IAEA-TECDOC-1425

Developments in uranium resources, production, demand and the environment

Proceedings of a technical committee meeting held in Vienna, 15–18 June 1999

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International Atomic Energy Agency

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FOREWORD

Globalization has led to the growing importance of the uranium production industries of the world's developing countries. Though trade restrictions continue to impede completely free access to the worldwide uranium market, the uranium resources and production capabilities of the developing countries are becoming increasingly important in assuring the adequacy of uranium supplies to meet projected worldwide demand. Therefore, papers presented at this meeting provide an important overview of uranium production operations in developing countries as well as offering insight into future production plans and potential.

Along with their increasing contribution to worldwide uranium supply, the environmental impact of uranium production in developing countries has come under increasing scrutiny from the nuclear power industry, the end users of this supply, and by communities impacted by uranium mining and processing. Therefore, the environmental consequences of uranium production were included in the meeting agenda as noted in the meeting title, "Developments in uranium resources, production, demand and the environment." Accordingly, the papers presented at this meeting are about evenly divided between discussions of known and potential uranium resources and uranium production technology and the environmental impact of uranium mining and processing, its related remediation technology and its costs.

Though emphasis is placed on uranium programmes in developing countries, an overview of COGEMA's worldwide activities is also presented. This presentation provides insight into the strategies of arguably the Western world's most integrated and diversified uranium company, including the geographic diversity of its exploration and production activities as well as its participation in secondary supply sources such as commercialization of weapons grade uranium.

Uranium supply from the developing countries could be increasingly important in satisfying worldwide reactor requirements over time. At the same time, it represents only one segment of total supply, which also includes production from developed countries plus secondary supply including inventory draw down, HEU, MOX, reprocessed uranium and re-enrichment of tails. A model developed by the IAEA is presented that provides for long term forecasting of uranium requirements for given sets of parameters including nuclear power projections and fuel cycle strategies. A companion presentation reviews the relationship between options at the backend of the nuclear fuel cycle and uranium market prices. These relationships impact the economics and therefore the availability of secondary supply.

The IAEA officers responsible for this publication were J.R. Blaise and C. Ganguly of the Division of Nuclear Fuel Cycle and Waste Technology.

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SUMMARY

Beginning in the early 1990s, worldwide exchange of information on uranium resources and production began to improve dramatically. The IAEA has taken the lead in providing forums for the developing countries to discuss their uranium resource potential and production capabilities. The proceedings from these meetings and other forums have been instrumental in adding credibility to the potential that the uranium industries of the developing countries have to contribute to long term supply and hence the sustainability of the nuclear fuel cycle.

Along with maintaining and expanding their respective uranium production industries, the developing countries are becoming increasingly aware of the environmental impact of uranium mining and processing – both from past and current operations. Therefore, the papers presented at this meeting cover the front end of the fuel cycle from uranium resource potential to production, decommissioning and reclamation of production facilities.

The delay in publishing this document does not diminish its value to the uranium industry because most of the information is not time-sensitive. Many of the papers represent case histories of environmental impact and reclamation of uranium mining projects in developing countries. Others describe availability of uranium resources in developing countries and the potential for their development. Little has changed since the papers were prepared and that which has changed provides interesting historical perspective on predictions regarding the future of uranium development in developing countries under ever changing supply-demand conditions.

In situ leaching of uranium

Historically, uranium production in the developing countries has been dominated by underground or open pit mining and conventional milling. However, experimental in situ leaching (ISL) of uranium was begun as early as 1961 in Ukraine, and today ISL is the cornerstone of the uranium production industries of Kazakhstan and Uzbekistan. In addition, several other developing countries have either begun ISL operations or are assessing the amenability of their uranium resources to ISL extraction. The number of ISL papers presented at this meeting reflects its importance to the future of uranium production in developing countries.

China. China, in an effort to reduce production costs, has focused exploration in basins in the north western and northern parts of the country that have the potential to host deposits amenable to ISL extraction. The Yining deposit in north western China, which began ISL pilot tests in 1993, produced about 100 tU in 1996.

Kazakhstan. ISL accounted for nearly 90 percent of Kazakhstan's uranium production in 1997, with the remainder coming from the Stepnogorsk mine-mill complex in the northern part of the country. Kazakhstan maintains three ISL production facilities, two in the Chu-Sarysu basin and one in the Syr Darya basin. The uranium ore in these basins is concentrated along roll fronts in Cretaceous and Paleogene sediments. Kazakhstan expects to reverse the recent decline in ISL output with the addition of production from joint ventures with two Western companies. The Inkai and KATCO joint ventures will develop the Inkai-Mynkuduk and Moynkum deposits, respectively.

Mongolia. Joint ventures with two Western countries are targeting the ISL potential of sedimentary basins in central and southern Mongolia. One of the joint ventures conducted pilot leach tests between 1994 and 1996, but both joint ventures have focused most of their efforts on exploration, including geologic and geophysical surveys and drilling.

Niger. Uranium production in Niger has historically been by underground and open pit mining and conventional milling. However, the ISL amenability of the Imouraren deposit is currently under evaluation. The ore at Imouraren, which was discovered in the late 1960s, is concentrated along roll fronts in Jurassic sandstones.

Russian Federation. ISL-amenable resources have been discovered in three districts or regions in Russia: Transural, Western Siberia and Vitimsky. Uranium mineralization in all three districts occurs in basal channel (valley-type) sandstone deposits. ISL pilot testing has been completed at the Dalmatovsk deposit in the Transural district, and pilot testing has been initiated at the Khiagda deposit in the Vitimsky district. Russia expects to expand annual ISL capacity to between 4500 and 5000 tU by 2005.

Ukraine. ISL production began in Ukraine in 1961 and extended through 1969. Since then, Ukraine's production industry has been based on underground mining and conventional milling. Ukraine is once again turning its attention to the ISL potential within the sedimentary cover of the Ukrainian shield, where it has discovered 10 sandstone deposits that are potentially amenable to ISL extraction. To minimize impact on the leach aquifer, Ukraine is planning to test alkaline leaching as an alternative to acid leaching. It is also evaluating the economics of recovering as by-products several other elements that occur in the complex ores.

Uzbekistan. ISL is the only uranium mining method currently being used in Uzbekistan, with the last of its open pit and underground mines having been shut down in 1995. Uzbekistan currently has three ISL production centres, which currently exploit eight individual deposits. The uranium ore is distributed along roll fronts in Cretaceous, Paleogene and Neogene sandstones. Known resources (RAR+EAR-I) associated with ISL-amenable sandstone deposits total about 114 700 tU, or 62% of known resources.

Underground and open pit mining and conventional milling

While increasing emphasis is being placed on lower cost ISL projects, conventional mine/mill complexes still form the backbone of the uranium industries of many developing countries. Summary information is provided for countries that submitted papers at this meeting.

Kazakhstan. In 1997, the Stepnogorsk mine/mill complex accounted for about 13% of Kazakhstan's uranium output. Though these operations were suspended in 1997, the mill is on standby status and can resume operations when economically feasible.

Russian Federation. The Priargunsky mine/mill complex in the Streltsovsk district in south-eastern Siberia accounted for about 97% of Russia's uranium output in 1997. The Streltsovsk deposits occur as veins and stockworks in volcanic rocks. Though its ore grade is declining and production costs are rising, Priargunsky will be the mainstay of the Russian industry for the foreseeable future. Surface heap leaching and underground block or stope leaching are used to control costs and to more efficiently utilize the low-grade resource base.

Ukraine. Uranium output in Ukraine comes exclusively from two underground mines in the Kirovograd district, with ore processing at the Zheltiye Vody mill. The ore in the Kirovograd district is hosted in Precambrian metasomatic (albitite) deposits.

Alternative or secondary sources of uranium

Two countries, India and Romania, reported on the potential of uranium recovery from non-conventional sources. Both countries review the potential of recovering uranium as a by-product of processing phosphate rock to manufacture fertilizer. They both note the environmental advantages of lowering the radioactivity of the fertilizer products as well as the future economic potential of the uranium itself under improved market conditions. Both countries also describe experiments to recover uranium from fly ash obtained from the burning of uraniferous coal. In both cases, however, though the process is technically feasible, it is uneconomic under current market conditions.

India, because of its limited energy resources, is compelled to consider a wide range of alternative sources of uranium. Therefore, it also discusses the technical processes for recovering uranium from monazite and from seawater. Though technically feasible, both processes result in prohibitively expensive end products.

Environmental consequences of uranium production

For many developing countries, uranium production was a strategic activity with national security implications, and its environmental consequences were of only minor concern. However, with the integration of many of these countries into the worldwide uranium marketplace, the environmental impact of uranium production has become a concern, both to the nuclear power industry and to communities potentially affected by nearby operations. Consequently, the scope of this meeting was expanded to include the environmental aspects of uranium production, and many countries responded with case histories of reclamation projects.

Argentina. The Malargüe mill processed uranium ore between 1954 and 1986, during which time it produced 752 tU and generated 700 000 tonnes of uranium tailings. Final reclamation and decommissioning of the Malargüe complex, including dismantling surface facilities, soil decontamination and tailings disposal, is expected to be completed in 2003 at a projected total cost of USD 11.2 million.

China. The Anhua uranium mine in Hunan province was in operation between 1971 and 1986. Ore from the mine was hauled by rail to the Hengyang mill for final processing. Reclamation of the mine complex, which included 31 mine openings (drifts or inclined shafts), began in 1992 and was completed in 1997. The main problems faced in the reclamation project included contamination from radioactive mine water seepage, radon exhalation from waste rock piles and cadmium contamination of nearby farmland. Reclamation of the Anhua mine resolved all of these problems, and the techniques developed at Anhua will be applied to reclamation of other mine sites in China.

Czech Republic. Underground mining and acid-based in situ leaching of uranium have been underway in the Straz uranium district since 1968 and 1980, respectively. Restoration of the ore bearing aquifer is underway to prevent contaminated waters from reaching water supply wells for a nearby community. A mathematical model is being developed to predict natural attenuation processes in the leach aquifer.

