore bodies. The uranium ore is represented by coal-clay sand, which is similar to country rock. Uranium mineralization is associated to coal-clay substance cementing sandy particles. Distribution of uranium mineralization on plan and in section is rather non-uniform.

Three water-bearing horizons are located within the deposit, including the Buchak horizon where ore bodies are located. All water-bearing horizons are isolated from each other by sustained in section and plan impermeable horizons and are not used by the local population.

Radionuclide composition of underground waters of the Buchak aquifer, which is productive for uranium, is characterized by rather high concentration of radium and lead (isotope 210), exceeding in the natural condition allowable concentration limits. This makes this water unsuitable for water supply according to the requirements HPEV-97.

During commercial operation about 50,000,000 m$^3$ of productive solution were sent through the processing plant. Uranium recovery was 76%, compared to a 70% design.

During mining 39 monitoring wells were drilled basically through the productive Buchak horizon. The essence of supervision consists in periodic (2 times per year) testing of water and complete chemical analysis, including definition of radionuclides. On this basis, maps of distribution of the ISL residual haloes were built up.

Since 1987, after the end of mining and surface recultivation, large-scale regime supervision has been carried out by unit #13 of Hydrospetsgeology (from the town of Alexandrov, Russia). In 1991, in connection with the failure of budget financing, Unit #13 stopped its works. Till 1995 regime supervision was not carried out at all. In 1995 the hydrogeological group for supervision over ISL sites was created at the VostGok Mill. During three years the regime network of wells was restored.

During mining by ISL method of the Devladovskoe deposit, the environmental pollution occurred basically by the following:

(a) Pollution of ground surface as a result of emergency situation by pregnant solutions from pipelines spills,
(b) Pollution of underground waters as a result of interaction of working solutions with ore and country rock.

The pollution of ground surface during mining of the Devladovskoe deposit had local character in places of pipelines' breaks. As it was shown by special research such pollution penetrates on small depth. In a course of recultivation the polluted ground was removed, taken out, and disposed in special trenches. In a result of recultivation the soil cover was restored. Radiating conditions on deposit surface was restored to norms.

The pollution of underground waters had a halo character and affected all mined deposits. On a map of distribution of the polluted underground waters of the productive water-bearing horizon, in which processes of uranium leaching from ore bodies proceeded, three contours of haloes of underground waters pollution by natural radionuclides for the following periods were built up (Figure 2):

1) At the end of mining (1982-1984).
2) At the end of supervision by unit #13 (1987-1991).
3) On the moment of restoration of large-scale regime supervision by the VostGok Mill (1996-1997).

At the end of mining operation, the halo of the polluted waters occupied all area of mining, extending from northeast to southwest over 4.5 kilometers and 400-600 meters wide. Downwards the flow of underground waters extended by 950 meters from the extreme southwest border of the mined area. The basic reason of such movement of the halo along the underground water flow was periodic injection of low mineralized superficial water from ponds and fresh water, in injection wells within southwest flank of a deposit. Thus, the created additional pressure in the most polluted part of the halo resulted in downward movement.

In 1987-1991 the halo of residual solutions of radionuclides repeated basically the 1984 contour, though there were some differences showing occurring processes of underground self-cleaning. In particular, some wells earlier polluted, appeared in a contour of clean waters.

*FIG. 2. Radionuclide pollution of the Buchaksky water-bearing horizon at the Devladovske deposit as of 1984, 1991 and 1997.*

In 1997 the contour of pollution had also changed. However, water was cleared from radionuclides up to natural condition in a little number of monitoring wells, especially in the upper part of a section.

The occurring process of self-cleaning from radionuclide pollution proves to be true also by following data:

(a) Average uranium content in a halo of the ISL residual solutions in 1997 was 2.2 mg/1 and had decreased slightly in comparison with data of 1984 when it was 2.6 mg/1,

(b) Average radium content in 1997 was 0.741 l0$^{-11}$ Ci/l and had decreased 6.2 times in comparison with 1984 data. Thorium content in 1997 had decreased 20.7 times in comparison with 1984 data of 1984,

(c) Lead content accordingly had decreased 2.5 times,

(d) Polonium content did not changed appreciably (0.5-0.7 l0$^{-11}$ Ci/l),

(e) Average value of pH had increased from 3.9 up to 6.2,

(f) Average content of sulfates had decreased 1.4 times, and

(g) General mineralization had decreased 1.2 times.

| | 1984 | 1997 |
|---|---|---|
| U | 2.6 mg/l | 2.2 mg/l |
| Ra | 4.6 10 –11 Ci/l | 0.741 10-11 Ci/l |
| Th | 30 10-11 Ci/l | 1.45 10-11 Ci/l |
| Pb | 35.4 10-11 Ci/l | 14.2 10-11 Ci/l |
| pH | 3.9 | 6.2 |
| Sulfates | 6 g/l | 4.2 g/l |
| General Mineralization | 9.5 g/l | 7.8 g/l |

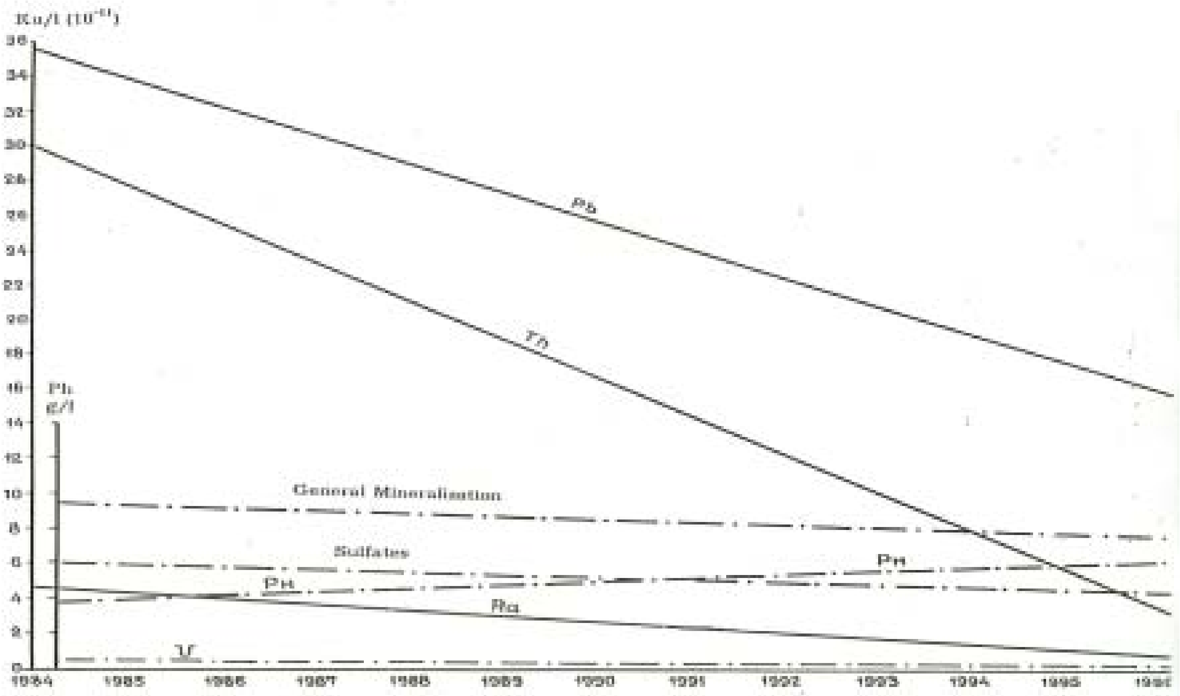

*FIG. 3. The graphic scheme of the ISL residual solutions self-cleaning within the Devladovskoe deposit.*

Using available monitoring data of natural radionuclides, within productive water-bearing horizon after mining of Devladovskoe uranium deposit by ISL method, it is possible to note that the halo of pollution as a whole, is not moving. The phenomena of its self-cleaning is appreciable in the heads of paleodepressions.

The pH increase, demineralization and desulfatization of ISL residual solutions is shown (Figure 3). Gradual, and sometimes rather fast, reduction of the content of radionuclides is also shown. On the basis of the comparative analysis of haloes it is possible to conclude that expected speed of migration (10 meters per year) was not achieved and, probably, practically will be less.

## 2. Bratskoe deposit

Bratskoe deposit is situated in the Nikolaev area and, as well as Devladovskoe deposit, is located in Buchak sediments of Paleogene in the head of Bratskaya paleodepression. Average thickness of these sediments is 6 meters. They are located at depths from 8 m up to 42 m from surface (Figure 4).

The deposit consists of five ore bodies, which are concentrated in sub-horizontal zones, extending along the paleo-depression. The uranium ore is represented by coal sand in which uranium component is coal and clay substance cementing sandy particles. The largest quantity of uranium is associated with its sorption on coal substance.

The productive Buchak horizon is limited by kaolin clay, which thickness varies from 0.3 up to 15 meters, and by impermeable levels of Paleozoic-Cenozoic weathered crust which thickness is 4-20 meters.

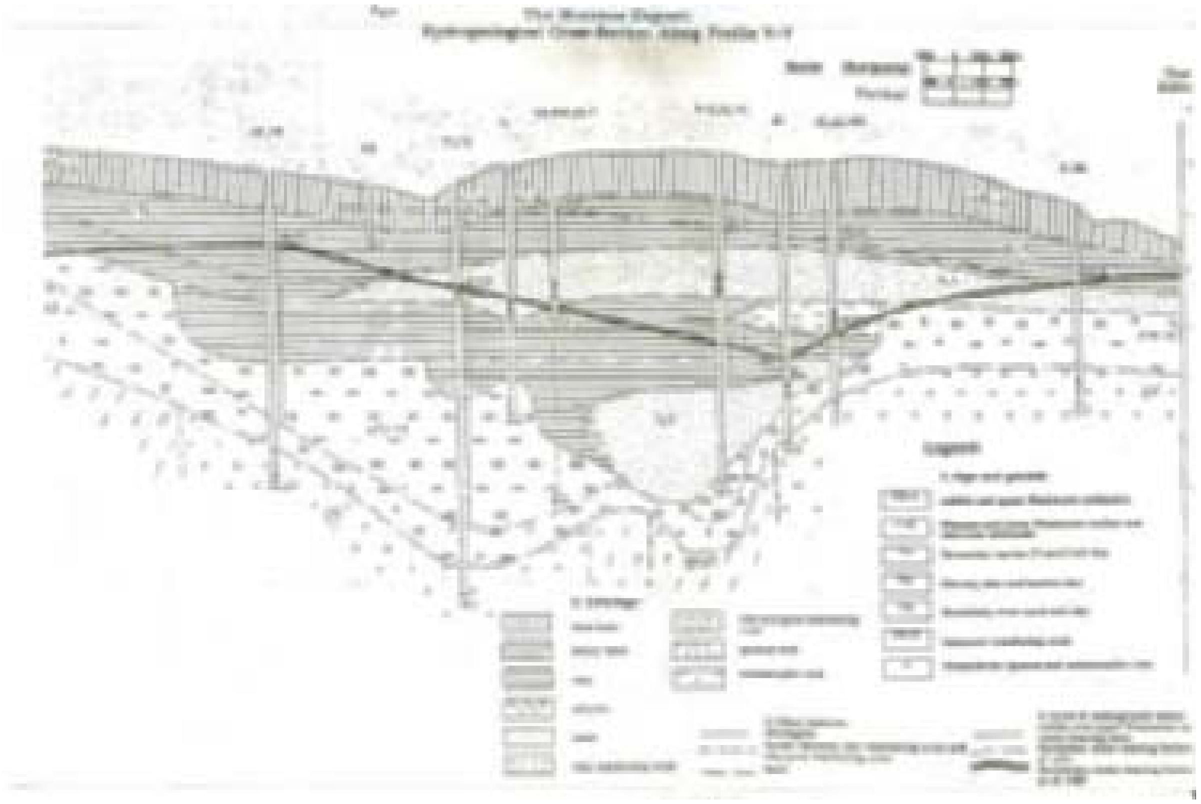

FIG. 4. The Bratskoe deposit: Hydrogeological cross-section along profile V-V.

The deposit was mined during 14 years (1975-1989). Sulfuric acid, at a 8-15 g/l concentration, up to 30 g/l during limited periods, was used as leaching agent. During last year of operation, no acid was injected. Recovery of uranium was 72.3%, compared to a designed recovery of 70%.

The map of pollution of Buchak water-bearing horizon was built at the end of mining (1991) (Figure 5). Length of the halo of ISL residual solution was about 2,8 km over a width of 500-700 meters. In separate areas such phenomena as radionuclides self-cleaning, was observed within Devladovskoe deposit.

Some characteristics of the halo of residual solutions (higher values of average pH in comparison to Devladovskoe deposit, lower mineralization) allow to make the assumption that downwards flow of the halo of radionuclides as a whole, remains in the limits observed in 1990-1991.

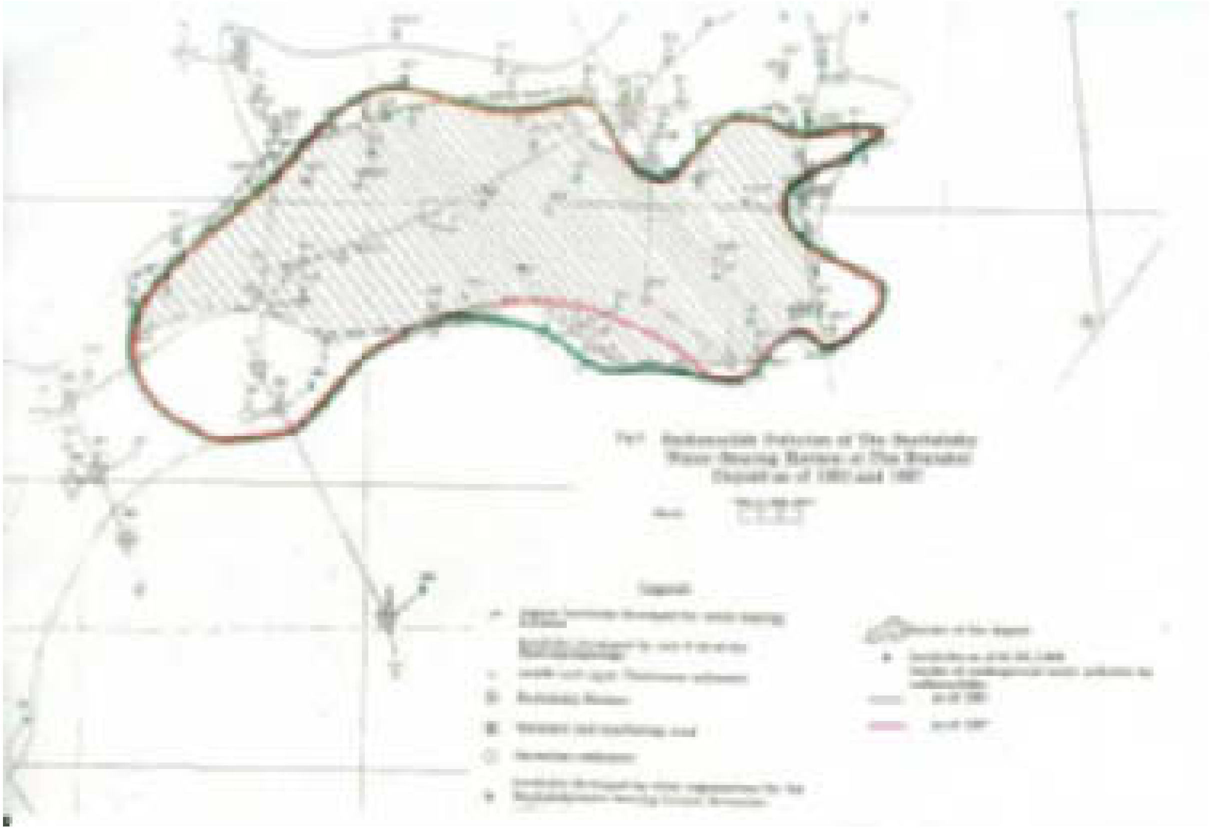

*FIG. 5. Radionuclide pollution of the Buchaksky water-bearing horizon at the Bratskoe deposit as of 1991 and 1997.*

## 3. Results of monitoring

The analysis of numerous actual data, collected during supervision of the Devladovskoe and Bratskoe deposits, mined out by ISL method, allows to make the following conclusions:

(a) Underground waters of productive Buchak horizon in the initial condition were not usable for water supply because of high mineralization. The increased concentration of $Ra^{226}$ and $Pb^{210}$, which background contents prior to the beginning of mining exceeded state standards of allowable concentration limits, are established in them.
(b) As a result of uranium mining by ISL method, productive Buchak water bearing horizon, limited at different directions by reliable impermeable formations has appeared to be polluted by natural radionuclides above background concentration.
(c) At the end of mining, the halo of ISL residual solutions, polluted by radionuclides, was basically within the limits of the uranium deposits, having moved downwards over 950 m for Devladovskoe deposit and over 450 m for Bratskoe deposit.
(d) According to the data of actual supervision within Devladovskoe deposit, this halo is no longer moving. During the 14 years after the end of mining, it did not substantially moved downwards underground waters flow and has remained within its 1984 borders. The most active processes of transformation of residual acid solutions occur in western part of the halo, on the border of the fresh rocks that have not been leached by acid solutions. Thus, the halo does not leave practically the initial border, which was established at the end of mining.
(e) The processes of self-cleaning of a halo of ISL residual solutions have begun along boards of paleodepressions and especially in the upper part of underground waters flow.

(f) The general tendency of demineralization, desulfatization and denitrification, as well as reduction of the average contents of radionuclides in a contour of primary halo of ISL residual solutions, is distinctly shown. It promotes additional hydro geological separation of ISL zones and practical exception of ecological risk in the future.

(g) Monitoring of levels and chemical contents of underground waters, as well as of migration of contours of pollution, testify about geological isolation of residual technological solutions. In this connection the risk of further penetration of radionuclides in biosphere is absent. The usual now technogenic-geological system – "residual technological ISL solution-geological environment" can be considered as a place of long preservation of technological ISL solutions in natural geological environment within deposits and separate ore bodies.

(h) The halo of residual solutions at Bratskoe deposit is smaller according to its shape than a similar halo at Devladovskoe deposit. It also has lower contents of natural radionuclides, except uranium, lower general mineralization and contents of sulfates, higher pH.

(i) Taking into account the practically complete analogy between described deposits, there is a base to transfer results of supervision on Devladovskoe deposit to Bratskoe deposit, including character of underground migration of natural radionuclides.

(j) The main factors determining favorable conditions to underground protection during mining of ISL amenable uranium deposits discovered in Ukraine, is "the natural security" of productive Buchak horizon, which is caused by the following:
    - Its restriction in different directions by reliable impermeable formations,
    - Isolation of deposits from surface by up to 50-70 meters of clay sediments,
    - Very slow speed of underground waters flow, (few meters, sometimes few tens of meters per year) in connection with small hydraulic slope of underground flows,
    - Location of ore on natural geochemical barrier, and
    - Significant contents of coal and clay material in country rocks that promotes localization and further self-neutralization of residual technological ISL solutions.

(k) Taking into account all mentioned above, and also the natural very high degree of lithological and filtration heterogeneity of the productive horizon, for uranium and other rare elements, in the sedimentary cover of the Ukrainian shield, the restoration of underground waters up to natural conditions is not expedient and is practically impossible.

In addition, it is also necessary to mention some interesting facts:

(a) During mining of Bratskoe deposit, the ground between lines of injection and pumping wells was used for planting of agricultural cultures by the workers of mining complex. Rigid radiating and sanitary-epidemiological control of products did not revealed any deviations from norms, and

(b) After mining and recultivation, different kinds of agricultural cultures were planted within the area of Devladovskoe deposit. Radiological and sanitary-epidemiological research on wheat, corn, potatoes, vegetables has shown that production does not contain radioactive and others toxic substances above allowable concentration limits, and can be used as food.

In 1999-2000 Kirovgeology carried out researches, which task was to compare two different technologies of uranium leaching (carbonate and acid) from sandstone deposits of Ukraine, by conducting laboratory geotechnological studies of Safonivske and Novoguriivske deposits in a static mode.

On each of these deposits, 4 special wells were drilled and, after radiometric study of core, the samples were selected, crushed and then ground up to 0.074 mm (200 mesh).

Uranium leaching from these samples was carried out by sulfuric acid solution at a concentration of 15g/1, and sodium solution at a Na2CO$_3$ concentration of 30g/1, with an oxidant (potassium permanganate).

Results of the laboratory studies established close performance in uranium recovery by both methods: for ores with an average grade of more than 0.005%, the uranium recovery by acid leaching was on average about 90%, and by carbonate leaching about 85%.

Thus, conducted activity demonstrates a principal opportunity of effective uranium leaching from sandstone deposits of Ukraine, not only by acid solutions but also by more ecologically safe sodium solutions. The operations in this direction proceed.

The next step is field tests using sodium leaching. According to the results, initial evaluation of the exploitation of each deposit, amenable to ISL method, should be made.

As a result, we think that it is possible to conclude that, carried out monitoring of condition of natural radionuclides haloes of residual solutions in uranium deposits mined out by ISL method in Ukraine, as well as researches conducted on carbonate leaching, testify real opportunity to mine sandstone type deposits without essential environmental impact. It is completely real as there is a practical experience of minimization the negative influence, not only on surface but also underground.

## 4. Main conclusions

(a) Underground waters of productive horizon had high mineralization and were not usable for water supply.
(b) After uranium mining, productive water-bearing horizon was polluted by natural radionuclides above background concentrations.
(c) At the end of mining the halo of pollution was within the limits of the uranium deposits, having moved downwards flow of underground waters over 0.5-1 km.
(d) This halo is no longer moving. 14 years after the end of mining, it has not essentially moved downwards underground waters flow.
(e) The processes of self-cleaning have begun along boards of pale depressions in the upper part of underground waters flow.
(f) The general tendency of demineralization, desulfatization and denitrification, as well as reduction of the average content of radionuclides in the halo of pollution is shown.
(g) Monitoring testifies the geological isolation of the residual solutions. In connection to that, the risk of further penetration of radionuclides in biosphere is absent.
(h) The most favorable factor, for uranium mining in Ukraine by ISL method, is “the natural security” of productive Buchak horizon associated to the following:

  - Its restriction from different directions by reliable impermeable formations,
  - Isolation of deposits from surface by thick clay sediments,
  - Very slow velocity of underground waters flow,
  - Location of ore on natural geochemical barrier, and
  - Significant contents of coal and clay material that promotes further self-neutralization of residual solutions.

(i) Taking into account all mentioned above the restoration of underground waters up to a natural condition is not expedient.
(j) Monitoring of conditions of residual haloes of pollution testifies quite real opportunity to apply ISL mining to new “sand” type deposits, without essential infringement of ecological condition of environment.

# Groundwater restoration research of acid ISL in China

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**Abstract.** Based on the research on groundwater restoration of acid in situ leach mining project in West of China, development of groundwater restoration research in China is shown. The restoration test results demonstrate that Electrodialysis reversal (EDR) is an effective method for groundwater restoration. The plan of in-situ leach groundwater restoration is shown in this study also.

**Key words.** Uranium, In situ leach, Groundwater restoration, Electrodialysis reversal.

## 1. Introduction

In situ leach mining of uranium (U) has developed into a major mining technology, which compares favorably with traditional open pit mining and underground mining for recovery of uranium ore. Since the first in situ leach mining of uranium deposits was initiated, the percentage of U product in China by in situ leach mining has grown steadily. In situ leaching offers less initial capital investment, shorter start-up times, greater safety, and less labor than conventional mining methods. There is little disturbance of the surface ground or surface water, no mill-tailings piles, and no large open pit. Also many of hazards of working in a U-processing plant are reduced.

In situ leach mining also has environmental disadvantages. During mining, large amount of groundwater is circulated. When a sulfuric acid leach system is used, the acid is introduced into an area where many chemical reactions may occur. Also, injection of oxidant with leaching solution will cause valence and phase changes of indigenous elements such as As, Fe, Mo, S and V etc. Thus other species along with U will be solubilized. Furthermore, the surrounding groundwater can become contaminated by migration of the leaching solution from mining zone.

Following mining, the water in the mined zone is left with an ionic strength that exceed the natural baseline level for some constituents. Much attention has been directed toward the high fate of heavy metals solubilized during the mining process. Groundwater restoration of the site has become a main question. Restoration is necessary to reduce the amount of undesired chemical constituents left in solution when mining operations have ceased, and thus to return the groundwater to a quality consistent with potential use.

## 2. Present situation of Chinese in situ leaching

Through years' development, there is a commercial scale uranium deposit, amenable to in situ leach mining operation for uranium recovery in West of China [1]. Dilute sulfuric acid is used as leaching solution in this acid-leaching system. At surface, the U in pregnant solution is recovered by ion-exchange techniques; the residual U-barren solution from the ion-exchange operation being regenerated with suitable leaching chemical and re-circulated to the wellfield for reuse. To minimize the likelihood of migration of the leaching solution from production zone, the system is usually operated with more solution being withdrawn than injected [5].

As a part of the planning and procedure for in situ mining project, relevant enterprises in China have paid more attention on the research of groundwater restoration from the beginning.

The question and problem faced by this in-situ leach mining site are groundwater restoration and site reclamation, to protect the valuable groundwater and to prevent adverse environment changes.

To achieve restoration, constituents added to the groundwater for mining and those mobilized during the mining process must be removed or rendered non-mobile. The optimum restoration technique for a given site will be largely determined by inherent geologic and hydrologic condition of that site, and observation during the initial research and development phase.

Table I. Groundwater baseline level data of the mine.
(Unit: mg/l unless otherwise indicated)

| Parameter | Baseline concentration | Parameter | Baseline concentration | Parameter | Baseline concentration |
|---|---|---|---|---|---|
| pH | 7.8 | $K^+$ | 7.59 | $H_2SiO_3$ | 11.67 |
| Eh,mV | 215 | $Ca^{2+}$ | 34.65 | Mn | 0.05 |
| TDS | 389 | $Mg^{2+}$ | 25.86 | Cd | 0.005 |
| Total hardness | 180.0 | $Fe^{3+}$ | 0.41 | Ni | 0.01 |
| $HCO_3^-$ | 155.3 | $Fe^{2+}$ | 6.0 | Pb | 0.05 |
| $CO_3^{2-}$ | 10.00 | $Al^{3+}$ | 1.90 | Zn | 0.10 |
| $SO_4^{2-}$ | 372.5 | $F^-$ | 0.33 | V | 0.01 |
| $Cl^-$ | 55.5 | As | 0.002 | U | 0.63 |
| $NO_3^-$ | 0.009 | Cr | 0.005 | Se | 0.219 |
| $Na^+$ | 80.93 | Cu | 0.01 | $Ra^{-226}$, pCi/L | 18.6 |

Those baseline level data (Table I) can be used to estimate the groundwater pollution level, and can guide the design of groundwater restoration.

## 3. **Determination of groundwater restoration process** [4]

As the wellfield is still in operation, there is no ceased mining area for restoration test. Uranium content of leaching solution is the main factor to determine when the wellfield should cease. During the mining process, uranium concentration in leaching solution decreases gradually, and groundwater changes simultaneously. In order to meet the demand of the restoration, and according to the geologic condition and well layout of the site, test wells are selected. The solution from the test wells is taken as the affected groundwater for restoration test (Table II). The geologic information indicates that solution in test well cannot be separated from production wells. Accordingly, it can be made sure that the contamination of groundwater in coming ceased well will be less than within test wells. So as to determine the representativity of test wells.

Table II. Main constituents of the affected groundwater.
(Unit: g/l unless otherwise indicated)

| Parameter | $SO_4^{2-}$ | $Cl^-$ | $NO_3^-$ | Ca | $Mg^{2+}$ | $Na^+$ | $Al^{3+}$ |
|---|---|---|---|---|---|---|---|
| Concentration | 7.8 | 0.15 | 0.23 | 0.38 | 0.24 | 1.13 | 0.24 |
| Parameter | ΣFe | $NH^{4+}$ | TDS | pH | Eh, mv | Total hardness | U |
| Concentration | 0.24 | 0.04 | 10.1 | 1.81 | 450 | 1.06 | 0.02 |

According to characteristic of the affected groundwater, detailed research work has been conducted to get an accepted and economic technique to remove chemical constituents from the affected groundwater, which renders the resulting water fit for re-injection into the aquifer for restoration. Those processes include reverse osmosis [2], neutralization and precipitation, electrodialysis.

Test results indicated that due to the high content of TDS, total hardness and $SO_4^{2-}$ in affected groundwater, reverse osmosis process did not suit to treat this kind of water. During the treatment process, calcium sulfate became scale on the surface of reverse osmosis membranes easily, this kind of scale affecting the function of reverse osmosis; thus preventing the treatment process. Also high content of ΣFe in this effected groundwater has a damaging affection on the reverse osmosis membranes. Pre-treatment is needed to remove the high content of total hardness, $SO_4^{2-}$ and ΣFe before this kind of water enter the reverse osmosis process, that will result in a more complicated process and higher treatment cost.

Neutralization and precipitation is another method to treat this kind affected groundwater. Limestone is used as precipitator in fluidized bed process [3]. Free acid, TDS, heavy metals and anions except $SO_4^{2-}$ can be removed effectively. But the ground water needs to be treated further to meet the standard to re-inject into the aquifer for restoration. More detailed research about this method is still under way.

Through allsided study on electrodialysis process, a conclusion has been obtained that electrodialysis process is an effective method for the site groundwater restoration.

## 4. Groundwater restoration with electrodialysis process

### *4.1. Flow sheet* (See Figure 1)

TDS and $SO_4^{2-}$ content of the treated solution can be used to describe and evaluate this process. The crucial value can be figured out according to hydrogeological information, and the value will approach the physical circumstances of wellfield.

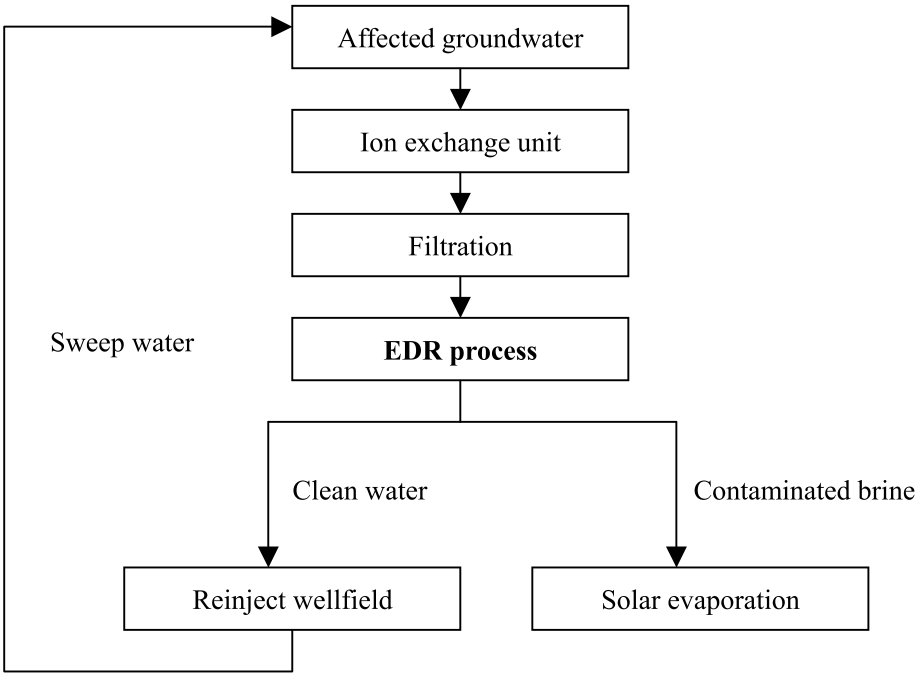

*FIG. 1. Flow sheet of groundwater restoration with electrodialysis process.*

Treatment capacity of the EDR unit is 1m$^3$/h. Surface-separation process consist of pumping affected water from the underground production area and treating the water in ion exchange-filtration-electrodialysis reversal (EDR) unit system, The clean water from EDR unit is used to reinject the aquifer for groundwater sweep, and residuals from the treatment process is disposed by solar-evaporation process to avoid undesirable pollution of surface water or of the land.