Kyrgyzstan. Uranium processing operations conducted at 33 sites in Kyrgyzstan between 1946 and 1993 generated approximately 42 million m^3 of mill tailings. A study has been completed that concludes that 11 of the 33 sites pose risks to nearby communities potentially involving loss of life, chronic health effects or loss of environmental, social or economic integrity. The estimated remediation costs for the 11 high-risk sites are estimated at USD 16.5 million.

Russian Federation. Uranium production in Russia has generated environmental concerns associated with two operations: Priargunsky in the Chita region and the now closed Lermontov operation in the Stavropolsky region. In both cases, the tailings ponds represent the most environmental concern, both as sources of surface water and groundwater contamination and radon exhalation from the pond surface. Both sites also face environmental concerns related to drainage from waste rock and low-grade ore dumps.

Integrated supply strategies

As a complement to the emerging importance of the developing countries in the nuclear fuel cycle, this meeting also included a discussion of the strategies of a diversified Western uranium production company. These strategies include geographically diversified exploration and production sources as well as participation in secondary supply sources, namely HEU from military stockpiles. This presentation also includes discussion of a geostatistical model for calculating resources associated with roll front deposits that are typically exploited by ISL extraction.

Uranium production from developing countries represents only a part of the broader worldwide supply picture. Therefore, the meeting included discussion of a model developed to assist in long-term forecasting of uranium supply-demand relationships to round out consideration of the broader supply picture. A companion presentation reviews the relationship between options at the backend of the fuel cycle, including direct disposal, reprocessing and recycling, and uranium market prices.

Conclusions

The uranium resources and production industries of developing countries have become increasingly important to the worldwide uranium supply picture. ISL, with its lower costs and reduced environmental impact, has become the cornerstone of several countries, and many other countries are considering its potential. At the same time, conventional mining and milling will continue to be the mainstay of the industries of many of the developing countries.

Along with the developing countries' increased participation in the worldwide uranium market has come increasing awareness of the environmental consequences of uranium production. As cleanup of past operations is undertaken and improved operating practices at current operations are being implemented, developing countries are realizing that environmental protection must be a part of uranium production and an important production cost component.

An overview of COGEMA's recent uranium supply activities related to conventional and secondary sources

G. Capus

COGEMA, France

Abstract. When COGEMA was created 23 years ago, it was mainly devoted to fueling the French Nuclear Power Plants programme. Today, at the end of the century, harvesting decades of exploration, development, investment and marketing efforts, the COGEMA Mining Branch is one of the two world uranium top producers and sellers. Since the early days, the goals have evolved, uranium supplies do not appear as tight as they were forecasted in the late 70s. Now being competitive is not just a prerequisite to survive among competitors. It also helps sustaining a nuclear generation industry facing fierce competition from other energy sources in more and more deregulated markets, in other words, it helps keeping the uranium market well alive. For all these reasons, shifting from high cost mines to low cost mines is obviously the prevailing trend for the uranium industry as a whole. A trend, which started in the mid-80s is continuing since then. Being able to produce at the least costs is definitely the dream of everyone. COGEMA's operations are close to reach this goal, thanks to mining very high grade orebodies, if the general public perception of related environmental issues and the derived regulatory constraints remain within reasonably justified limits. The following pages are aimed to illustrate how COGEMA tries to match the development of its future uranium production and resource portfolio with market reality, by arbitrating between new investment needs and unavoidable secondary supplies.

1. COGEMA's uranium production

COGEMA's mine production, which is by far its primary source of uranium supply, is amongst the highest in the world.

This production comes from a number of mine sites and subsidiaries located in France, Western Africa and North America (Table I). A careful reading of Table I show how deep are the ongoing changes occurring within COGEMA's production centers.

Table I. COGEMA's uranium production key figures 1998

COGEMA group workforce	Uranium in ores	Uranium in concentrates		Workforce
	tonne U	tonne U	thousand lb U_3O_8	
Africa	4453	4451	11573	2160
France	572	508	1321	*540
North America	1195	1176	3058	654
Others	---	---	---	50
Total	6220	6135	15952	3404

* Including Headquarters Gen&Adrn and R&D laboratories & pilot plant.

A shrinking share of domestic uranium

Since 1993, COGEMA remains the only uranium producer in France, and following the closure of the Lodève Mine and mill in early 1997, the Cherbois/Bernardan site of the Société des Mines de Jouac is the only active producing center. This mine is scheduled for closure by

2001, reaching the end of economic resources. In 1998, it represented only 8% of COGEMA's production. Since its 1988 peak year, France's uranium production fell continuously (Fig. 1). At 1998 year end, a cumulative historical production of about 75 000 tU is evaluated.

Despite this fast decline, France's uranium production still represents the main part of the European Union uranium production (64% of the total). It is of interest to note that EU uranium production hardly represented only 4% of the total uranium loaded in EU reactors in 1998 (Fig. 2).

Table II. COGEMA group major uranium mining subsidiaries & ventures

Name	Country	COGEMA ownership %	Note
Pathfinder Mining Corp.	USA (Wyoming)	100%	Finishing Sites Reclamation
COGEMA France	France	100%	Finishing Sites Reclamation
COMUF	Gabon	68.42%	Closed in early 1999/under reclamation
Société des Mines de Jouac	France	100%	Producing, closure by 2001
Cluff Lake	Canada (Saskatoon)	100%	Producing, closure by 2000
MALCO	USA (Wyoming)	71%	Producing
COMINAK	Niger	34%	Producing
SOMAIR	Niger	61.4%	Producing
McClean Uranium Ltd.	Canada (Sask.)	70%	Scheduled for starting production by late 1999
McArthur River Project	Canada (Sask.)	30.195%	Scheduled for starting production by late 1999
Key Lake Mining	Canada (Sask.)	16.667%	Scheduled for starting milling McArthur ore by late 1999
KATCO	Kazakhstan	45%	Pilot Test
Cigar Lake Mining Corp.	Canada (Sask.)	37.1%	Scheduled for starting production by 2002
Midwest	Canada (Sask.)	76%	Scheduled for after 2005
Koongarra	Australia (NT)	100%	Project on hold
Sissons Schultz	Canada	99%	Project on hold & exploration

A steady contribution of African uranium

Since 1989, COGEMA's operations in Africa (Niger and Gabon) are producing 4 000 tU/year plus or minus 10% (Fig. 3). Last year was an exceptional year with African uranium representing 73% of COGEMA's production, but the closure of COMUF mines in Gabon in early 1999 will contribute to return COGEMA's African production to a lower level. Interestingly Rio Tinto, another EU mining operator, is producing in Africa (Namibia) and seems to follow an evolution parallel to COGEMA's operations (Fig. 4).

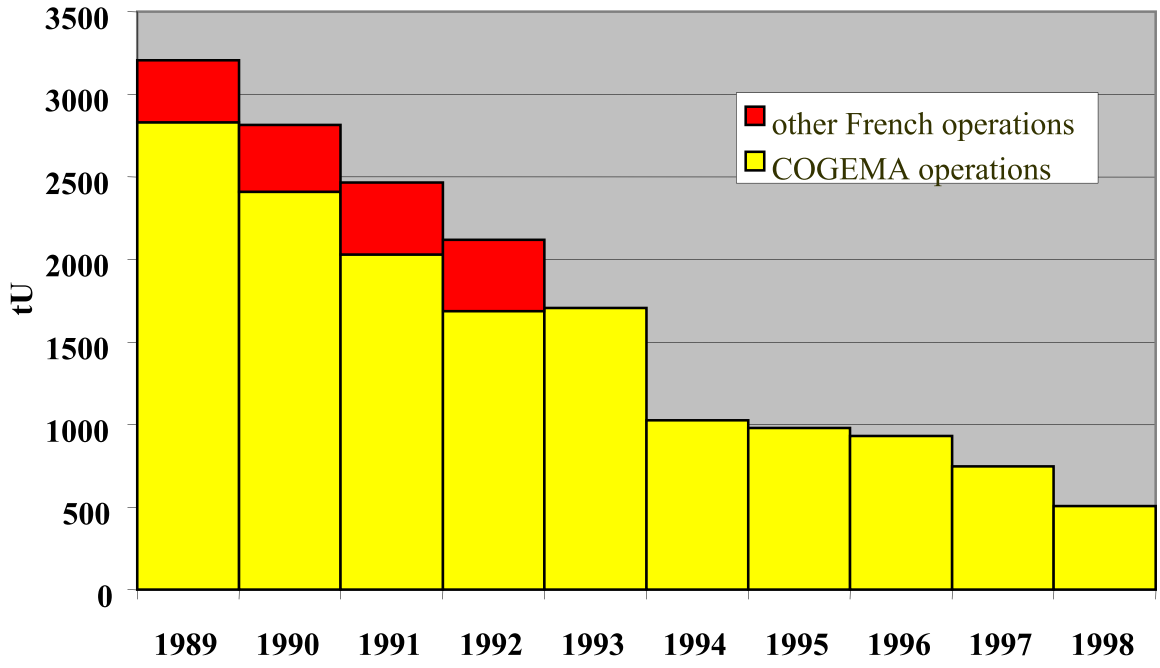


FIG. 1. Recent evolution of uranium concentrates production in France.