Ion exchange systems have been used in conjunction with those water treatment equipments especially for the removal of residual mobile uranium in affected groundwater, although the process can be used for deionization.

Due to the high content of TDS, total hardness and $SO_4^{2-}$ in affected groundwater, during Electrodialysis process, calcium sulfate is easy to become scale on the surface of electrodialysis membranes. To solve this problem, a special electrodialysis unit is adopted, that is Electrodialysis Reversal (EDR) unit. This unit utilizes an automatical system to change electric pole periodically. Before calcium sulphate becomes stable crystallization on the surface of the membrane, change the electric pole to prevent polarization occurs on the membrane. Polarity change can make calcium sulfate leave the membrane and flow out the unit with discharge.

## 4.2. Experimental results

### *4.2.1. The affection of various TDS content on EDR process*

During the restoration process, TDS content in affected groundwater will reduce gradually, so to determine the affection of TDS content is useful to guide the restoration. Refer to the baseline value and restoration requirement; conductivity of clean water from EDR unit is controlled at the level of 1500μs/cm, its TDS content equal to 0.8g/L. The results are showed in Table III.

Table III. The affection of various TDS content on EDR process.

| TDS (g.L$^{-1}$) | 5.00 | 9.53 | 12.26 |
|---|---|---|---|
| Conductivity (μs.cm$^{-1}$) | $0.75\times10^{-4}$ | $1.25\times10^{-4}$ | $1.38\times10^{-4}$ |
| PH | 1.87 | 1.70 | 1.61 |
| Current drain of clean water recovery (Kw.h.m$^{-3}$) | 3.10 | 4.55 | 5.39 |
| Current efficiency, % | 82.1 | 81.6 | 76.5 |
| Clean water recovery rate, % | 82.6 | 69.2 | 61.3 |

At the beginning of restoration, TDS content in affected groundwater is in the range of 8-12g/L, the first several pore volumes high TDS content groundwater will be disposed in solar-evaporation pond directly. All the values of EDR operation are in an acceptable and economic level. As restoration goes on, TDS content will reduce to about 5g/l soon. At that time, clean water recovery rate reach 82.6%, it is helpful for the restoration.

### *4.2.2. The relation of concentration factor to clean water recovery rate in EDR process*

Water recovery rate is an important parameter for an EDR unit. High water recovery rate means more clean water can be used to sweep the aquifer, the restoration cost will reduce accordingly. In order to get more clean water, concentrated water is circulated in EDR unit. Under the condition of economic operation, try to obtain a maximum TDS content in concentrated water. The test results of concentrated water circulation are showed as following.

Table IV. The test results of concentrated water circulation.

| No. | Parameter | TDS g.L$^{-1}$ | pH | Desalination rate, % | Concentration factor | Clean water recovery rate, % |
|---|---|---|---|---|---|---|
| 1. | Feed water | 5 | 1.87 | 87.0 | 6.33 | 82.6 |
| | Concentrated brine | 26.1 | 1.36 | | | |
| | Clean water | 0.88 | 2.47 | | | |
| 2. | Feed water | 9.55 | 1.80 | 93.93 | 3.05 | 69.2 |
| | Concentrated brine | 27.0 | 1.34 | | | |
| | Clean water | 0.58 | 2.47 | | | |
| 3. | Feed water | 12.4 | 1.71 | 92.89 | 2.65 | 61.3 |
| | Concentrated brine | 30.5 | 1.31 | | | |
| | Clean water | 0.88 | 2.58 | | | |
| 4. | Feed water | 12.4 | 1.63 | 91.98 | 2.63 | 61.6 |
| | Concentrated brine | 30.70 | 0.99 | | | |
| | Clean water | 0.97 | 2.53 | | | |

Table IV indicated that those desalination rates are all above 90%, but the clean water recovery rate declines as TDS content increases in feed water. Limited by calcium ion content in feed water, the maximum TDS content in concentrated water is about 30g/l. the Concentration factor of concentrated water need to follow an economic level.

### *4.2.3. Contaminants Removal rate in affected groundwater*

With EDR unit, different contaminants in affected groundwater present a high removal rate. Especially for $SO_4^{2-}$, $NO_3^-$, $NH_4^+$, introduced by the uranium recovery process, its removal rate reach 90%. Also high fate of heavy metals in groundwater has been removed effectively, and its content in clean water can meet the restoration demand. Table V shows the main results.

Table V. Results of contaminants in affected groundwater with EDR unit.
(Unit: g/l unless otherwise indicated).

| | Feed water | Clean water | Concentrated brine | Removal rate % |
|---|---|---|---|---|
| Conductivity µs.cm$^{-1}$ | $1.4\times10^4$ | 1500 | $2.95\times10^4$ | 89.3 |
| TDS | 12.36 | 0.875 | 30.46 | 92.9 |
| $SO_4^{--}$ | 8.89 | 0.65 | 21.6 | 92.7 |
| $Ca^{2+}$ | 0.490 | 0.030 | 0.856 | 93.9 |
| $Mg^{21}$ | 0.297 | 0.039 | 0.651 | 86.9 |
| $\Sigma Fe^{1}$ | 0.571 | 0.058 | 1.48 | 89.8 |
| $Fe^{2+}$ | 0.530 | 0.052 | 1.21 | 90.2 |
| $NH_4^+$ | 0.164 | 0.022 | 0.311 | 86.6 |
| $NO_3^-$ | 0.716 | 0.010 | 1.214 | 98.6 |
| $Cl^-$ | 0.078 | 0.009 | 0.195 | 88.5 |
| $Al^{3+}$ | 0.300 | 0.036 | 0.780 | 88.0 |
| $Na^+$ | 0.807 | 0.018 | 3.289 | 97.8 |
| Free acid | 2.50 | 0.11 | 4.23 | 95.5 |

## 5. Conclusions

The restoration of affected groundwater to pre-mining condition and protection of groundwater resources is of greatest environmental concern. Restoration test was completed on October 1999. The above studies have demonstrated that groundwater restoration to an acceptable quality of original use, following sulfuric acid leaching, is achievable. Technology used was electrodialysis reversal and reintroduction of treated water into the aquifer.

With electrodialysis reversal technology, the main problem during restoration, calcium sulphate crust on the surface of membranes has been solved effectively.

Further studies on groundwater restoration are still carried on in the field. It is believed that improve EDR unit performance can achieve 90% re-injection, this improvement would reduce treatment pore volumes required as well as the evaporation pond volume and surface requirement.

As the mining of whole wellfield is not ceased, and limited by the field geological condition, restoration of the whole mined-out area will be commenced as soon as feasible. To observe the hydrological condition and evaluate groundwater pollution, unremitting monitoring on mining field groundwater has been performed.

For more requirement on environment from the public and the future of uranium industry, research on leaching will focus on the research of an optimal lixiviant and leaching process that is operationally effective in uranium recovery, will not affect the hydraulic properties of the formation, and will not present significant restoration problems.

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# Natural and anthropogenic multi-pathway risks associated with naturally occurring uranium mineralization in aquifers: Scoping calculations

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**Abstract.** A multi-pathway, probabilistic risk model related to “undiscovered” uranium deposits in an agricultural area in Southern Colorado is compared to known uranium districts in which in situ leach (ISL) mining activities are underway or planned. The control area is a portion of the Alamosa Basin designated by a National Uranium Resource Evaluation (NURE) study as favorable for regional redox-controlled, roll-front sandstone uranium deposits (Johnson, V.C., McCarn, D.W. et al, 1982). Favourability for occurrence of uranium deposits is based on depositional environment, alteration fronts, coincident geochemical fronts, and the presence of elevated concentrations of uranium in ground water proximal to the favorable zone.

Near-field, high-volume, artesian, agricultural water wells in the 60 km long favorable zone are remobilizing uranium, probably radium, possibly other redox-sensitive metals (As, Se, Mo, V, etc.), and radon out of the redox zone and distributing this material as contaminants onto agricultural crops using large, central-pivot irrigation systems. Previous limited geochemical sampling has demonstrated concentrations as high as 140 µg / L $U_3O_8$ from these wells. High-volume pumping in near-field wells in the reduced zone or in the redox zone is postulated to cause oxidizing waters to flow across the redox zone thereby mobilizing uranium in a manner similar to commercial ISL uranium mining. Recent sampling of the surficial aquifer demonstrates high correlation of elevated uranium values with the favorable zone in the confined, artesian aquifer further suggesting that remobilization may be occurring.

Because of decades-long water use in the area, significant contaminants are likely to have built-up in soils. Planned fieldwork in the control area includes a multiphase surface radiometric survey of the area soils to identify radium anomalies, soil & water geochemical sampling, crop sampling, and soil mapping of the affected area to identify re-concentration mechanisms such as caliches or reduction and retention of uranium in peat-forming soils which are common in the area. Identification and closure of the relatively few near-field wells responsible for remobilization of environmentally sensitive metals and radionuclides would result in a reduction of future contamination of agricultural soils and crops and consequent reduction of risk.

A model of roll-front concentration and remobilization from agricultural pumping may also be considered as a possible analog for the far-field effects of a high-level nuclear waste repository such as the Yucca Mountain Project. The analog includes soil re-concentration as well as possible pre-concentration mechanisms. At present, the far-field model accommodates only advection and diffusion to create a dilute plume intercepted by agricultural wells.

This paper describes the scoping calculations used to estimate soil buildup of radionuclides, transfer to crops, and the eventual increased risk to a designated critical group.

## 1. Introduction

A methodology of examination of water-bearing basins is proposed based on techniques developed for uranium exploration and nuclear waste management risk assessment. Agricultural water use from these basins and aquifers in the Western United States may cause remobilization of heavy metals such as uranium, radium, arsenic, selenium, and molybdenum into irrigation, domestic, or livestock waters. The associated metals may concentrate in soils and be available for uptake into native as well as food plants.

The methodology makes use of geological, geochemical and geophysical techniques to identify areas of increased risk. Formalized mineral deposit models and recognition criteria are used to probabilistically assess regions within basins favourable for the concentration of these metals.

Anthopogene water use in aquifers significantly modifies the natural flow of water and may induce leaching of pre-existing mineral deposits. Distribution of these waters for agricultural purposes can introduce heavy metals and radionuclides into the food chain.

Simple remedial actions such as modification of water use, relocation of "near-field" wells adjacent to zones of mineral deposition, selection of crops with low uptake characteristics, and identification of contaminated soils can significantly reduce risk. Alternate methods include the use of advanced sorbants to remove contaminants from water prior to land application.

## 2. Location of study

The Alamosa Basin, Southern Colorado is part of the Rio Grande Rift and is a Basin and Range Province structure bounded to the west by the San Juan Volcanic Field and to the east by the Sangre de Cristo Mountains.

The surface expression of the Alamosa Basin is the San Luis Valley, and is dominated by agricultural activities using irrigation waters from both the confined, artesian aquifer and an unconfined, surficial aquifer. This confined, artesian aquifer was identified by Johnson, McCarn et al (1982) [24] as favourable for regional redox-controlled, roll-front uranium deposits (Figure 1). At least 7,500 flowing, artesian wells are present in the aquifer (Powell, 1958), many of them in the favourable zone.

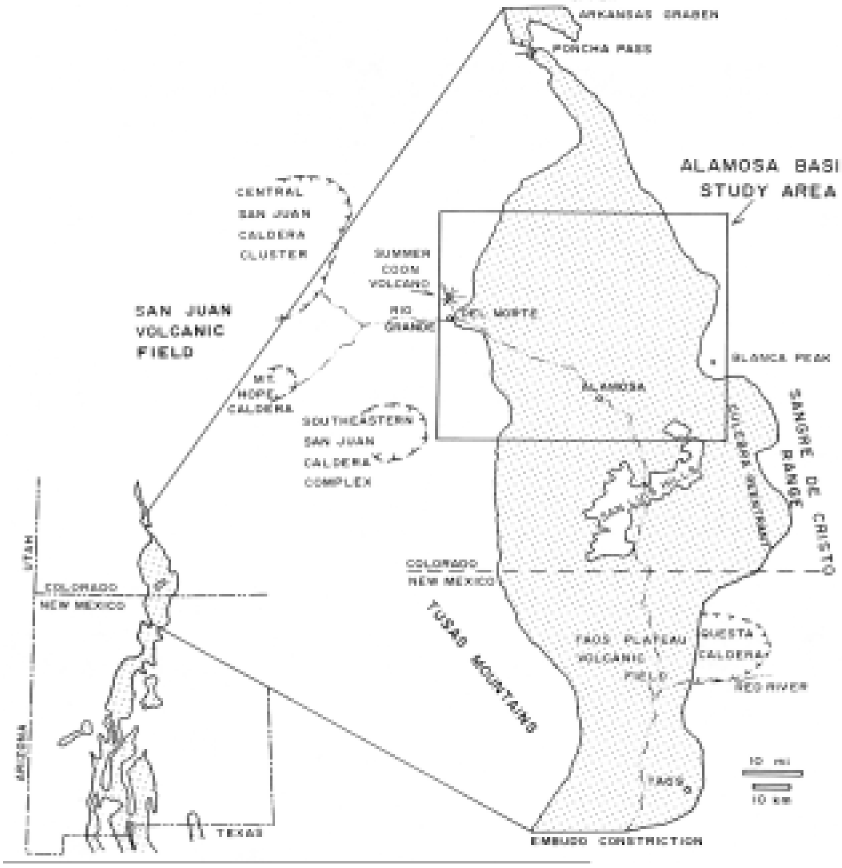


FIG. 1. Location of study.

## 3. Objectives

The objective of this study is to determine the means and extent of uranium, radium and heavy metal remobilization in the San Luis Valley and to develop a multi-pathway risk model of transfer to the accessible environment and human/animal receptors. Origin, transport and fate of these contaminants is analyzed. Geochemical data from ground water and basin analysis models is incorporated into the risk assessment. Comparison of the risk model to ongoing ISL and other uranium mining operations may give insight into the role of radionuclides and heavy metals into the overall risk of mining.

The objective of this paper is to develop a multipathway risk model, based on the historical, agricultural use of the basin and to provide scoping calculations. These scoping calculations are based on:

(a) Geological model of roll-front uranium deposit favourability;
(b) The historical types and areas of each crop grown;
(c) Estimated annual water budget including irrigation, precipitation, and evapotranspiration;
(d) Estimates of the area underlain by mineralized rock, the endowed area, and barren zones;
(e) Measured and estimated uranium, radium, and heavy metal concentrations in water; and
(f) Soil characteristics of the San Luis Valley.

The GENII computer codes (Napier et al, 1990) [28] are used to simulate irrigation, reconcentration in soils, uptake to plants, radionuclide intake to animals and man. Potential health effects are then estimated.

## 4. Nuclear waste management analog

The Yucca Mountain Project (YMP), as part of the biosphere model, includes the use of irrigation well waters intercepting the hypothetical plume from the repository. At present, the model assumes advection and diffusion to disperse the plume prior to intercept. The data derived from this study may be useful to YMP in estimating uptake as well as reconcentration mechanisms from agricultural water use.

Because of the well-documented irrigation and farming history of the Alamosa Basin, validation of empirical models of reconcentration such as GENII (Napier et al, 1988), in a similar, desert environment, could provide a present-day analog for the Amargosa desert. Dose calculations and assumptions presented in the Yucca Mountain Biosphere Process Model Report (CRWMS M&O 2000i) [18] could be reviewed in the light of the experience with the Alamosa Basin.

A second objective is to assess the validity of far-field reconcentration and remobilization mechanisms of the Alamosa Basin with the Biosphere Model of the Yucca Mountain Project. At present, the Biosphere Model assumes advection and diffusion of released material in the repository to create a dilute plume of material intercepted by agricultural wells. The source term is then reconcentrated into agricultural soils, transferred to plants, and ultimately provide a dose to man.

In the Alamosa Basin, the operant mechanism prior to anthropogene development was concentration of uranium and other metals at a redox-front. This now appears to provide a significant source-term that can be studied. Another feature regarding agriculture is the use of phosphate fertilizers that contribute to the radium and uranium source term, which might complicate the issue of soil reconcentration.

### *4.1. Features, events, and processes*

Features, Events, and Processes (FEP) form an essential part of the formal analysis of the Yucca Mountain Repository and is a critical part of the model validation process (CRWMS M&O 1999a, b; CRWMS M&O 2000a, b, c, d, e, f, g, h, i) [8 to 18].

FEPs that can significantly change the performance of the repository must be modelled. Initially 1,786 FEPs were reviewed, classified, and 47 of them were considered an important Biosphere issue. None of these FEPs involves ore-forming processes as a pre-concentration mechanism for radionuclides, which are later released via anthropogene activities.

There are several discrete mechanisms in the far field at Yucca Mountain capable of providing a mechanism of reconcentration for materials.

These are:

(a) Surficial Uranium Deposits: Carlisle (1978) identified the Amargosa Desert as very favorable for non-pedogenic calcrete uranium deposits. Occurrences of such calcretes occur in similar geologic settings near Las Vegas.

(b) Basal-Tabular Uranium Concentrations: The Amargosa Desert contains oxidized valley-fill sediments directly overlying reduced Paleozoic limestones.

Reconcentration of repository material in ore-forming mechanism is an active process, which selectively removes material with high efficiency from groundwater. Even if this process were to be interrupted after several hundred years, the amount of material remobilized by an anthropogene event such as high-volume irrigation well would significantly increase potential doses.

### *4.2. Present day analog*

This paper proposes a natural analog for a reconcentration & remobilization FEP that can be demonstrated to be operating based on present evidence in the Alamosa Basin. This study of the Alamosa Basin incorporates a mathematical and conceptual model of multipathway risk similar to that used for the Yucca Mountain Biosphere analysis.

## 5. Characteristics of regional redox controlled, roll-front deposits

The general characteristics of regional redox-controlled, roll-front deposits include a very specific, yet common, geochemical condition in basinal sediments reflecting either the depositional nature of the basin, or regional oxidation of the basin, or both. The deposits are epigenetic. That is, they form after the deposition of the sediments and generally reflect continuing, regional diagenetic changes in the sediments.

Roll-front deposits are created best in high-permeability, well-developed aquifers that permit large volumes of water and dilute mineralizing solutions to migrate through the redox front allowing for the concentration of minerals. They may also reflect remobilization of pre-existing syngenetic deposits. Roll-fronts tend to be very continuous over large distances and reflect basin-wide, regional conditions. Examples of roll-front deposits have been described throughout the world and include China, Kazakhstan, Mongolia, Uzbekistan, New Mexico, Texas, and Wyoming [5,7,19,21,27,30,35].

### *5.1. Geochemistry of roll-front deposits*

In the type examples of redox-controlled, roll-front, sandstone deposits all cases exhibit well-defined, regional redox fronts over large areas. In the basins, the redox pairs generally associated with roll-fronts are the ferrous-ferric pair ($Fe^{+2}$-$Fe^{+3}$) and the sulfide-sulfate pair ($S^{-2}$-$S^{+4}$). This is generally represented by the oxidation of pyrite to sulfate with the production of limonite. In the Grants Mineral Belt, a zone of limonite alteration is well defined throughout the basin and is bounded by a reduced, pyritic zone in the basin interior to the north.

Oxidizing, uranium, selenium, arsenic, and molybdenum-bearing solutions migrate downdip and precipitate when a reducing environment at the regional redox boundary is encountered. Through time, uranium accumulates along with other redox-sensitive metals to form ore deposits. Where zones of higher permeability exist, more water is allowed to flow and more uranium tends to be concentrated.

### *5.2. Geometry of roll-fronts*

The overall geometry of roll-front deposits is ribbon like in plan and single ore bodies can be described as C-shaped rolls in cross-section. Roll-fronts are typically sinuous and frequently “stacked”. That is, multiple ore-rolls appear in close spatial proximity to each other and are separated vertically, and are frequently characteristic of the deposit type. The stacked rolls in most deposits are usually within 100 to 500 m from each other, although in some cases may be up to 5,000 m. Vertical dimensions range from 0.5 to 3 m in height and 5 to 20 m in width, although the deposits in Kazakhstan are generally much broader and may range up to several hundred meters.

Individual rolls are frequently laterally continuous over several hundred meters, but may merge with other rolls or disappear in large part as a function of lithologic controls and hydrologic and geochemical conditions. Overall, stacked roll-fronts can be continuous over several tens of kilometers. Local ore controls within the stacked rolls typically reflect slight changes in permeability of the sandstone such as multiple, fining-upward sequences of fluvial sand or fan deposition, local clay interbeds, fine mudstone (overbank) deposition, and the presence of local concentrations of organic reductants.

### *5.3. Continuity of deposits*

Deposits of the roll-front type tend to be continuous over substantial distances. The Crownpoint ore trend extends continuously for over 30 km, and the regional redox front can be traced for over 150 km in which several other ore trends are present such as the Churchrock trend. The roll-fronts of the Chu-Saryssu Basin also exhibit similar geometries and ore trends often extend over 50 km in length. The overall length of the redox front extends over 200 km. The major ore zones occur in four different stratigraphic horizons, each having multiple stacked rolls. Roll-front deposits of the Wyoming basins have similar dimensions.

The favourable zone defined by Johnson, McCarn et al (1982) in the Alamosa Basin has dimensions consistent with all of these deposits, is 60 km long and 5 km wide. Favourability for occurrence of uranium deposits is based on depositional environment, alteration fronts, coincident geochemical fronts, and the presence of high concentrations of uranium in ground water proximal to the favourable zone sampled from irrigation wells in the area.

### *5.4. Baseline water quality data*

Baseline water quality data are being compiled for roll-front uranium deposits in Kazakhstan, Texas, New Mexico, and Wyoming as a means to develop surrogate estimates for the control area. COGEMA, Kazatomprom, and Uranium Resources, Inc. have so far supplied data. These data include multiple samples at each well location for the common anions and cations as well as trace metal concentrations for metals such as selenium.

## 6. Control area

In order to establish a basis of comparative risk, other anthropogenic activities can be compared to the risk of mining. A control area was selected based on previous work by Johnson, McCarn et al (1982), in which high volume water use for agriculture appear to induce leaching in a manner similar to ISL mining [22,34]. The control area is in the San Luis Valley, Southern Colorado as shown in Figure 1. The basin underlying the San Luis Valley is the Alamosa Basin. Figure 2 shows the arcuate zone of favourability, which is similar in overall dimensions to redox-controlled, roll-front uranium deposits in New Mexico, Wyoming and Kazakhstan.

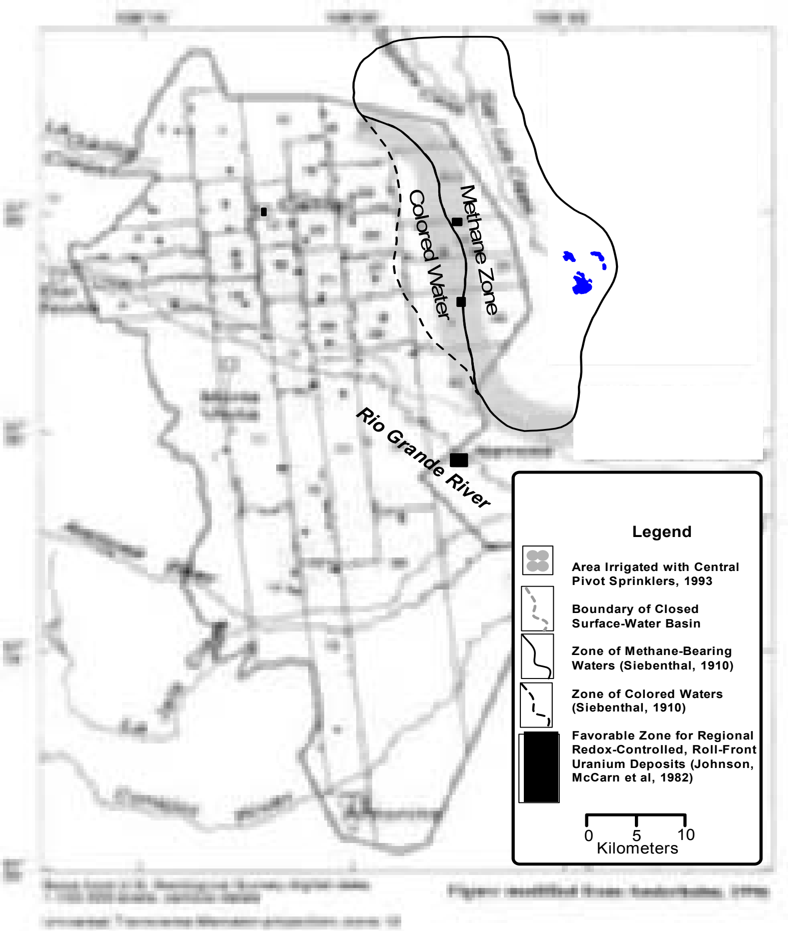


*FIG. 2. Zone favourable for regional redox-controlled, roll front uranium.*

## 7. Assessment of uranium resource favourability

During the energy crisis of the early 1970s, Congress funded the National Uranium Resource Evaluation (NURE) programme, which assessed the favourability for uranium deposits throughout the United States on a 2-degree quadrangle basis (about 60,000 km$^2$ each). Johnson, McCarn et al (1982) investigated the Trinidad Quadrangle and determined that a 60 kilometer-long, 5 kilometer-wide zone (300 sq. km) (Figure 2) was favourable for regional redox-controlled, roll-front uranium deposits similar to those found in the Wyoming basins. The area was assigned as a speculative resource area by analogy to the Wyoming basins.

The limits of the favourable zone in Figure 2 are defined by interpretation of four cross-sections based on borehole data from Powell (1958) to identify alteration fronts by Johnson, McCarn et al (1982) and the position of methanogenic and brown-stained waters from Siebenthal (1910) [33]. Limited hydrogeochemical sampling in the northern part of the near-field zone by Johnson, McCarn et al (1982) confirmed the presence of high concentrations of uranium at or near the redox front. These data correlate well with the uraninite stability field and show a significant drop in oxidation potential in waters from the oxidized to the reduced sediments.

Powell (1958) published numerous drillers' logs that reflect the colour, or redox state, of sands and clays within the basin defining the limits of the near-field zone. Siebenthal's western limit of methanogenic wells is coincident with the eastern boundary of this zone. Sampling by Johnson, McCarn et al (1982) established that the hydrogeochemistry of the northern part of the zone is consistent with roll-front uranium deposits based on Eh, pH and presence of elevated concentrations of uranium at the front (Figure 3).

Comparison of the favourable zone to the Underhill's (1993) [37] ISL mining criteria reveals that the geology and hydrology of the favourable zone meets all requirements for ISL mining, and most of the requirements that would provide optimal characteristics. The missing optimal requirements such as ore reserve estimates [20] and concentrations of by-product metals are unknown at the present time.

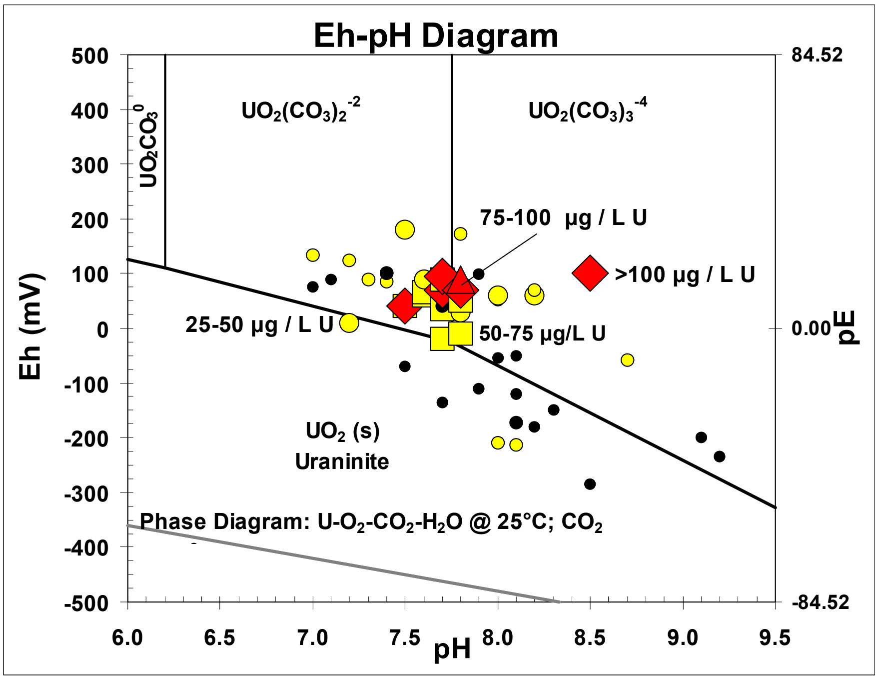


*FIG. 3. Near-field zone sampling results.*

## 8. Sediments of the Alamosa Basin

The Alamosa Basin is the northern part of the Rio Grande Rift, a Basin and Range structure characterized by crustal extension, a thinning crust, high heat flow, and extensive effusive volcanic rocks. The basin is asymmetrical, deeper in the east adjacent to the Sangre de Cristo Mountains, whereas the western flank is more gradual. The bulk of the sediments in the basin are derived from the adjacent San Juan Volcanic Field to the west. The basin has interior drainage, and a line of the ephemeral lakes characterizes the geographic low of the basin's depocenter.

### *8.1. Santa Fe group*

The Santa Fe Group directly overlies the upper Oligocene tuffs and is generally divided into two units. The lower unit is composed of claystone, sandstone and conglomerate. The unit displays a characteristic colour related to oxidation states of the sediments and is generally yellow, yellowish-brown, brown, red, light gray, medium gray, dark gray, green, greenish-gray, bluish gray, blue, and black (Powell, 1958). The colours change from oxidizing to reducing across the Alamosa Horst.

The Upper Santa Fe Group, called the Alamosa Formation by Siebenthal (1910) [33] and Powell (1958), reflect a change in the depositional framework to a lower energy, fluvial-lacustrine sequence from the higher-energy conglomerates below. Redox conditions are oxidizing to the west and become abruptly reducing over the Alamosa Horst. The reduced sediments include peat, lacustrine clays and black sands. This sequence culminates in widespread blue clay, about 1-2 m thick, which forms the upper confining zone for the artesian aquifer. The clay is overlain by Quaternary alluvium.

The most prominent surface feature of the basin is the Rio Grande Fan that extends outward from the San Juan Mountains into the basin. The coarse sands and gravels that characterize the proximal Rio Grande Fan facies interfinger with reduced lacustrine and peaty sediments toward the centre of the basin. The sediment colour and sandstone-to-shale ratio changes basinward from 100:1 at the basin margin to 1:2 near Hooper in the basin interior. Figure 4 shows the redox conditions of sediments in wells and the changing depositional environment as characterized by the sand to shale ratio. Many sand and gravel beds extend from the heads of the alluvial fans to the center of the basin (Powell, 1958, p.22). In the favorable, near-field zone (Figure 5) identified by Johnson, McCarn et al (1982), the ratio is about 1:10 to 1:1.

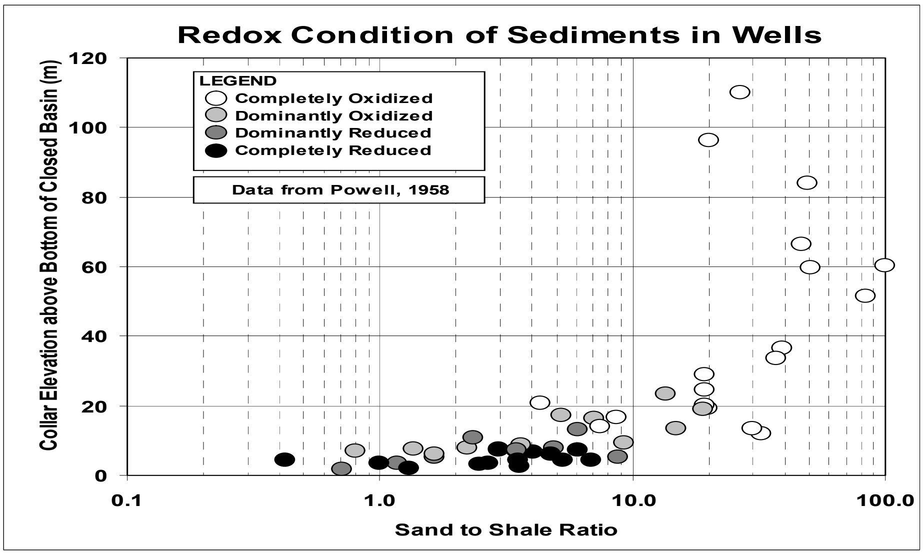


FIG. 4. Redox condition of sediments in basin.