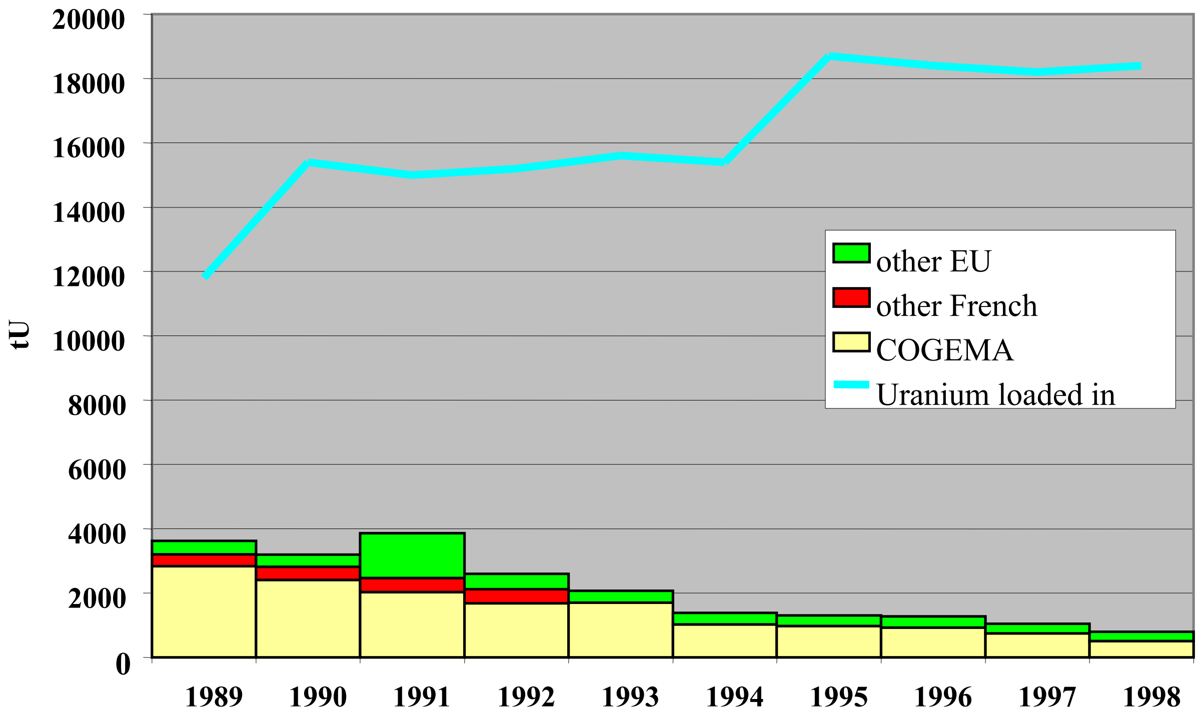


FIG. 2. European Union uranium production & consumption.

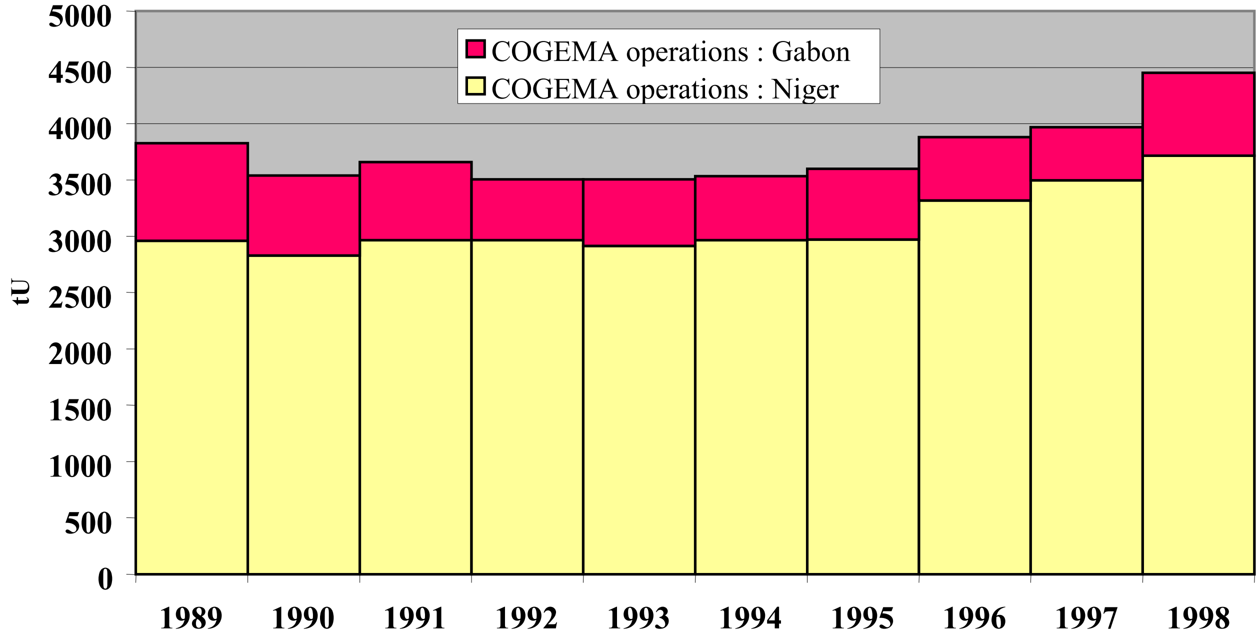


FIG. 3. COGEMA uranium concentrates production in Africa.

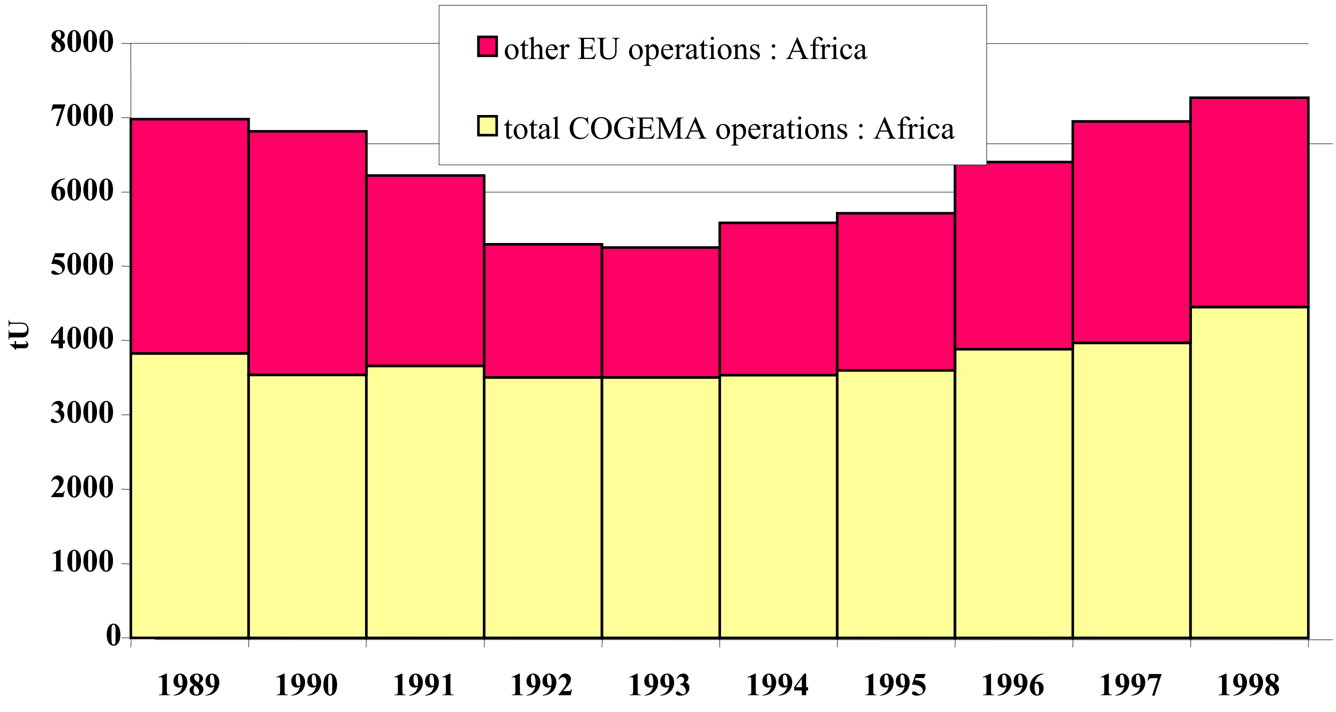


FIG. 4. European Union operators uranium production in Africa.

A still limited share of North American uranium

With a 19% contribution to COGEMA's production, North American Uranium production does not reflect its 64% share of COGEMA's total Reserves and Resources. A greater share was anticipated a few years ago, but licensing difficulties have delayed the start up of concentrate production at the McClean Jeb Mill in Northern Saskatchewan.

A significant event occurred in 1998 with the Uranerz interests sale to Cameco by its shareholders. By the way, the only other EU company producing uranium in North America vanished (Fig. 5). This situation will be partly compensated in 1999 by the deal concluded by COGEMA with Cameco to buy a complementary share into McArthur River project.

Adding the three source zones of COGEMA's production shows a rather regular pattern for the last 10 years, between 6 000 and 7 000 tU/year (Fig. 6). It is interesting to note that, while not entirely devoted to EU consumption, this total production represents 1/3 of the total uranium loaded in EU reactors in 1998. Depending upon regulatory approval and market conditions, a move towards an increased share of Canadian production is expected that is more in accordance with COGEMA's Reserves & Resources portfolio basis.

2. Development & new mine construction programmes

The projects are listed in Table II. Orebody development programmes, i.e. drilling evaluation grids and pilot tests are essentially limited to the Canadian projects in Saskatchewan and to new ventures in Central Asia, Kazakhstan and Uzbekistan.

Construction of new mines is at the moment limited to Saskatchewan. The main active projects are:

- McClean, where mining has already started, but where the final approval for starting milling operations is still pending, after various delays due to the tailings disposal facility licensing and construction.
- McArthur River where commercial mining operations are scheduled for starting later this year.
- Key Lake mill where its operator, Cameco Corporation, will start a refurbishing programme this summer in order to begin McArthur River ore treatment by the end of 1999.

The Cigar Lake project will follow with a startup date scheduled at around 2002, depending among other factors upon market conditions and licensing.

It is too early to elaborate about Central Asian projects. They are certainly promising, but it is better to wait for the full implementation of the ongoing pilot tests.

The above mentioned projects are the result of years of involvement in exploration with various partners. These projects are naturally favorite targets when the time comes to make new investment choices or when an opportunity window opens.

3. Uranium interests acquisition

When market prices are low, a number of opportunities are accessible for those who believe in the future of nuclear energy. This is especially true in the field of uranium mining.