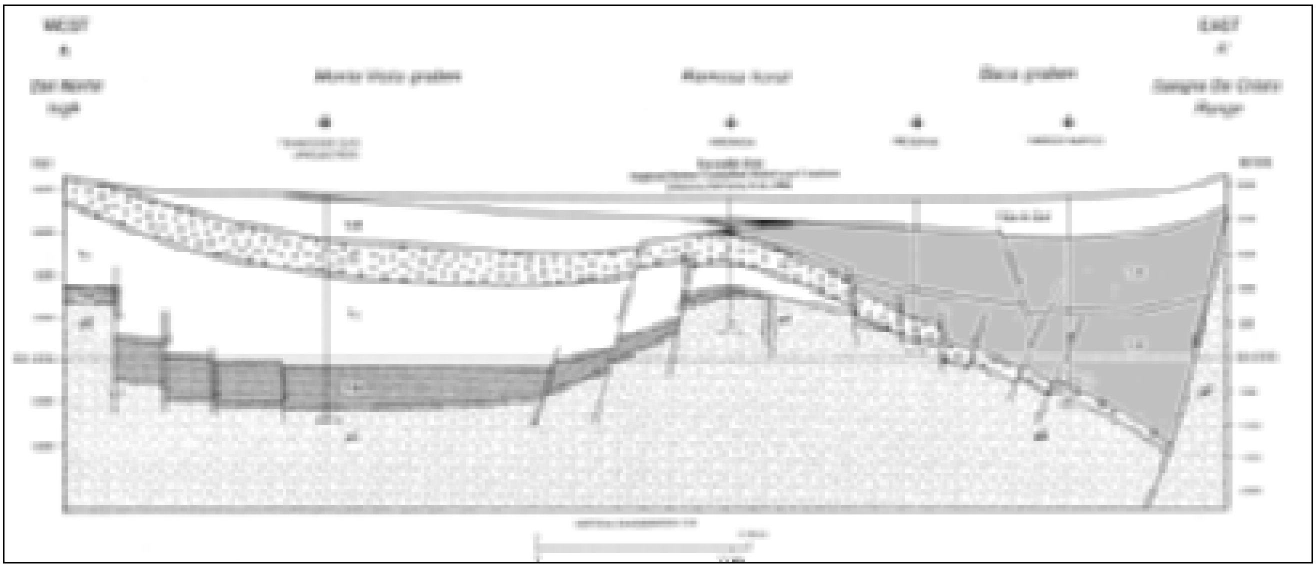


*FIG. 5. Structure of the Alamosa Basin (from Brister & Breis, 1994).*

### *8.2. Alteration zones and chemical characteristics*

The chemistry of the water and chemical characteristics of the sediments also changes basinward from oxidized to reduced [26]. The near-field zone based on alteration of sediments is directly correlated with the eastern edge of the zone of methanogenic waters - tinted waters mapped by Siebenthal (1910, p.47). Siebenthal described the extent of flammable gas in water wells in a belt 50 km long and 20 km wide and noted the presence of a zone of brown-tinted, coloured water, apparently migrating in the direction of highest water use to the west.

Throughout the area, blue clay, 1 to 2 m thick, of lacustrine origin, overlies the zone of artesian waters in the distal fan facies. This regional redox interface defines the zone of uranium favourability from Johnson, McCarn et al (1982). Characterization of the geochemistry of the northern portion of the favourable zone demonstrated the presence of:

(a) Sediment color changes from oxidized to reduced based on well log data from Powell (1958) (Figure 4);
(b) Drop in redox potential (~200 mV) of ground waters correlated with the methanogenic zone of Siebenthal (1910) (Figure 3); and
(c) Elevated concentrations of uranium in ground waters (Figure 3).

## 9. Structural features of the Alamosa Basin

The structure of the Alamosa Basin, presented in Figure 5 modified from Brister & Gries (1994) [4], clearly demonstrates the relation of structure to the favourable zone identified by Johnson, McCarn et al (1982). The Alamosa horst directly corresponds to a changing depositional environment in the upper section allowing the interfingering of fluvial sands of the braided, Rio Grand River system with interior lacustrine and peaty sediments of the basin interior. This allowed for the development of a regional redox front within the upper portion of the basin. The eastern margin of this zone also corresponds to the area of methanogenic wells documented by Siebenthal (1910, p.47), Johnson, McCarn et al (1982).

Based on Brister & Gries (1994), overall structure is a half-graben, flanked to the west by the San Juan Volcanic Field highland and to the east by the high-angle, reverse fault of the Sangre de Cristo Mountains, and separated by the Alamosa Horst. The eastern half-graben, the Baca graben, is asymmetrical, deeper in the east, and represents a closed-basin depositional environment characterized by periodic cyclical deposition of lacustrine clays interbedded with peat and fine- to coarse-grained sandstones, interpreted to be post-depositionally reduced by diagenetically produced humates and methane.

The Santa Fe Group sandstones to the east, in the Baca Graben have also been syn-depositionally faulted, as evidenced by seismic data from Brister & Gries (1994). This faulting has rotated the basement upwards in the area of the Alamosa Horst and downwards along the bounding normal fault of the Sangre de Cristo Mountains. Faulting continues up through the Late Tertiary-Quaternary unconfined aquifer. Depositional features of the Monte Vista Graben are missing completely in the Baca Graben demonstrating that the area was not active during the early history of the Monte Vista Graben. The Baca Graben contains over 3,000 m of Santa Fe Group sediments directly overlying the thinning welded tuff compared to only 750 m of sediments in the Monte Vista Graben. The Monte Vista Graben was active earlier than the Baca Graben.

## 10. Agricultural water use in the Alamosa Basin, Colorado

In the Alamosa Basin and throughout the western United States, agricultural water use is an important aspect of local economies. Thousands of agricultural wells are present within the basin supporting one of Colorado's most important intensive agricultural areas. The primary crops are alfalfa, hay, potatoes, barley and wheat as shown in Table I. Leafy vegetable production includes lettuce, spinach and carrots. Total production value per year is US$ 300-400 million. Figures 6 shows a typical central-pivot irrigation system in operation, and Figure 7 is an aerial view of a portion of the area showing the intensity of agriculture and irrigation.

*FIG. 6. Central-Pivot irrigation in the San Luis Valley.*

The Alamosa Basin contains the single largest resource of water in Colorado and researchers of the U.S. Geological Survey including Siebenthal (1910) and Powell (1958) have reported these resources. The basin has provided for local agricultural irrigation for over 100 years. Because of the artesian character of the basin, agricultural wells have water levels above ground level. Powell (1958) documented over 7,500 flowing artesian wells in the San Luis Valley.

Table I. Primary crops of the San Luis Valley (2001 Preliminary Figures).

| Crop | Hectares | Tonnes /Hectare | KgYield/m$^2$ | Tonnes Crop | \$/Tonne | Crop Value (Millions) |
|---|---|---|---|---|---|---|
| Alfalfa | 67,582 | 9.30 | 0.93 | 628,724 | \$110.23 | \$69.3 |
| Grains | 37,717 | 6.15 | 0.61 | 231,936 | \$128.60 | \$29.8 |
| Other Hay | 37,636 | 4.26 | 0.43 | 160,300 | \$104.72 | \$16.8 |
| Potatoes | 27,478 | 35.32 | 3.53 | 970,416 | \$205.03 | \$199.0 |
| Leafy Vegetables | 9,200 | 11.52 | 1.15 | 106,027 | \$150.00 | \$15.9 |
| Totals | 179,613 | | | 2,097,402 | | \$330.8 |

*Source: Colorado Agricultural Statistics, 2002.*

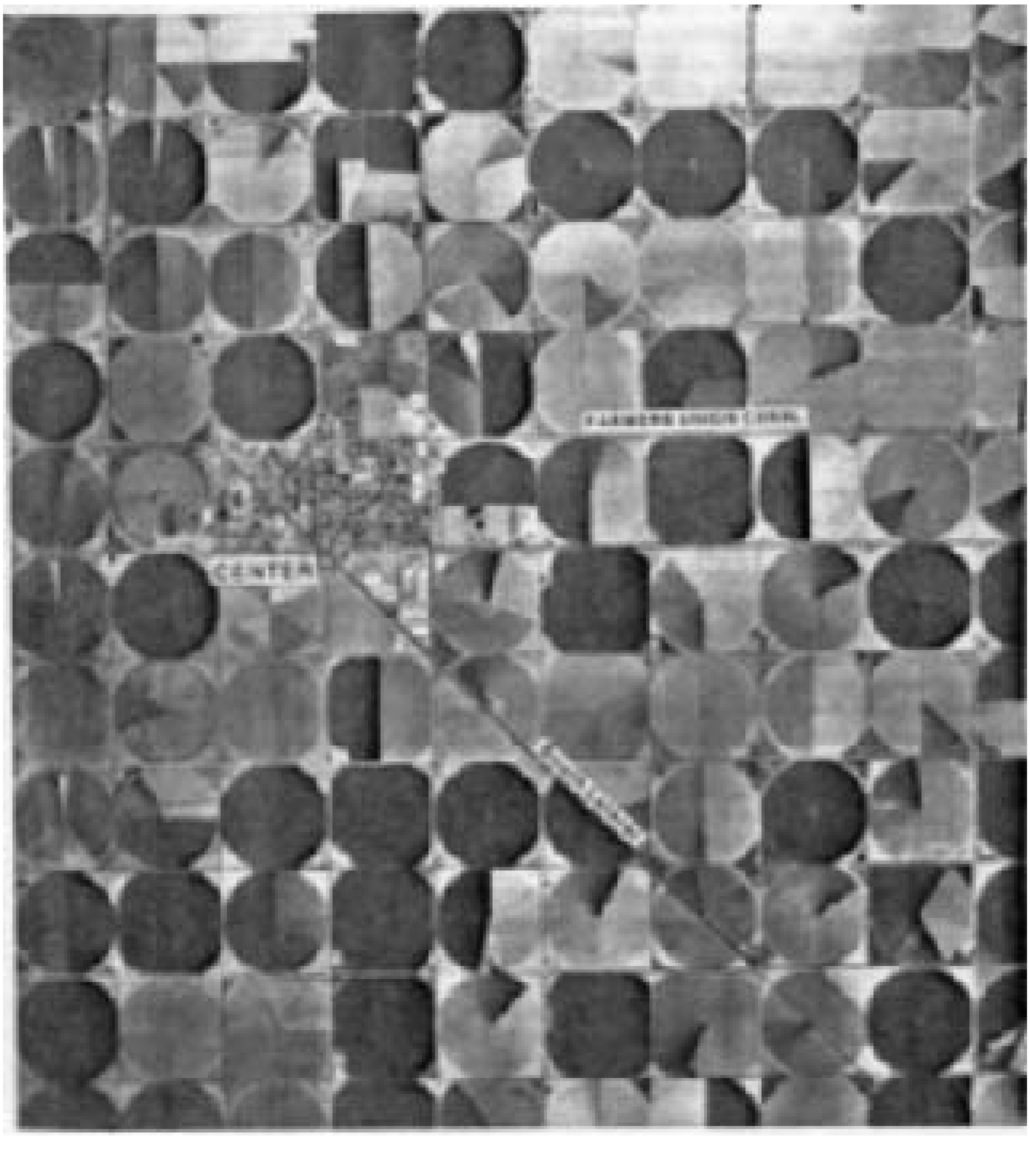


*FIG. 7. Aerial photograph of the Alamosa Basin.*

For the past 50 years, irrigation has been accomplished by large, central-pivot irrigation systems, and previously by flooding the fields. Approximately 925 × $10^6$ $m^3$ are extracted from the basin each year to meet the consumptive requirements. Approximately 180,000 hectares are currently under irrigated production.

In Powell's 1958 study, pumping tests on 8 free-flowing artesian wells (Table II) revealed that both the Santa Fe and Alamosa formations in the confined aquifer have high permeability. The average estimated permeability is about 5 darcies for the confined zone as defined by the Santa Fe formation. As shown in Table II, the transmissibility of the confined aquifer averages 22,125 gal/day/ft. By comparison, the Westwater Canyon Member of the Morrison Formation, Grants Mineral Belt, New Mexico, an excellent candidate for ISL mining (Pelizza & McCarn, 2003) [31], has a transmissibility of 2,556 to 2,698 gal/day/ft (McCarn, 1997) or about 400 millidarcies permeability. The thickness of the Westwater is comparable to the thickness of the confined aquifer.

Table II. Estimated transmissibility and permeability of the confined aquifer.

| Coefficient of Transmissibility (Gal/day/ft) | Jacob - Lohman method | Theis Recovery method | Average value | Estimated Effective Thickness | GPD/Ft$^2$ | Estimated Millidarcies |
|---|---|---|---|---|---|---|
| | | | **Santa Fe Formation** | | | |
| **37-8-13dc1** | 30,800 | 28,600 | 29,700 | 375 | 94.3 | 4,599 |
| **37-8-13dc2** | 60,300 | 63,100 | 61,700 | 375 | 195.9 | 9,554 |
| **37-9-20cc1** | 12,800 | 16,700 | 14,750 | 375 | 46.8 | 2,284 |
| **37-9-34cc** | 30,200 | 30,800 | 30,500 | 375 | 96.8 | 4,723 |
| | | | **Alamosa Formation** | | | |
| **37-8-3bc** | | 7,000 | 7,000 | 375 | 22.2 | 1,084 |
| **37-8-6dc5** | 14,500 | 14,300 | 14,400 | 375 | 45.7 | 2,230 |
| **37-8-7bc5** | 13,000 | 11,400 | 12,200 | 375 | 38.7 | 1,889 |
| **38-8-29dd2** | 6,600 | 6,900 | 6,750 | 375 | 21.4 | 1,045 |
| **Average** | **24,029** | **22,350** | **22,125** | **375** | **70.2** | **3,426** |

*From Powell (1958, p.42 and Table 10).*

## 11. Recent studies in the San Luis valley

As part of the Rio Grande water-quality assessment in 1996 by the U.S. Geological Survey, a study of groundwater quality of the upper, unconfined aquifer (Anderholm, 1996) [1] demonstrated the presence of high concentrations of aluminum, barium, iron, manganese, molybdenum and uranium. These parameters exceeded the maximum contaminant levels set by the U.S. Environmental Protection Agency (EPA). All samples in the study exceeded the EPA proposed standard for $^{222}$Rn, which ranged from 700 to 1,900 pCi/L. This study area coincided with the "near-field" zone of the proposed project. It is postulated that much of the uranium in the upper aquifer originated in roll-fronts in the lower, confined aquifer remobilized by agricultural well pumping. Anderholm (1996, p.51) found that uranium anomalies in the surficial aquifer were located in the eastern part of the San Luis Valley, which correlate with the favourable zone from Johnson, McCarn et al (1982).

## 12. Conceptual model of uranium remobilization in the Alamosa Basin

High-volume, artesian, agricultural wells in the near-field reduced zone or within the redox zone create a groundwater depression and consequent axial flow from all directions towards each well. As flow is established during the peak irrigation season, mildly oxidizing waters move across the redox zone and the associated zone favourable for uranium mineralization, causing the mobilization of soluble uranyl carbonate aqueous phases.

As the uraninite and other mineral phases are leached, radium trapped within the mineral structure is released and moves with the uranium towards the well. In a similar fashion, other redox sensitive metals such as arsenic, selenium and molybdenum are mobilized. Figure 8 shows the conceptual model of uranium remobilization potentially caused by agricultural water use in the near-field zone.

Conceptual review of the location of the agricultural wells with respect to a mineralized zone is critical. Wells located in the oxidized zone may cause reduced waters to flow across the redox front, causing minimal remobilization.

Wells located too far to the east of the redox zone, in the oxidized zone, may cause flow across the zone, but the chemical kinetics of uranium may not cause re-reduction. Mobilized radium may continue to the well.

Wells located at the redox zone or slightly into the reduced zone would provide optimal locations for the remobilization of metals and radium from mineralization. Following extraction by the producing well, analytes are distributed to large areas via central-pivot irrigation systems.

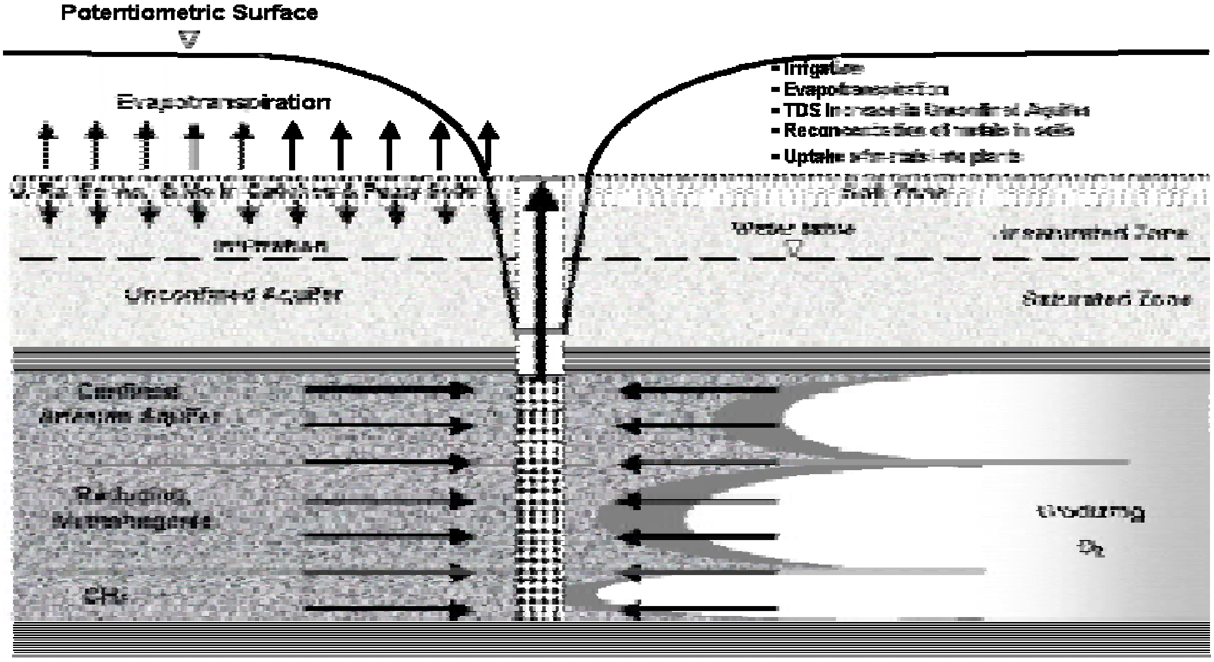


FIG. 8. Model of uranium remobilisation.

### *12.1. Reconcentration of radionuclides in soil* [29]

Intuitively, agricultural water containing trace-metal analytes will concentrate in the upper soil zone due to evapotranspiration of over 95% of the water volume. Over decades of water use, the concentrations will depend on a number of factors including: the partitioning coefficient, $K_d$ (ml/g), of an analyte and the soil; the water balance, the years of irrigation, and other soil parameters.

Baes and Sharp (1981) [2], Napier et al 1988, IAEA (1994), and CRWMS M&O (1999a, b and 2000a, b, c, d, e, f, g, h, i) discuss methods and mechanisms for radionuclide and heavy metal reconcentration in soils which includes the biosphere process model report for Yucca Mountain. As shown in Equation 1, the theoretical basis derives from the soil characteristics including density $\rho$ (g/cm$^3$), moisture $\theta$ ml/cm$^3$), depth of soil $d_s$ (cm), and the partitioning coefficient, $K_d$ (ml/g) of an analyte and the soil. The calculation uses the water balance, which includes precipitation, P (cm), irrigation, $I_t$ (cm), and evapotranspiration, E (cm), to calculate a leaching coefficient, $\lambda_L$, for the soil.

Equation 1: $\lambda_L = \dfrac{P + I - E}{d_s \theta ( 1 + \dfrac{\rho}{\theta} K_d )}$

In order to calculate buildup of an analyte through time (Equation 2), the rate of change of the concentration of the analyte is defined as a function of the irrigation water per day (cm), the concentration of the analyte (pCi/L), air deposition per day, less the concentration of the analyte times the sum of the soil leaching coefficient, $\lambda_L$, and the radioactive decay constant $\lambda_{Rad}$.

Equation 2:

$$M'(t) = I(t) \times 0.01 \times C_{water} \times 1000 \ (t) + A_{dep}(t) - M(t) \times \left(\lambda_L(t) + \lambda_{Rad}\right)$$

As the M(t) term approaches saturation, the derivative, M'(t) term approaches zero. The source term buildup M(t) and the M'(t) are in units of pCi / $m^2$. The source term $C_w$ is in units of pC / L. No air deposition is modeled, but the term is left in for completeness. The 1000 factor allows for an appropriate conversion between liters and cubic meters.

### *12.2. Source term estimates* [6,32]

Source term concentrations for radium and uranium for the entire Alamosa basin are not available at the present time. Johnson, McCarn et al (1982), performed sampling of the northern part of the zone favourable for uranium in 1979, although no radium values were measured. Measurements made in the upper, unconfined aquifer by Anderholm (1996) for uranium and radium demonstrated a high correlation with the zone identified by Johnson, McCarn et al (1982). Based on these data, a nominal estimate of 36.6 pCi/l was used for the scoping calculation, and is intended only as a "starting point" for more rigorous analysis.

Because of the spatial correlation of uranium in the upper, unconfined aquifer with the zone identified by Johnson, McCarn et al (1982) in the underlying, artesian aquifer, the source of the uranium in the upper aquifer may be directly related to historical irrigation activity.

A compilation of baseline, water quality data from similar, regional redox-controlled, roll-front uranium deposits in Texas, New Mexico, Wyoming, and Kazakhstan is being developed. These data represent published baseline water quality data from ISL mining units. When the data compilation is completed, the distribution of radium, uranium and radon will be statistically analyzed, and a stochastic risk model will be developed using distributions conditioned by these data.

Initial review of these data indicates that the 36.6 pCi/l value used in the present scoping calculation may underestimate the source term. Additionally, the high radon concentrations (700 to 1,900 pCi/L) within the Alamosa Basin may also be used to validate the range of the in situ concentration of radium.

A second issue for the calculation of risk that is not fully accounted for in a scoping calculation is the length of time fields have received water. A review of the data from Powell (1956) reveals that 50% of the wells have produced water for 95 years, with the 75th percentile of 110 years and a 25th percentile of 65 years. Therefore, a scoping estimate of 50 years tends to significantly under-estimate the total source term deposited.

### *12.3. Water balance in the San Luis valley*

The primary crops in the San Luis Valley include wheat, barley, oats, alfalfa, feed hay, potatoes and vegetables. A total of 180,000 hectares are under cultivation. As shown in Table III, the total volume of water required from the aquifer is about $1,268 \times 10^6$ $m^3$ in addition to rainfall amounting to $150 \times 10^6$ $m^3$. Of this water, about 10% or $15 \times 10^6$ $m^3$ is estimated to recharge into the unconfined aquifer. Table III was derived from an estimation of the monthly consumptive plant requirements, and corrected for off-season irrigation requirements, irrigation efficiency, and water balance allowing 10% recharge to the unconfined aquifer. The recharge is approximately the same as the effective precipitation.

Irrigation methods of today are about 80% efficient, so about 20% is immediately lost to evaporation. In the past, when fields were flooded, the efficiency was about 60%. In the water balance, an average efficiency of 75% is assumed. The balance of the water, about $1,274 \times 10^6$ $m^3$ undergoes evapotranspiration to meet the needs of the crops or is lost by direct evaporation. About 8.2 cm of effective rainfall falls each year to meet part of the plants consumptive water requirements. The amount depends on the crop type. The net water balance (P + I – E) is about 7.9 cm. Basin wide, this represents a recharge is $142 \times 10^6$ $m^3$.

Table III. Estimated water balance for the Alamosa basin.

**Water balance summary**

| Crop | Effective precipitation | Irrigation requirements (cm) | Evapo-transpiration (cm) | Recharge (cm) | Area (Ha) |
|---|---|---|---|---|---|
| Grain | 5.7 | 62.5 | 60.6 | 7.7 | 37,717 |
| Potatoes | 5.1 | 55.8 | 53.3 | 7.7 | 27,478 |
| Alfalfa | 10.2 | 83.0 | 84.6 | 8.6 | 67,582 |
| Vegetables | 5.1 | 38.5 | 38.9 | 4.6 | 9,200 |
| Other Hay | 10.2 | 75.1 | 77.5 | 7.8 | 37,636 |
| Average | 8.2 | 70.6 | 70.9 | 7.9 | 179,613 |
| **Annual Volume ($\times 10^6$ $m^3$)** | **147.1** | **1,268.3** | **1,273.8** | **141.5** | |

*Irrigation Requirements - From: Part 683 - Water Requirements, Estimated Seasonal and Monthly Consumptive Use of Crops, Table CCO683.50(r), Monte Vista, Colorado; TR-21 Blaney Criddle Method, CO210-VI-COIG, December, 1988, and corrected for irrigation efficiency, off-season water requirements, and recharge.*

### *12.4. Soil parameters for leaching rate*

Soil parameters include the soil depth $d_s$, volume fraction moisture, θ ($cm^3/cm^3$), soil density, ρ ($g/cm^3$), and the partitioning coefficient between the analyte and the soil, $K_d$ (ml/g). Typical soil depths are 15 cm; moisture 0.5; and soil density 1.5 $g/cm^3$.

The partitioning coefficient, $K_d$, is estimated based on IAEA recommendations (1994) in the Handbook of Parameter Values. A conservative value for $K_d$ of 75 ml/g was applied to uranium, with sensitivity calculations using a $K_d$ of 25 and 100. As can be seen later, uranium only contributes about a small fraction (0.5%) to the total dose, and can be disregarded. Uranium is modelled, however, because it is a surrogate for other metals, and may be correlated to radium concentrations in the groundwater.

For Radium, a $K_d$ of 490 was chosen with sensitivity calculations using a $K_d$ of 250 and 1,000. Radium and its daughters contribute most of the dose to the critical group.

The calculated leaching rate, $\lambda_L$, for radium used in the simulation was $6.4 \times 10^{-4}$ per year compared to the default value for GENII of $5.9 \times 10^{-4}$ per year. For uranium, the calculated leaching rate, $\lambda_L$, was $4.2 \times 10^{-3}$ per year compared to the GENII default value of $1.3 \times 10^{-3}$ per year.

In order to estimate soil buildup, it is assumed that crops have been rotated in a uniform way over the long term, and that a base-case can be estimated using the weighted average of each crop type.

Figures 9 and 10 present estimates of soil buildup based on the leaching rate $\lambda_L$, for all crops. Appendix A provides estimates of sensitivities for all soil properties as well as the calculation of the $\lambda_L$. Generally, the only factor that influences dose response for both radium and uranium is the thickness of soil, $S_d$. If uranium contributed significantly to the dose, then the $K_d$ might also play a part.

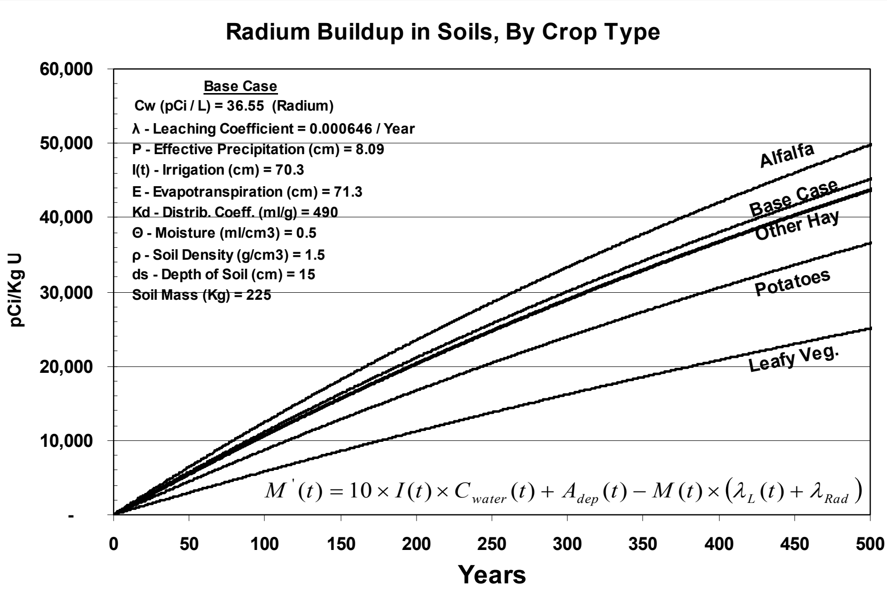


*FIG. 9. Estimated radium buidup in soils.*

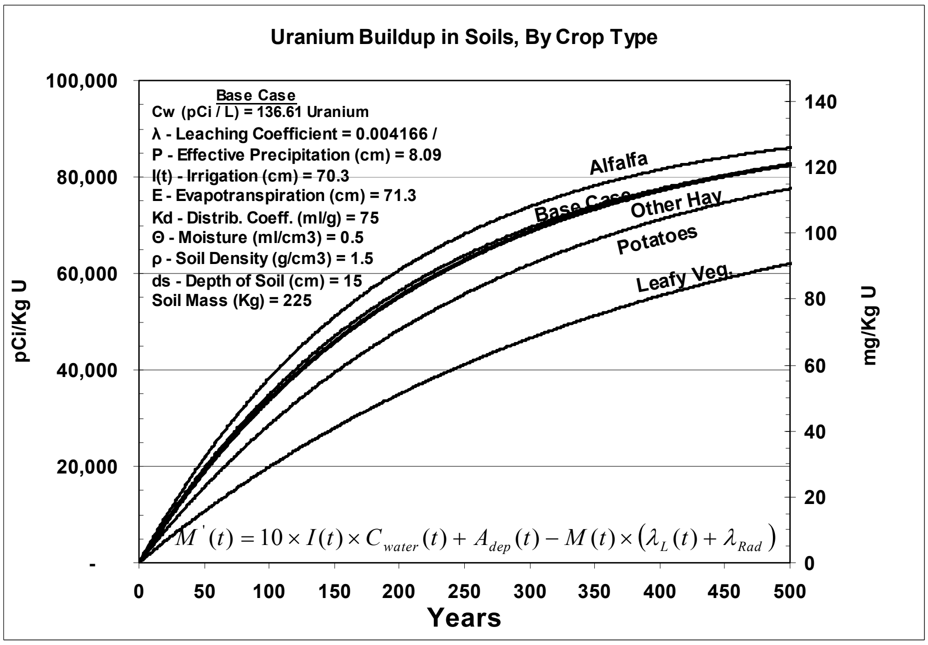


*FIG. 10. Estimated uranium buildup in soils.*

The history of soil use must also be taken into account. Although the valley has been in almost continuous development for the past 100 years, an individual area may have only been in production for between 25 and 75 years, with a mean estimator of 50 years. Some parcels may have been in production for as long as 125 years. Salt buildup in soils was a major problem during the early years of flood irrigation, and a number of areas were abandoned in the 1930s and re-established in the 1950s. Typically, the soil was “washed” for several years using central-pivot irrigation to flush caliches and other salts from the soils before crop production began.

## 13. Multi-pathway risk model

Two primary, different mechanisms have been operant in the Alamosa basin since the natural development of the Alamosa Basin. First, a geogene, ore-forming process (Plate 1) allowed the concentration at a natural redox boundary of redox sensitive metals including uranium. As time went on, this process continued along with the concurrent process of in-growth of radium daughters.