Among recent events, a very significant deal was announced by COGEMA Resources Inc. (CRI) on January May 5, 1999. Under this transaction, selected uranium assets, all located in Saskatchewan (Canada) were acquired from Cameco (Table III) with effect as of January 1, 1999, subject to regulatory approvals and in one case subject to rights of first refusal.

Table III. COGEMA interests in selected projects following recent acquisitions

Property	COGEMA Ownership 1999, %	Total Uranium tU	Average grade % U	COGEMA Share, tU
McArthur River	30.195%	185 800	12.1%	56 100
Key Lake	16.667%	4 769	0.95%	795
Cigar Lake	37.1%	135 900	11.5%	50 400
Midwest	76%	16 000	3.9%	11 200

The main assets are a further 14% interest in the McArthur River Project and a 17% interest in the key Lake Project where the McArthur River ore will be milled by year end 1999.

So the transaction strengthened CRI resource base with high-grade ores.

A smaller but significant deal was announced at the same time. An additional 0.725% interest in the Cigar Lake Project was bought by CRI from Korea Electric Power Corporation.

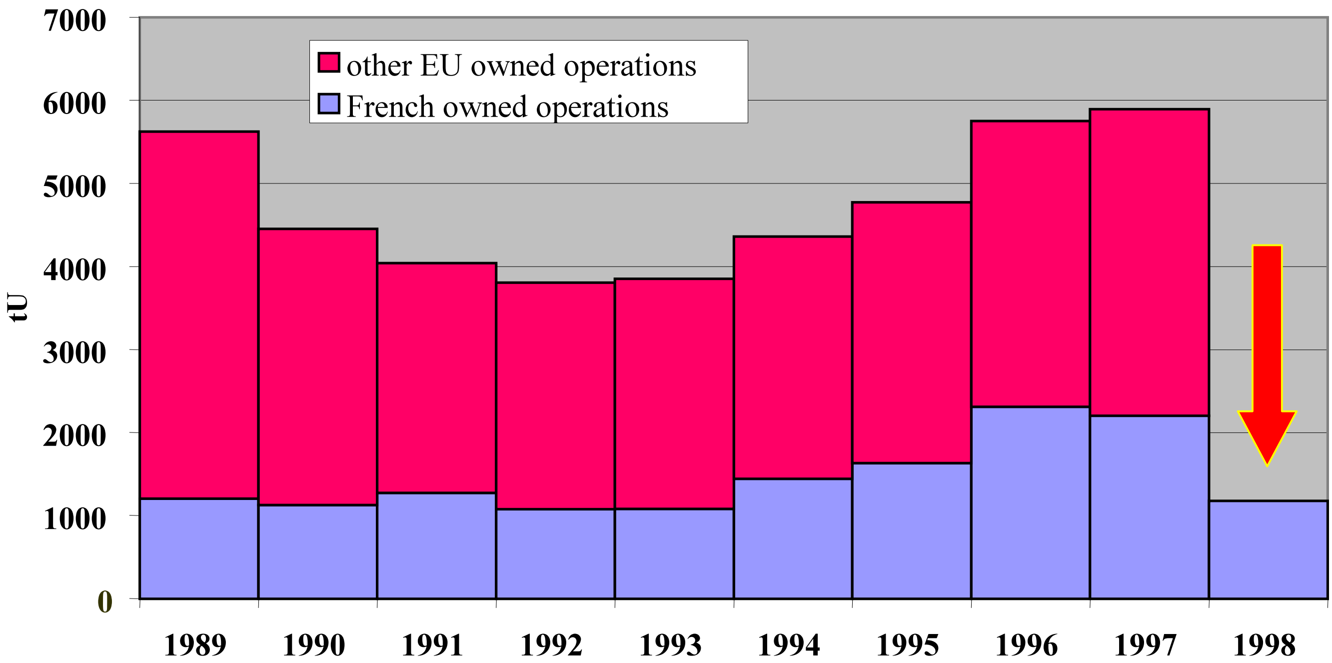


FIG. 5. European Union operators uranium production in North America.

4. A very significant portfolio of economic resources

As of January 1, 1999, COGEMA owns a large uranium economic resources portfolio. In addition to that, this portfolio presents the following advantages:

- Uniquely diversified from a geo-strategic point of view,
- Includes a large share of Reserves (lowest uncertainty category),
- Mainly composed of high grade orebodies,
- Includes a fair share of ISL amenable resources.

Very few uranium producers own a greater Reserves and Resources basis than COGEMA with 283 500 tU, especially in the case of non-byproduct uranium (Fig. 7).

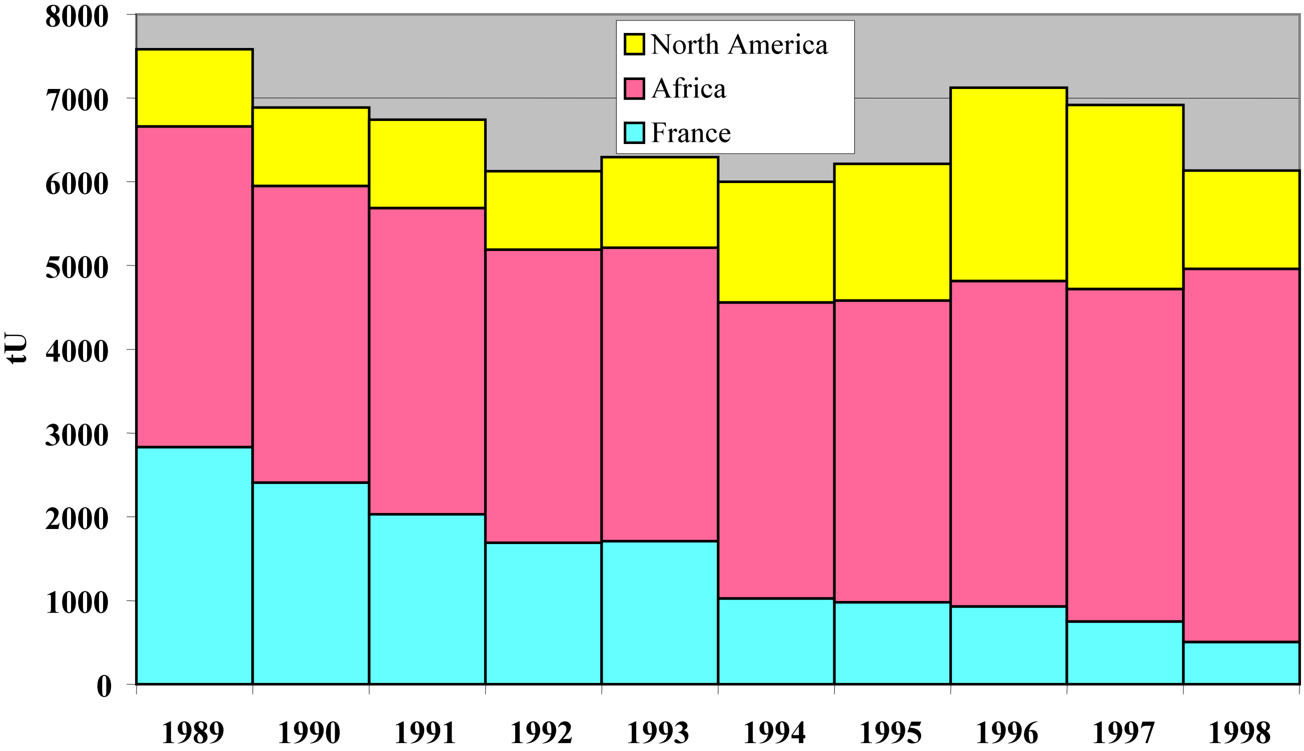


FIG. 6. Uranium production from COGEMA operations.

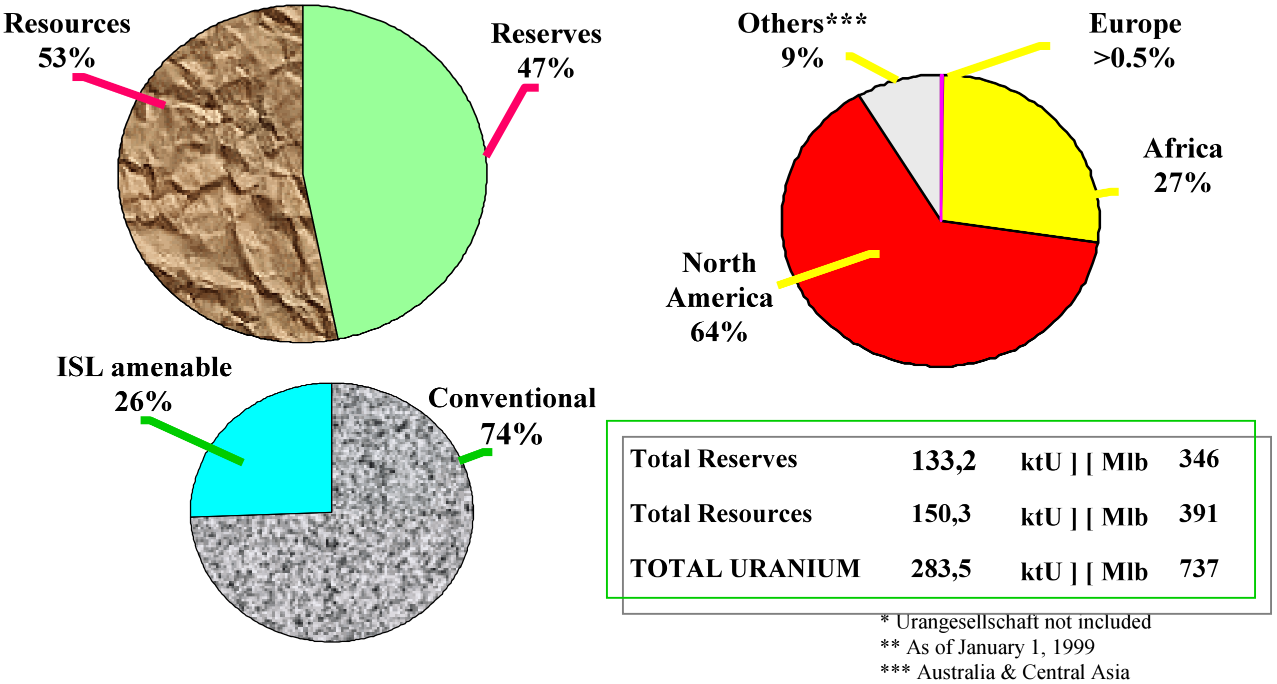


FIG. 7. COGEMA GROUP Uranium Reserves & Resources**.*

Among the various world uranium producers, COGEMA offers a unique geographical diversification (Fig. 7). If its historical basis of European resources is now exhausted due to prevailing market conditions, COGEMA’s African subsidiaries still represent a significant share of its total uranium with more than ¼%. North America of course represents a large part of the total with 64% and this part contains the highest ore grades.