The second mechanism, as shown in Plate 2, is the anthropogene development of the basin for ground water resources beginning in about 1880 (Powell, 1958). Since this period began, the removal of water from the basin has been significant. Because of the large water withdrawals by 1910, Siebenthal described the westward movement of brown-stained water from the reduced sediments of the Santa Fe Group.

By 1958, Powell identified over 7,500 flowing, artesian wells supporting the agricultural industry of the valley. The water has been used to irrigate about 180,000 hectares of land causing periodic problems with caliche and salt formation in the soils in the eastern part of the San Luis Valley.

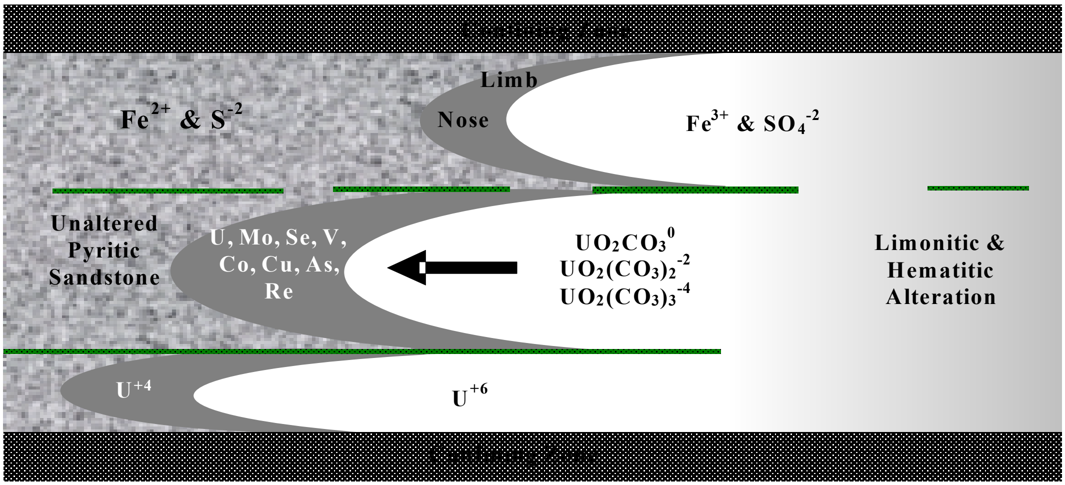
# Geogene Development of Alamosa Basin, Upper Oligocene - Present

WATER RECHARGE FROM SAN JUAN VOLCANIC TERRAIN, DILUTE CONCENTRATIONS OF U, MO, AS, SE

FLUID FLOW THROUGH OXIDIZED AQUIFER

METALS ENCOUNTER REGIONAL REDOX FRONT

METALS CONCENTRATE IN REGIONAL REDOX-CONTROLLED, ROLL-FRONT URANIUM DEPOSITS OVER TIME



INGROWTH OF RADIUM AND RADIUM DAUGHTERS

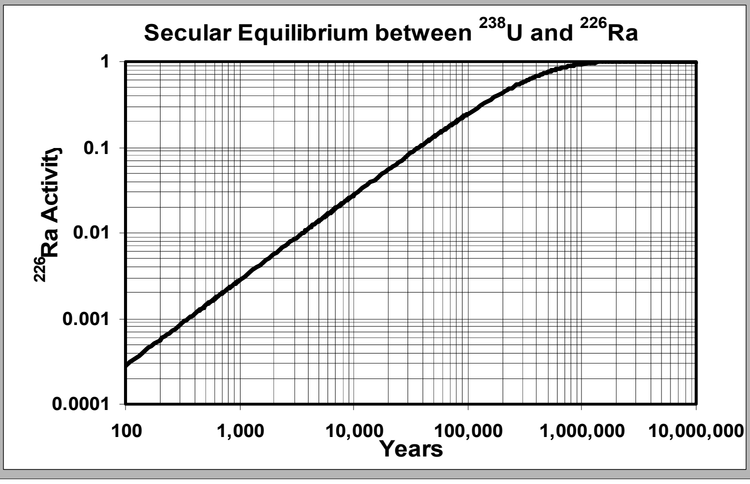


*Plate 1: Geogene Development of the Alamosa Basin*

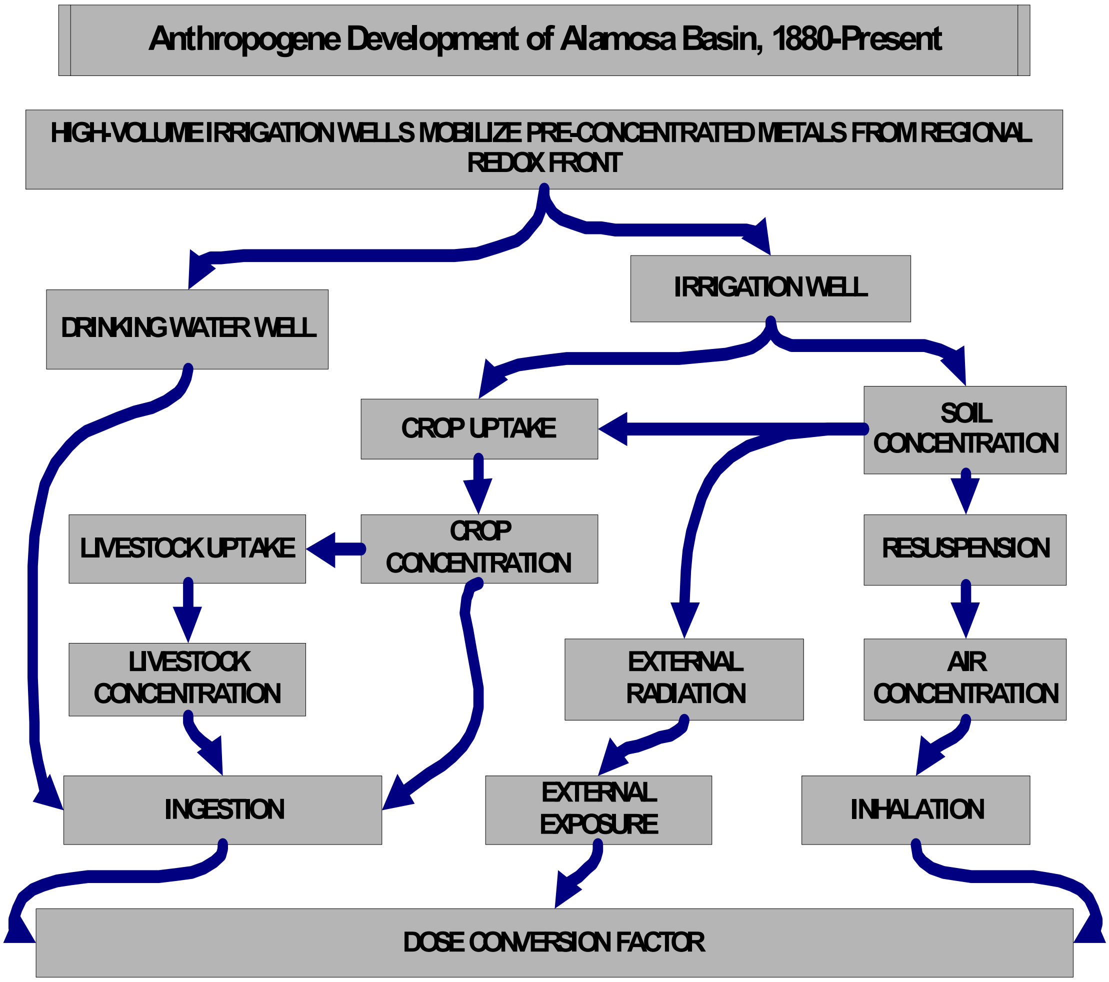


*Plate 2: Anthropogene Development of the Alamosa Basin*

### *13.1. Identification of the critical group*

The critical group represents the human receptor and may be defined as 1) an average member of the critical group; or 2) the individual who, from normal habits, might be expected to receive the greatest potential dose, significantly above that of the average. In order to establish the dose received, it is assumed that the food and water will be obtained locally. Since the Alamosa Basin agricultural production is used in all aspects of direct consumption as well as feed for poultry, meat, milk and eggs, this assumption is reasonably substantiated.

## 14. GENII Computer codes

GENII was developed to meet health physics requirements for assessment of dose to a critical group based on a model of agricultural accumulation of contaminants in soil, transfer to plants and ultimately to man (Napier et al 1988). These codes uniquely model soil accumulation of radionuclides and the multi-pathway risks including exposure via inhalation, ingestion and external exposure. The codes were developed to model exposure pathways based on the ICRP-30 (1979) recommendations [23].

The GENII codes were modified to provide for a stochastic model in the Yucca Mountain Project, called GENII-S. Detailed studies were conducted to develop Analysis/Model Reports (AMR) of the Biosphere Model. These reports detail parameters and characteristics including external, inhalation and ingestion pathways, identification of the critical group, transport parameters, dose conversion factors and a critical review of Biosphere-related FEPs. The AMR reports were synthesized into a Biosphere Process Model Report.

Input for the GENII codes require a model of the crop types, water balance and an estimate of the leaching coefficients for the soil types.

## 15. Dose calculations using GENII

The example in Appendix A is for a 50-year history of previous irrigation and a nominal source term of 36.6 pCi/L Radium in irrigation water. Doses estimated by GENII appear to be quite unacceptable to the public at large. In order to reduce the uncertainty in the estimate, a comprehensive programme should be implemented to sample soils, waters and vegetable products originating from the area.

Such as study would also allow the comparison of a present-day analogue to Yucca Mountain calculations. Soil, irrigation water, gamma-spectrometric surveys and empirical determinations of $K_d$ should provide estimates of soil buildup in an area that already has 100 years of irrigation history.

### *15.1. Source-term estimates used*

The source term used in the sensitivity studies is 137 pCi/L natural uranium, which corresponds to a concentration of 200 μg/L U. This would correspond to the estimated value for the near-field concentration. Neither Johnson, McCarn et al (1982) nor Anderholm (1996) analyze for radium. Anderholm (1996) does provide an estimate of excess alpha activity (not radon), which cannot be accounted for as uranium. If this were interpreted as radium, the concentration corresponding to the uranium source term would be about 37 pCi/L activity. This value might range higher or lower, but is a representative value for radium activity when compared to other known uranium deposits such as the Crownpoint Deposit (U.S. NRC, 1997) [36], Kirchmann (1980) [25] and Bonhote et al (1984) [3].

#### *15.1.1 Transfer parameters*

Transfer parameters from soil to plants, plants to animals and to man were the recommended parameters from Napier (Pers. Com., 2002) and are the default parameters used by the GENII codes (Napier et al, 1988). The lifetime dose to health effects parameter was $4\times10^{-5}$ health effects / REM.

Nominal values of transfer coefficients, the default values for GENII, were used in the calculations. Only the leaching coefficients and water balance were modified to fit the Alamosa Basin model. These factors are listed in Appendix B in an example calculation. Figure 11 provides an estimate of lifetime doses corresponding to the example in Appendix B, and Figure 12 provides an estimate of health effects per thousand.

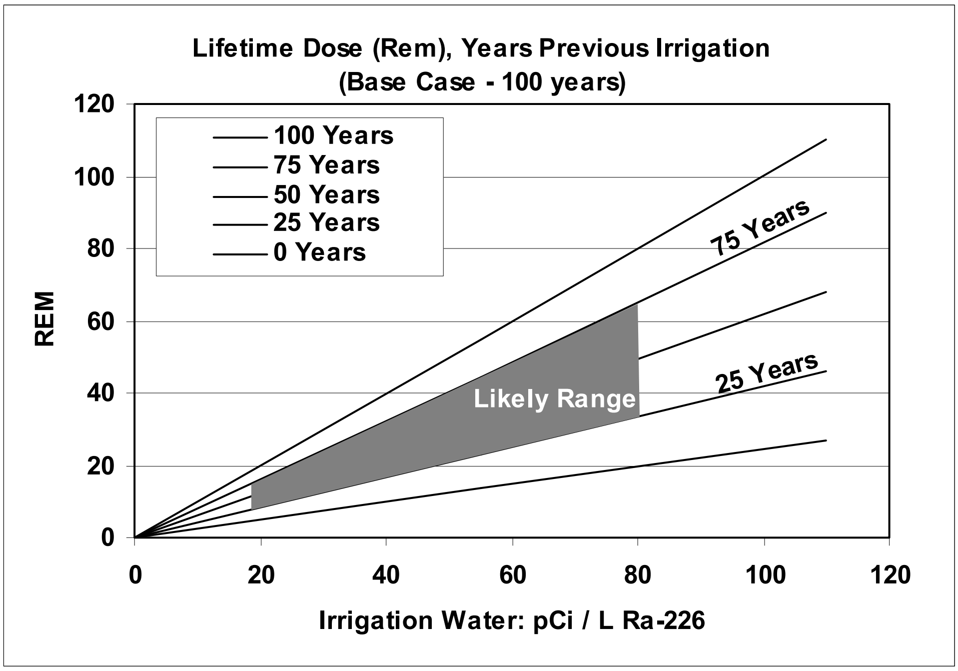


*FIG. 11. Lifetime dose of the critical group, range outlined.*

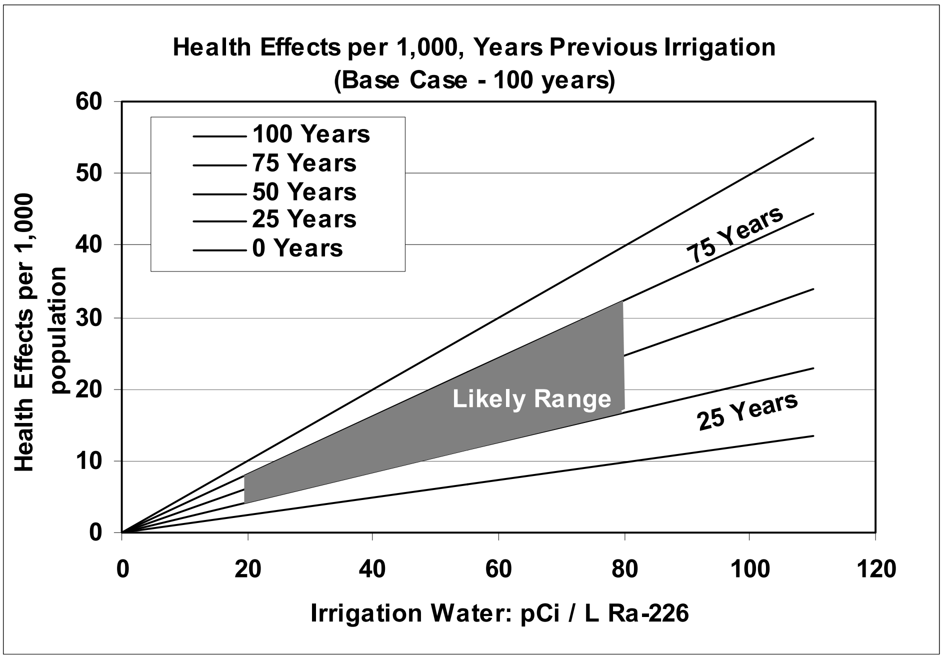


*FIG. 12. Lifetime health effects/thousand critical group, likely range outline.*

## 16. Summary

Regional redox-controlled, roll-front uranium deposits are common in the western United States and provide a well-defined mechanism for reconcentration of very dilute mineralizing solutions at low pressures and temperatures. Through time, uranium, selenium, arsenic, rhenium and other redox sensitive metals can reach significant and even economic concentrations. Far-field plumes from a high-level waste repository can concentrate material in regional redox zones in a manner identical to natural mineralizing solutions as well as in other, well-defined, environments. Formalized recognition criteria for ore deposit models can assist in identification of favourable targets where reconcentration can occur.

Regional redox-controlled, roll-front deposits are primary exploration targets for the uranium mining industry because the mineralized zones can be easily mined through in situ leach (ISL) mining techniques.

In the San Luis Valley, a 60 km long by 5 km wide zone of favourability for regional redox-controlled, roll-front uranium deposits has been identified in an artesian aquifer heavily used for irrigation. The characteristics of the geology and hydrology are favourable for ISL mining technology and the area was assigned speculative resources during the NURE study (Johnson, McCarn et al, 1982). Remobilization of uranium and other redox sensitive metals is postulated to occur from high-volume agricultural pumping causing heavy metals and radionuclides to be applied to farmland, and thus to the accessible environment. Recent sampling of the upper, unconfined aquifer by USGS revealed that uranium anomalies are spatially correlated with the favourable zone.

Scoping calculations suggest that significant buildup of radium and uranium in soils is possible, and a detailed investigation focused on soil, water and vegetation sampling is indicated to determine the risk. A combined geological, geochemical and geophysical programme is proposed to evaluate the extent of impact of high-volume, agricultural well use in the San Luis Valley and to develop a multi-pathway risk model applicable to the Yucca Mountain project.

## ACKNOWLEDEGEMENTS

The author wishes to thank Bruce Napier, Staff Scientist of Pacific Northwest National Laboratory for his highly constructive criticism and review of the paper, as well as checking the calculations of the GENII model as it applies to this problem. The author also would like to thank Alexander Boitsov, Brian Brister, Mark Pelizza, Dennis Stover, Doug Underhill and Terry Wetz for their constructive criticism and technical review.

# APPENDIX A: LEACHING COEFFICIENT SENSITIVITY FACTORS.

**Sensitivity: Estimation of leaching coefficient – radium.**

| **Crop** | **Recharge 5%** | | **Recharge 20%** | | **$S_d$=25** | | **$K_d$=250** | | **$K_d$=1000** | | **Base Case** | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Soil/Crop Parameter** | **$Day^{-1}$** | **$Year^{-1}$** | **$Day^{-1}$** | **$Year^{-1}$** | **$Day^{-1}$** | **$Year^{-1}$** | **$Day^{-1}$** | **$Year^{-1}$** | **$Day^{-1}$** | **$Year^{-1}$** | **$Day^{-1}$** | **$Year^{-1}$** |
| **Consumptive Use (cm)** | 0.193 | 70.6 | 0.193 | 70.6 | 0.193 | 70.6 | 0.193 | 70.6 | 0.193 | 70.61 | 0.193 | 70.6 |
| **Recharge (cm)** | 0.019 | 7.1 | 0.039 | 14.1 | 0.019 | 7.1 | 0.019 | 7.1 | 0.019 | 7.06 | 0.019 | 7.1 |
| **Total Required Water (cm)** | 0.213 | 77.7 | 0.232 | 84.7 | 0.213 | 77.7 | 0.213 | 77.7 | 0.213 | 77.67 | 0.213 | 77.7 |
| **P - Precipitation (cm)** | 0.022 | 8.2 | 0.022 | 8.2 | 0.022 | 8.2 | 0.022 | 8.2 | 0.022 | 8.19 | 0.022 | 8.2 |
| **$I_t$ - Irrigation (cm)** | 0.190 | 69.5 | 0.210 | 76.5 | 0.190 | 69.5 | 0.190 | 69.5 | 0.190 | 69.48 | 0.190 | 69.5 |
| **E - Evapotranspiration (cm)** | 0.193 | 70.6 | 0.193 | 70.6 | 0.193 | 70.6 | 0.193 | 70.6 | 0.193 | 70.61 | 0.193 | 70.6 |
| **$\lambda_L$ - Leach Rate** | 1.8E-06 | 6.4E-04 | 3.5E-06 | 1.3E-03 | 1.1E-06 | 3.8E-04 | 3.4E-06 | 1.3E-03 | 8.6E-07 | 3.1E-04 | 1.8E-06 | 6.4E-04 |
| **Percent Recharge** | 10% | | 20% | | 10% | | 10% | | 10% | | 10% | |
| **$d_s$ - Depth of Soil (cm)** | 15 | | 15 | | 25 | | 15 | | 15 | | 15 | |
| **$\Theta$ - Moisture (ml/$cm^3$)** | 0.5 | | 0.5 | | 0.5 | | 0.5 | | 0.5 | | 0.5 | |
| **$\rho$ - Soil Density (g/$cm^3$)** | 1.5 | | 1.5 | | 1.5 | | 1.5 | | 1.5 | | 1.5 | |
| **$K_d$ - Distrib. Coeff. (ml/g)** | 490 | | 490 | | 490 | | 250 | | 1000 | | 490 | |
| **Soil Mass (Kg)** | 225.0 | | 225.0 | | 375.0 | | 225.0 | | 225.0 | | 225.0 | |
| **Area - Mineralized Zone (Ha)** | 10,000 | | 10,000 | | 10,000 | | 10,000 | | 10,000 | | 10,000 | |
| **Avg. Crop Yield Tonnes/Ha** | 11.68 | | 11.68 | | 11.68 | | 11.68 | | 11.68 | | 11.68 | |
| **Tonnes Crops** | 116,773 | | 116,773 | | 116,773 | | 116,773 | | 116,773 | | 116,773 | |
| **$C_w$ - Mineralized Zone (pCi/L)** | 36.55 | | 36.55 | | 36.55 | | 36.55 | | 36.55 | | 36.55 | |

# APPENDIX B: GENII DOSE CALCULATION.

```
Example of GENII Dose Calculation, 36.6 pCi/L Ra-226
50 Years of Previous Irrigation

Uptake/exposure period:                              70.0
Dose commitment period:                              70.0
Dose units:                                          Rem

Dose Commitment Year
1         2            3         ...
____________________________________
Internal  : |
Intake    :  |
Year:     3  |                          3.2E-02   ...
|                        +
2 |            3.1E-02   1.4E-02   ...             Internal
|                 +          +                     Effective
1 | 3.0E-02 + 1.3E-02 + 1.0E-02 + ... =  1.9E-01   Dose
Equivalent
||          ||          ||
Internal                                                     Cumulative
Annual       3.0E-02 + 4.4E-02 + 5.6E-02 + ... =  1.8E+01   Internal
Dose                                                         Dose
+          +            +          +
External
Annual       4.0E-02   4.1E-02   4.2E-02   ...      4.6E+00
Dose
||          ||          ||            ||
Annual                                                      Cumulative
Dose         7.0E-02 + 8.5E-02 + 9.7E-02 + ... =  2.3E+01  Dose

Maximum
5.3E-01   Annual
Dose Occurred
In Year 70
```

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# Site visit: Deposit 512, Yili Basin, Xinjiang Autonomous Region, China

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International Atomic Energy Agency,
Vienna

The report is based on information provided during the mine visit on 22 September, 2002.

## 1. Location

Deposit 512, also known as Kujieertai deposit, is located in the southern end of the Yili basin, 70 km south-west of Yining, approximately 20 km east of the Kazakh border. The area, south-west of the Tienshan Mountain, is covered by gravel and sub-clay formations of quaternary age, at an elevation of 1100–1150m.

Climate temperature: +40ºC during summer, -44ºC during winter, average +8.2ºC
Earth can be frozen to a depth of 1.2 m
Precipitation: 200 to 500 mm per year, including 1 m of snow from October to March
Evaporation: 600 to 1000 mm per year.

## 2. History

Deposit no 512 was discovered in the late 1950s, early 1960s, during coal exploration. First uranium recovery in the area was from coal processing.

After additional exploration in the late 1980s, uranium resources in the Yili basin (Deposits 510, 511, 512) were estimated around 10 000 t U, the largest sandstone uranium deposits of roll front type in China. Laboratory and field tests on the applicability of in-situ leach techniques to these deposits were conducted from 1987 to 1991. A larger test, on 12 wells in two 5-spot patterns (2 producers, 10 injectors) was conducted in 1994.

Following these positive tests, mining operation was initiated at a rate of 100 t U/year, later increased to 200/250 t U/year.

## 3. Geology

The Yili basin is a meso-cenozoic intermountain basin, developed on the basement of a pre-cambrian block (metamorphosed rocks and granites). The basin formations consist of continental coal-bearing clastic rocks and red clastic rocks. Uranium deposits are hosted in lower-middle Jurassic clastic rocks (Shuixigou group). The Shuixigou group can be divided into alluvial fan-braided stream depositional systems, delta depositional systems and lacustrine-swamp depositional systems. According to the geology of the ore-hosting formations, uranium mineralization can be classified into 3 types: sandstone type, mudstone type and coal type. Deposit 512 belongs to the sandstone type mineralization, and is related to interlayer oxidations.

In the deposit area, the Shuixigou group contains 13 coal seams, 4 of them being developed.

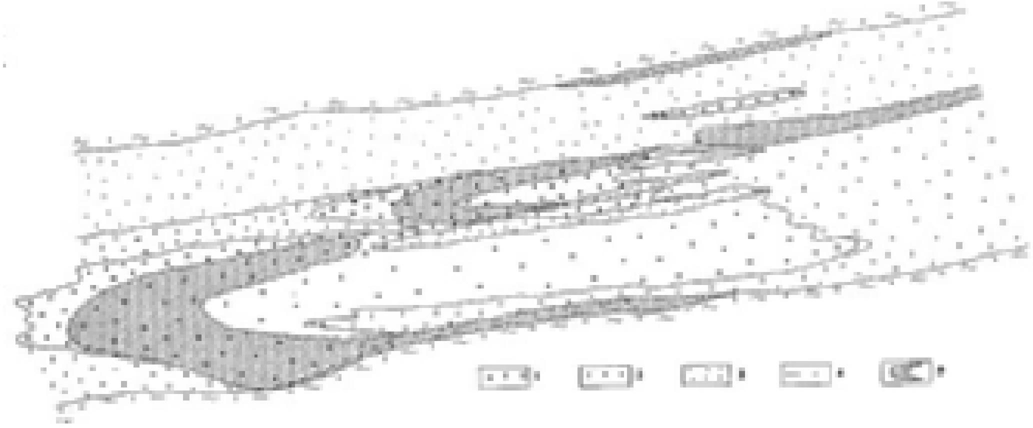
*Sketch geologic map of Yili Basin.*

*1) Quaternary, 2) Tertiary, 3) Jurassic, 4) Triassic, 5) Upper Paleozoic, 6) Lower Paleozoic, 7) Middle and Upper Paleozoic, 8) Hercynian granite, 9) Inverse fault, 10) Fault of unknown character, 11) Infered fault, 12) U-deposit, 13) U-occurrence.*

Deposit 512: the ore hosting sandstone (coarse to medium grained sandstone: quartz, feldspar, kaolin, muscovite, …) is 10 to 40 m thick, presents a great continuity, and dips 5 to 15 north, bounded above and below by an impermeable clay formation. It lies at a depth of 110 to 240 m. It is confined above and below by 4 to 40 m thick mudstone and silt claystone. The mineralization is located along the front of an oxidation zone, and consists of two mineralized bodies 200 to 500 m wide, 2 500 and 5 000 m long. In profile, the economic (cut-off 0.01% U) uranium ore bodies are located at the front of the oxidized zone, showing a roll-shape ore body at the contact with un-oxidized grey sandstone. The average thickness of the ore bodies is 3.7 m (maximum 12.3 m), 5 m thick at the front, 2.7 m at the upper limb and 0.8 m at the lower limb. In average, the ore grade is 0.04% U (between 0.01 and 1.50%U). Uranium minerals include pitchblende (80%) and coffinite (20%). Associated minerals include Mo, Re, Se, Sc, Ga, V. Carbonate content of the ore is 0.33%. The ore is favourable for acid in-situ leach mining.

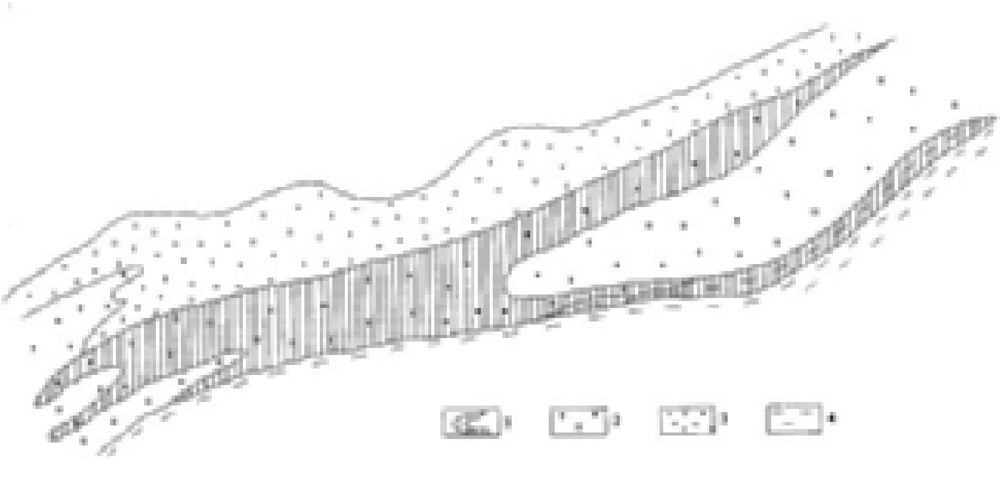
Intermediate-acidic and Hercynian granite, extensively distributed in the area, are considered as source of the uranium.

Uranium resources: 15 to 20 years of present production (3000-4000 t U). Actually, only uranium located at the front of the roll is mined. 60% of the resources are associated to the upper and lower limbs.



*Section showing the complex roll shape of the ore body in cycle V, profile No.4.*

*1) Pebbly gritstone, 2) Medium grained sandstone, 3) Fine grained sandstone, 4) Mudstone, 5) Uranium ore body*



*Section showing the shape of the ore body in cycle V, profile No.0.*

*1) Uranium ore body, 2) Pebbly gritstone, 3) Medium grained sandstone, 4) Mudstone.*

## 4. Hydrogeology

Water table is at a depth of 60 m. Permeability of the ore hosting sandstone ranges between 0.09 and 1.6 m per day. Permeability of the surrounding clay formations is 0.01 m per day. The water quality type belongs to $HCO_3$, Na, $SO_4$ type, with low salinity and weak alkalinity.

TDS: 0.23 to 0.69 g/l.
Ground water temperature: 11 to 18ºC.
pH: 7.3 to 8.6.
Uranium in water is as $UO_2(CO_3)_3^{++++}$

## 5. Wellfield operation

At the time of visit, 8 wellfields were in production or restoration. 272 wells (146 injectors, 126 producers) were in operation. Well patterns are 5-spot patterns (well spacing: 25 m) or line-drived.

Drilling cost: 250 yuan / m (US$ 30 / m), for a 100 mm diameter hole, including casing.

Injection and production pipes are buried at a depth of 1.2 m.

Production is made using air-lift or submersible pumps (4 head-houses, 8 producers connected to each head-house).

Uranium is leached using $H_2SO_4$ as lixiviant, $H_2O_2$ as oxidant.

Production: 350 to 420 $m^3$/h of pregnant solution, at an average grade of 55-60 mg/l are extracted. The average production per well is 2.8-3.3 $m^3$/h (well production using submersible pumps is slightly higher, but is still low compared to other ISL sites in USA or Kazakhstan). If all the wells were in operation all year round, annual production would be in the range of 170-220 tU per year. Uranium recovery, after 5 years of leaching, is between 75 and 85%.

## 6. Process/plant

Pregnant solution is temporally stored in a collection pond beside the plant. Uranium process includes resin fixation (2 IX columns, 220 t of local resin each), elution ($NH_4NO_3$) in 3 tanks, precipitation (NaOH). There is no yellowcake drying. Yellowcake shipped to Hengyang contains up to 50% of water. Plant recovery: 98% of uranium contained in pregnant solution.

## 7. Restoration

After production (production stops when the pregnant solution has an uranium content below 15-20 mg/l), the aquifer is restored. Actually, restoration is limited to the pumping of contaminated water from the aquifer, the extracted water being re-injected, after addition of lixiviant and oxidant, in wellfield in production as leaching solution.

## 8. Radiation control

There is no hazard for the public, as residents are scarcely distributed in the area. Workers: In order to limit worker’s exposure, working time is reduced for personnel working at the producing wells, air-lift separators, and collecting pond. An enforced air ventilation system is used in the plant.

Annual occupation dose limits:

20 mSv for workforce
0.5 mSv for public.

## 9. Personnel

A total of 150 persons work on the site (wellfield and processing plant).
Working time is 6 hours per day, 10 days in, 4 days off.

**Reference:** Characteristics of uranium Mineralization and Ore Controls of Kujieertai Deposit, Yili Basin, Xinjiang Autonomous Region.

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