However, Africa plus the other regions, mainly Australia and Central Asia, represent more than 1/3 of the total.

In the total mentioned above, the Reserves Category represents almost half the total (47%), and the high grade orebodies, with an average grade above 1% U, roughly the same percentage at 48%.

Also, of the same total, recoverable uranium in ISL amenable orebodies represents 26%.

5. The Russian HEU feed deal: a potentially substantial source of secondary supply

A long awaited agreement

After more than five years of intergovernmental (Russia and USA) and commercial negotiations, a commercial agreement with Techsnabexport (Tenex), the commercial arm of the Russian MINATOM, was signed by Cameco Corporation (Canada), Nukem Inc. (USA) and COGEMA (France).

This agreement, duly approved by the US and Russian Governments, enables the purchase by the three western companies of natural uranium in the UF_6 form belonging to Russia and derived from dismantled Russian Nuclear Weapons.

This weapons derived material is being delivered in North America under a 20 years agreement, known as the HEU agreement (or Sword to Ploughshare agreement), signed in late 1993 between the United States of America and the Russian Federation.

A significant contribution to weapon grade material reduction

The commercial agreement will contribute to ease the implementation of this “Sword to Ploughshare Agreement” and thus represents a major commitment of the civilian nuclear industry to reduce nuclear weapon grade material stockpiles.

The commercial agreement is also a meaningful way to see Russia being fairly paid for its efforts toward nuclear arsenals reduction.

In addition to that, the commercial agreement will lift, at least partially, the enormous uncertainties clouding the uranium market before it was signed. This will be beneficial not only to the signatories, but also to all market participants.

Under the terms of the commercial agreement, the three western companies have exclusive options to purchase about 260 million pounds U_3O_8 (100 000 tU) over the 15 remaining years of the HEU agreement. For its own commercial purposes, Tenex will retain a balance of about 100 million pounds U_3O_8 (38 500 tU), and the total involved over the 15 years is about 360 million pounds U_3O_8 (138 500 tU).

Stockpiling to lower market impact

According to the various bilateral agreements and legal requirements controlling the HEU deal and its commercial environment, the creation of stockpiles in both the US and Russia will delay the sales in the market of substantial amounts of natural UF_6.

- In the US, a stockpile of about 58 million pounds U_3O_8 (22 000 tU) will be withdrawn from the market for a 10-year period. It comprises 28 million pounds U_3O_8 from Russian weapons derived material and 30 million pounds U_3O_8 of DoE excess inventory. Russia will be paid $325 million for the 28 million pounds by the US Government.
- In Russia, a monitored stockpile build with the sent back natural UF_6 must reach the same amount before the Russian side will commercialize the uranium under its existing contracts. The Russian stockpile will receive the natural UF_6 not purchased in the US by the three western companies. However, from this stockpile, the Russians can use a 2500 tU/year allowance for HEU blending purposes.

A new kind of uranium mine

The commercial agreement represents for COGEMA an exclusive right to purchase a maximum of about 43 000 tU as natural UF_6 (111.8 million pounds U_3O_8) over the next 15 years (starting 1999). According to the US law, and pursuant to the commercial agreement, about one half of this maximum quantity could be delivered to US end users.

For COGEMA, and for Cameco Corporation as well (the quantities are potentially the same) the commercial agreement could provide a supply equivalent to a new uranium mine.

Will this uranium be normal uranium for the market?

Under current difficult market conditions, the future of this agreement contains a part of a conundrum and perhaps will bring with time headaches and nightmares if not properly managed both by the signatories and by market supervising authorities. It should be noted that each uranium tonne sold, let’s say by COGEMA from this inventory will be marketed as if it comes from its own production.

6. Exploration activities

Despite low market price conditions, COGEMA maintains a significant amount of exploration activities.

Exploration teams are not only active in Canada, Central Asia, Mongolia, Australia, but it is also contemplated to resume exploration in Madagascar, and cooperation agreements signed with other countries could lead to more precise ventures.

However, these activities remain on the backburner as the major challenges are to succeed at putting on stream the above-mentioned projects.

7. Deposit estimation techniques

Whatever the prevailing economic trends, Reserves & Resources Estimation activities remain a keystone for uranium mining.

With the discovery and related development of new kinds of orebodies (very high grade) or of new mining methods (ISL), estimation techniques are continuously adapted. A new methodology allowing a convenient evaluation of redox (roll) fronts to be mined using In Situ Leaching was recently developed by COGEMA's teams.

This new methodology exemplified the continuous process of innovative developments performed by COGEMA Mining Engineering Team.

A brief of this methodology is provided here as an annex of this paper (see Appendix I).
Related software and consultant services are also available for other interested parties.

8. Conclusions

Listing all the steps crossed by COGEMA since its beginning in uranium mining certainly brings a proof of its deep involvement in this industry.

Today COGEMA's reserves and resources portfolio is quite large and should allow satisfactory future development of the activity. It allows COGEMA to offer competitive and reliable supplies to all of its customers.

At the turn of the century, we hope that the combination of our strong uranium resource base, our very significant investments in the best future uranium mines and more recently our access to former military uranium surplus, will enable COGEMA to help its customers progress towards a renewal of nuclear generation. We think this will benefit the world population.

APPENDIX I

A new methodology for estimating uranium roll type deposit and ISL project, SERMINE software, JP Benac, 1997, COGEMA BU SER.

Geostatistical methods have been applied for many years for the evaluation of uranium deposits. Geostatisticians have developed a large panel of techniques, which apply diversely depending on the spatial characteristics of the mineralization.

All techniques share the same basic principles: modeling of the spatial variability of a variable (grade for example) through the variogram, and estimating the value of this variable on a larger support, i.e. a panel, by kriging. Kriging is based on a linear interpolation of neighboring sample grades. The weights assigned to samples are calculated using the variogr793rn model.

All methods aim to estimate given variables (i.e. grade) over fixed chosen geometric blocks. Blocks, being cubes or parallelepipeds, are satisfactory to model classical mining conditions, i.e. by shovels and trucks. Naturally they are less adapted to fit complicated geological shapes and to model accurately at the border of any (geological) volume. To solve these problems some partial blocks have to be considered.

The situation becomes more complicated when the geometry of the mineralization and the mining method cannot be satisfactorily simulated using regular geometrical blocks.

In uranium mining the most typical and difficult situation occurs in roll type deposits, currently mined by ISL. In roll type deposit the mineralization follows a redox front separating the non-oxidized and the oxidized sandstone. Local precipitation of U is controlled by reduced carbonaceous matter and a chemical balance related also to the hydrodynamic characteristics of the rock formation. As a result roll type deposits present a very particular geometry, and the application of geostatistical methods is conditioned by this geometry.

In general the estimation is conducted at 2D, by projecting the interpreted limits of the mineralization on a level plane. The front line, which is the line at the frontier between the nose and the reduced barren rock, is used as the external limit of the mineralization.

The method developed in Sermine software (JP Benac, 1997) generates curvilinear lines (isolines) H parallel to the front and isolines F perpendicular to the front (Fig. 8). These lines define a set of curvilinear cells, which compose the estimation grid. This curvilinear grid models accurately the complex geometry in plan view of the roll type deposit. The grid mesh depends on the isolines and therefore it fits precisely the roll.

The benefits gained by this curvilinear grid compared with a classical Cartesian grid are multiple:

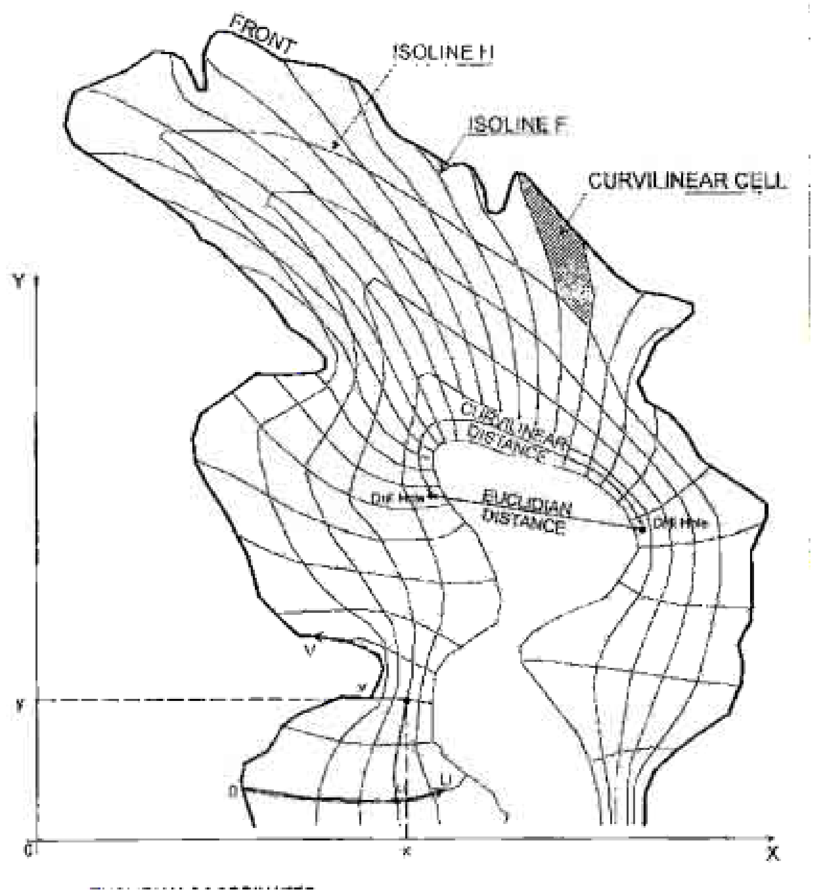
1. The grid takes into account the varying directions of the roll. Indeed, considering the deposit formation (precipitation of U downstream, from the interior of the roll to the front), the direction parallel to the front is the direction of highest continuity of the mineralization. The direction perpendicular to the front is expected to have the lowest mineralization continuity. Unlike a Cartesian grid, parametric grid follows exactly these 2 main directions.

2. The grid calculates the (true distance) between 2 intercepts (Fig. 8). For instance 2 drill holes along the front may be very close but separated by a permeability barrier. There is therefore no real correlation between these 2 points. The distance of interest between these 2 points is not the Euclidian distance but the length along the front, i.e. the parametric distance.

3. The parametric grid avoids to correlate drill holes which, from a geological point of view, should not be linked, and calculates the (true distance) between intercepts. The variograms are calculated in the parametric space in the main directions of the roll, with couples of values that are consistently correlated according to the geologic model and with (true distances) between values (Fig. 9). The variograms are therefore representative of the geological structures.

Kriging is performed on the parametric grid. Note that at this stage estimated panels (cells of the parametric grid) are regular polygons (rectangle or square). The estimated blocks are transformed back into the usual reference grid system, restituted as curvilinear polygons.

The validation of the method was carried out in details using the model of Grandprat (Christensen Ranch project located within the Powder River Basin, USA).



(X, Y) EUCLIDIAN COORDINATES
(U, V) CURVILINEAR COORDINATES

FIG. 8. Definition of the Curvilinear grid.

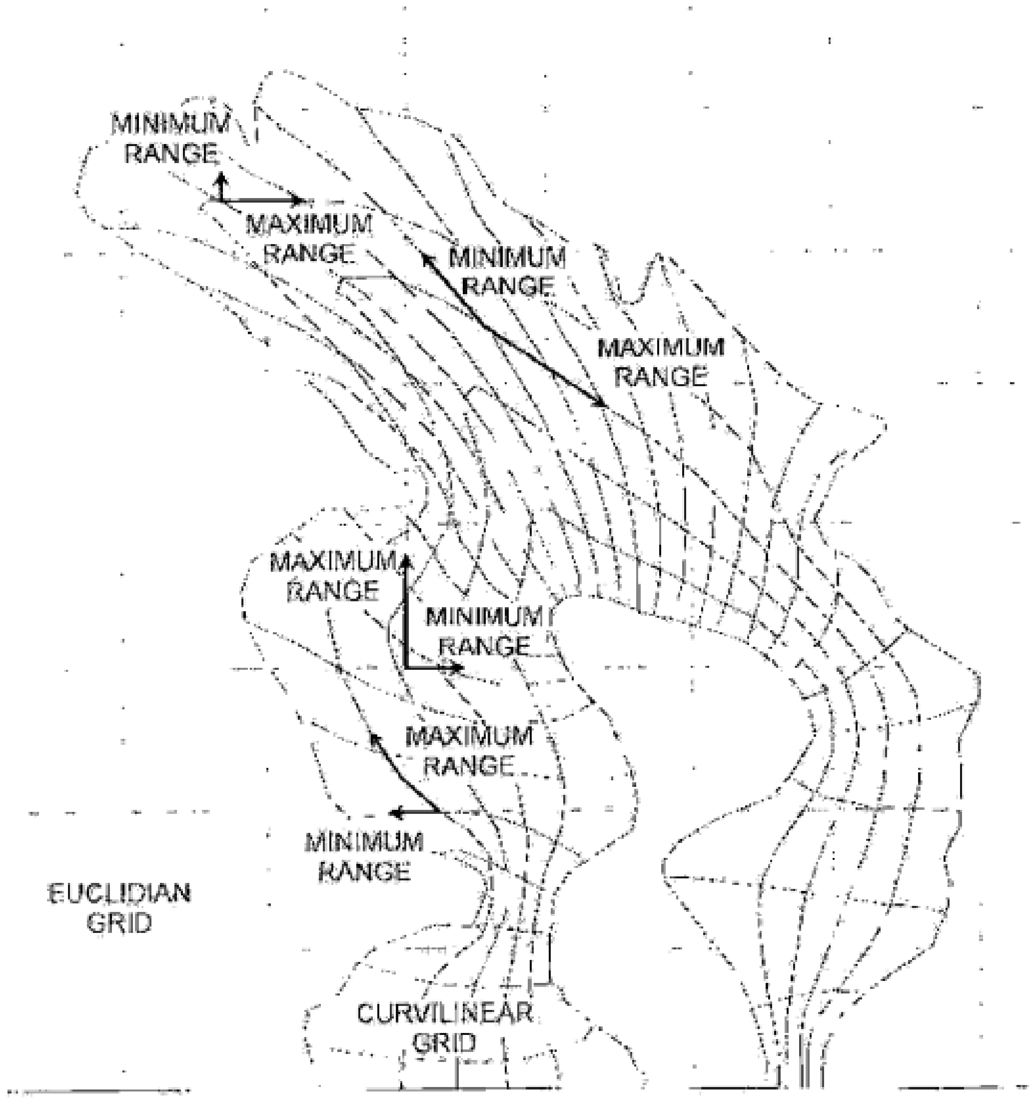


FIG. 9. Compared Variography in a Curvilinear grid and in an Euclidian grid.

Uranium production in the Commonwealth of Independent States, China and Mongolia

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Abstract. World uranium production has been below reactor requirements since 1990. Over this period the world inventory has been drawn down by over 160 000 t U. It now appears relatively little excess inventory remains. Substantial additional uranium production will be required to meet rising demand (Fig. 1). The uranium producing group consisting of the Commonwealth of Independent States (CIS): Kazakhstan, Russian Federation, Ukraine and Uzbekistan, together with the People's Republic of China and Mongolia, are expected to make a significant contribution to required production over the next 10 to 15 years. Much of the increase is expected to come from those countries with low cost uranium resources amenable to in situ leach (ISL) mining technology and sources of capital for new facilities. With the exception of Ukraine, all of these countries have known uranium resources that are amenable to ISL production. Sources of capital are not as readily available. This paper is a review of the status of and future potential for uranium production in the CIS, China, and Mongolia. Following a review of the current status of uranium production in the region, the factors expected to influence future production are discussed. For each country we look at individual projects with the potential for contributing increased uranium production.

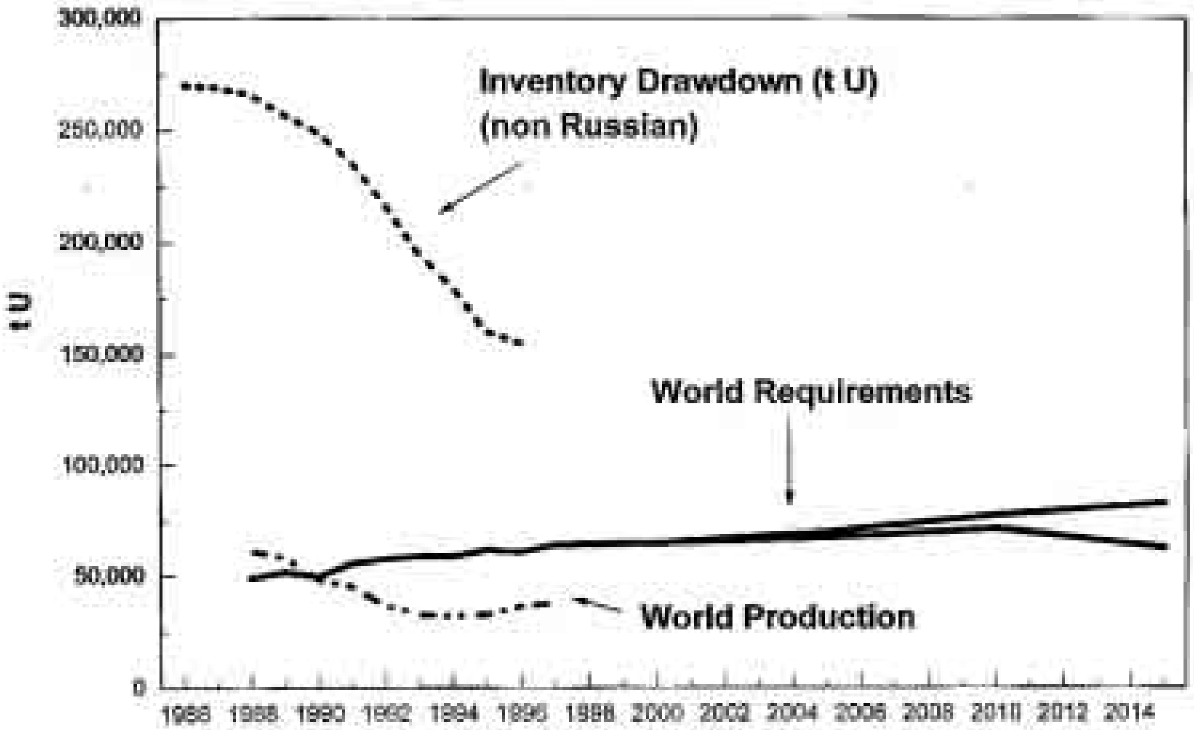
1. Overview

The uranium producing countries of Kazakhstan, Russian Federation, Ukraine, Uzbekistan, China and Mongolia make up a large geographic area ranging from eastern Europe through much of continental Asia (excluding the Indian sub-continent and southeast Asia). Together they comprise about 28 million km^2, or nearly 20% of the earth's land surface (Table 1). It should be noted that although the CIS Republics of Kyrgyzstan and Tajikistan both have uranium mills, and have mined and milled uranium in the past, neither country has known uranium resources nor has announced plans to restart production.

The countries under consideration have several aspects in common including geology, production technology, socio-economic situation and history which influence decisions related to uranium production. These countries are all undergoing an adjustment from a centrally planned command economy to a market based system. While Mongolia was not part of the former Soviet Union, the history of uranium exploration and production in Mongolia is closely tied to the Russian Federation [1]. Since the breakup of the Soviet Union in 1991, the Mongolian economy has been in transition to a market based system. The uranium resource inventories of the CIS and Mongolia, developed under the former Soviet system, are currently evolving to include consideration for production costs. Starting in 1980, China converted its uranium industry from military production. It has also been taking steps to improve the efficiency of its uranium production industry and make it's uranium more economically competitive. There are significant differences, however, with regard to the existing and planned nuclear power programmes of these countries.

Table I. Land area of uranium producing countries (CIS, China and Mongolia)

	Km^2 × 1000
Russia	13 169
China	9 609
Kazakhstan	2 727
Mongolia	1 573
Ukraine	606
Uzbekistan	450
Total	**28 134 (19% of world)**



Not accounting for: CIS civilian stockpiles; U.S. and CIS HEU.

FIG. 1. Production, requirements and the inventory in the world uranium market.

Uranium production to increase

Following the breakup of the Soviet Union uranium production fell in the CIS producing countries. (Ukraine may be an exception, Fig. 2). Uranium mining also stopped in Mongolia in 1994. For several years it has been projected that the declining trend of production in these countries would reverse and that production would increase significantly. It was not until 1996, however, that Russia reported a uranium production increase. Uzbekistan reported its first upturn in 1997. The estimated 1997 uranium production for the CIS and China are presented in a world perspective in Fig. 3. Mongolia had no production in 1997.

While the recovery of the uranium production industries of the CIS is taking place much more slowly than expected, it is now apparent production will increase significantly over the next few years in most, if not all, of the countries. In Mongolia uranium production is expected to restart and grow. These developments will in part depend on the continuing development of a legal and administrative structure that provides a stable system for involvement of western mining companies. It will also in part depend on increasing market prices. China is expected to increase its uranium output primarily in response to increasing domestic reactor requirements.

A production increase is expected because of the availability of low cost uranium resources that may be mined at a profit in most of these countries, together with the determination of China, Ukraine and Russian Federation to supply domestic nuclear programmes. Russia also requires uranium for other purposes. It needs 2200 t U/annum to fabricate fuel for sale to supply reactors of Russian design in Ukraine and central Europe [2]. In addition to its market sales of natural uranium, Russia requires blendstock for diluting Highly Enriched Uranium (HEU) to Low Enriched Uranium (LEU). This blendstock for the 500 t HEU under a 20 year sales contract with the USA is an estimated 43 500 t U natural equivalent [3].

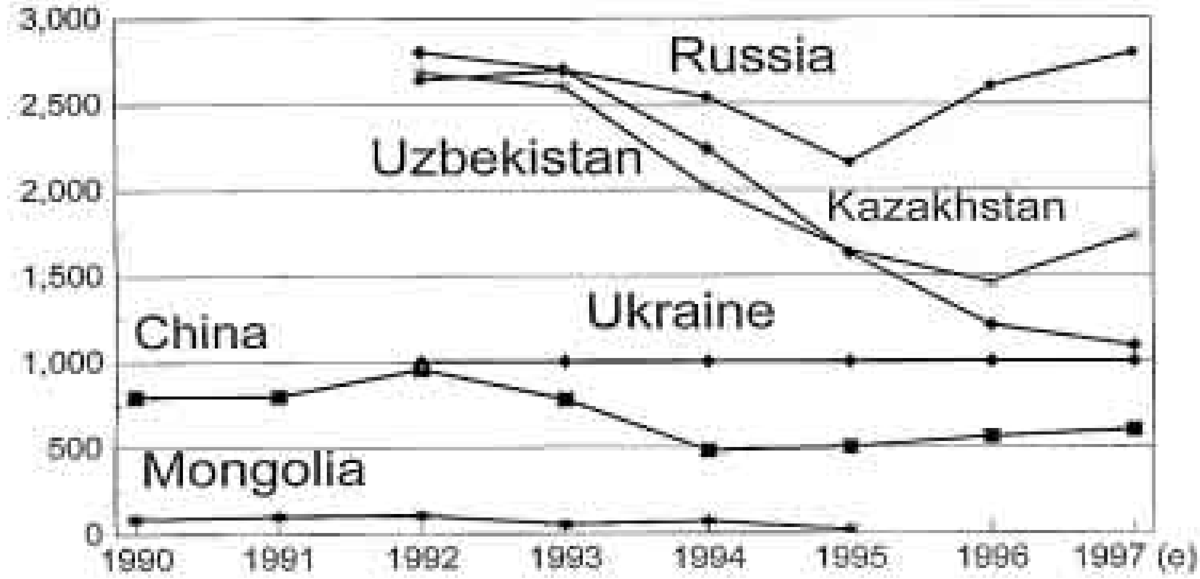


FIG. 2. Uranium production in China, CIS and Mongolia 1990-1997.

World Demand: 63 770 t U / World Production: 37 400 t U
Others: Argentina, Belgium, Czech Republic, Gabon, Germany, Hungary, India, Pakistan, Portugal, Romania and Spain

FIG. 3. Estimated 1997 world uranium production vs. reactor related demand.

Business ventures for uranium exploration and production with foreign mining companies have been established in Kazakhstan (3), Mongolia (3) and Uzbekistan (1). China's 2 exploration related joint ventures are expected to end in 1998. No joint ventures for uranium development with foreign companies exist in Russia or Ukraine. In addition to the much needed capital, the foreign venture partners provide western technology and management systems [4,5]. The domestic companies provide access to as uranium resources, technology, infrastructure and staffing, as well as their operational and administrative experience.

Other projects will be operated by domestic mining companies with capital provided by either governments, banks and/or cash flow from profitable operations. For example, the very large Muruntau gold mine operated by Navoi Metallurgy and Mining Combinat (NAVOI) in Uzbekistan provides the company with a cash flow that may supply capital required for uranium operations. Table 2 gives a summary of sources of capital for uranium mine development in the countries discussed in this report.

Table II. Sources of capital for uranium mine development

Country	Foreign Joint Ventures (Number)		National		
		Government	Bank	Organizations	Other
China	+ **(2)**	+		CNNC	
Mongolia	+ **(3)**				
Kazakhstan	+ **(3)**	+	+		
Russia	-	+		MINATOM	
Ukraine	-	+			
Uzbekistan	+ **(1)**				NMMC-Gold Production

Most of the uranium production in the CIS, China and Mongolia will come from only a few uranium deposit types. The most important types are sandstone hosted. Volcanic type deposits are expected to be the second most important deposit type, with vein-stockwork and metasomatic deposits also contributing. Much of the production, particularly from new projects, is to be recovered from sandstone hosted roll-front type deposits. These deposits are located at the interface between reduced and oxidized sandstone in water saturated rocks. The favorable sandstones are generally unconsolidated, have a low carbonate content (<2%) and are very permeable.

In situ leach (ISL) technology using acid solutions will be used for developing a majority of the new uranium mines in the region. This production technology effectively recovers uranium from roll-front type deposits occurring in unconsolidated, water saturated sandstones. Use of the technology was developed in the 1960s and 1970s under the Soviet system. It is well established as the lowest cost uranium production technology used in the region.

Although less important than ISL, conventional mining will continue to be an important uranium producer. Conventional mills will be used to process mined ores. This is supplemented by heap and in-stope leaching introduced in recent years to reduce production costs, as well as to recover uranium from low grade ores (Table 3).

Table III. Principal technology used for uranium production

Country	ISL	Processing:		
		Conventional Mill	Heap Leach	In-Stope Leach
China	■	■	■	■
Mongolia	*	(1)	■	
Kazakhstan	■	(inactive)	*	
Russia	*	■	■	■
Ukraine	*	■		
Uzbekistan	■			

* Planned

(1) Ores, or yellowcake slurry shipped to Russia for processing.

2. Motivating uranium production

The 3 principal motivations for producing uranium in the region are export sales, supplying domestic reactor requirements and creating employment. Russia also wants to continue filling its large uranium requirements for fabricated fuel sales and blending HEU to LEU.

- **Sales**

Producing uranium for export sales is the primary motivation for Kazakhstan, Mongolia and Uzbekistan. Both China and Russia continue to sell substantial amounts of uranium. Ukraine has also made 1 or more sales of its uranium in recent years.

- **Nuclear power programmes**

The countries may be grouped into those with, and those without nuclear power programmes. China, Russian Federation and Ukraine all have nuclear programmes, and all have announced plans for expanding uranium production to meet projected requirements (Fig. 4). The respective current annual uranium requirements are 300, 3600 and 2640 t U. Russia and Ukraine plan to maintain their power programmes at about current levels. With 3 nuclear power plants operating and 8 reactors under construction, China has by far the most rapidly growing nuclear power programme. Neither Mongolia nor Uzbekistan has a programme, nor have they announced plans for developing one. Kazakhstan has one small nuclear plant with modest annual uranium requirements of about 70 t U. Kazakhstan has announced plans to expand its nuclear programme with the first new plant projected to come on line by 2005. While self sufficiency of nuclear fuel supply is no longer a strategy followed by most countries with a market economy, it remains the policy in the CIS and China.

- **Employment**

With the exception of Mongolia, whose relatively small uranium mining industry was suspended in 1994, all of the countries have continued to provide employment and economic well being for their present and former workers. This is a particularly important consideration as all of the countries have large numbers of uranium industry employees. The objective of maximizing employment is, however, runs counter to the objective of improving production efficiency by reducing employee levels.

In recent years employment levels have decreased in all the countries, except Uzbekistan. In Uzbekistan employment increased from about 6700 in 1994, to about 8200 in 1996. Russia, with highest number of employees, experienced a decrease from 15 900 employees in 1993 to 13 000 in 1996. A summary of employment trends in the CIS and China is given in Fig. 5 [6].

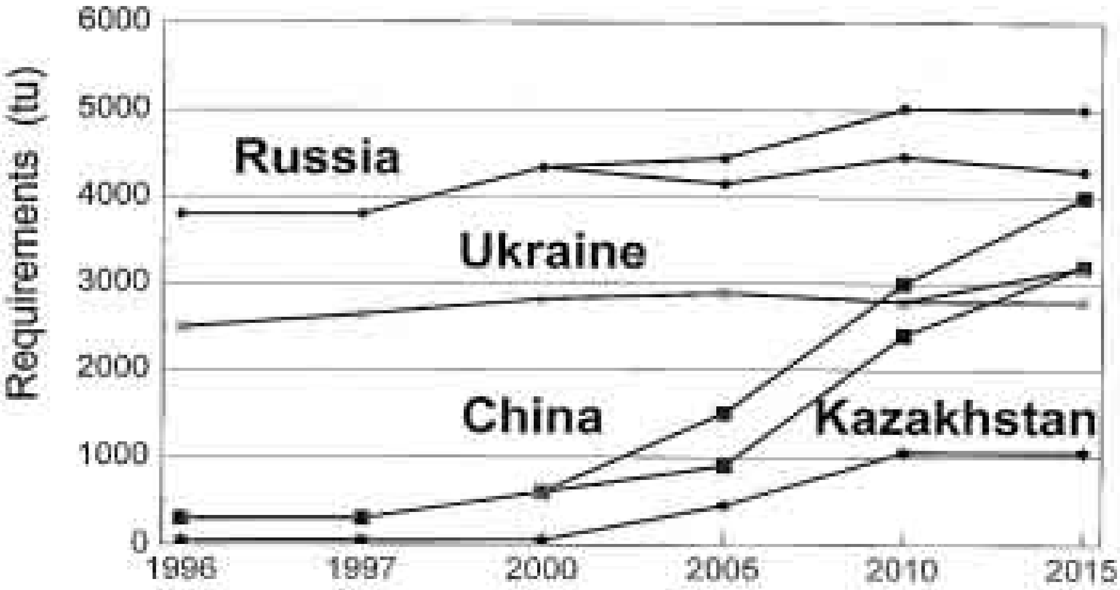


FIG. 4. Annual reactor uranium requirements to 2015 (low and high options).

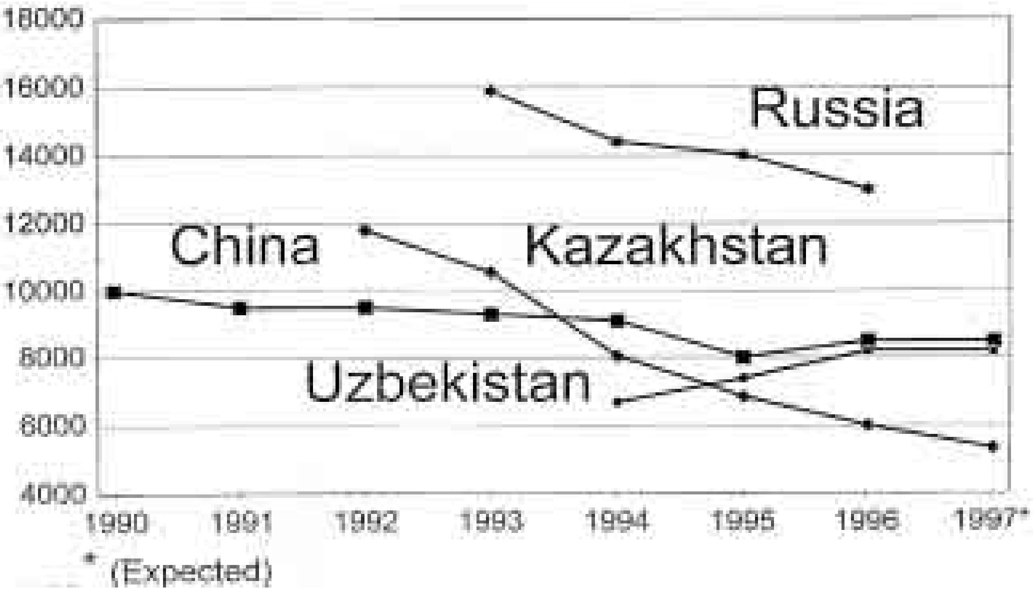


FIG. 5. Employment in uranium production, CIS and China.

In the past, large numbers of employees and their families were supported by the uranium industry. Furthermore, unlike western organizations, the mining companies have normally provided a wide variety of infrastructure and related services, including townsites, schools, health and welfare, social and retirement benefits. For example in Uzbekistan the uranium industry provided a regional electric power network and railroad system which it developed, maintained and operated. NAVOI's General Director reports that in 1995, 200 000 people were living in 5 towns in the Kyzylkum Desert that were dependent on the uranium and gold mining industries operated by Navoi Mining and Metallurgy Combinat.

3. Geology

The uranium deposits of the CIS, China and Mongolia have several features in common. Having an understanding of these deposit types provides additional insight into the future uranium production in the region (Table 4).

The only uranium deposit types with known low-cost potential occurring in more than one country are the sandstone and volcanic types. Of these, sandstone hosted deposits are much more widely distributed and have greater potential than volcanic-type deposits. Other deposit types with less importance include vein stockwork deposits in Kazakhstan and China. Alkali metasomatite-type deposits are the main source of uranium production in Ukraine. Granite hosted and black shale-type deposits are also a production source in China.

Table IV. Major uranium deposit types in CIS, China and Mongolia

Country	Sandstone:			Volcanic	Vein / Stockwork	Others
	Large Basin	Basin	Valley-type			
China		■	*	■	■	Black shist
Mongolia		■		■		
Kazakhstan	■				■	
Russia			■	■		
Ukraine			*			Metasomatite
Uzbekistan		■				

■ Major importance, * Minor importance

3.1. Sandstone-type deposits

The sandstone-type uranium deposits in the region are of the roll-front type, occurring at the interface between reduced and oxidized sandstone in water saturated rocks (Fig. 6). Where these deposits occur in basins they are called “stratum-bed oxidation-type” by Russian specialists and “interlayerred oxidation-type” in China [7, 8]. Deposits occurring in basal channel sediments are named “valley-type” in Russian usage [9], and “phreatic oxidation-type” [10] in China. The basal channels occur at the base of a sedimentary sequence, commonly within a depressions or “valley” eroded into the underlying basement rocks.

Most of the sandstone deposits in sedimentary basins are of Cretaceous and younger age. Some of the basal channel (valley-type) deposits occur in rocks as old as Jurassic.

Basins hosting uranium bearing sandstones in Asia range from small to very large. Uranium deposit size generally increases with basin size. The Chu-Saryssu artesian Basin in Kazakhstan is up to 250 km wide and extends for more than 1000 km from the foothills of the Tien Shan Mountains to the south and southeast, toward the Aral Sea to the northwest. This basin is separated from the Syr-Darya Basin to the southwest by the Karatau Uplift. These very large basins host the regional scale roll-fronts that separate the oxidized from the un-oxidized rocks. These basins also host Kazakhstan’s very large sandstone uranium deposits which comprise about 490 000 t U of in situ resources.

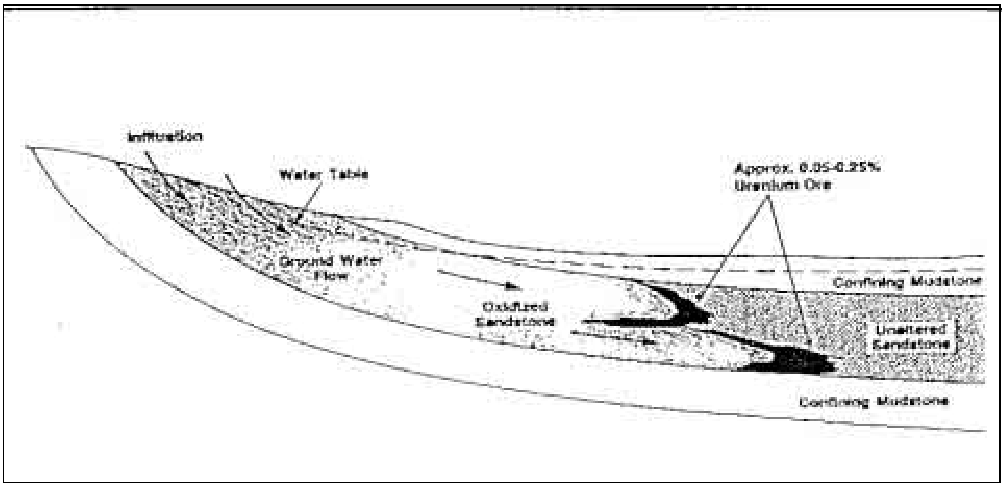


FIG. 6. Cross section of roll-front type sandstone uranium deposit.

The uranium province of the central Kyzylkum Desert of Uzbekistan occurs in a sequence of sedimentary rocks of Cretaceous to Paleocene age that were uplifted in a broad arch starting at the end of the Oligocene. This developed into a basin and range like system with small artesian basins between uplifted blocks of the Pre-Mesozoic basement. As compared with Kazakhstan the uranium deposits occur in more local roll-fronts zones developed within each individual basins [11].

Continental basins hosting sandstones of Mesozoic to Cenozoic age are widely developed in northern China. The relatively large scale basins include the Tarim, Junggar, Turpan-Hami and Yili Basin in Xinjiang Autonomous Region; the Qaidam Basin in Qinghai Province and the Ordous Basin in Shanxi, Gansu and Ninxia Provinces, as well as some basins in northeastern China. The area of the basins total nearly 2 million km^2. The Erlian Basin in the Inner Mongolian Autonomous Region is over 1000 km long and has a total area of about 130 000 km^2. The Yili Basin, the location of China's currently expanding ISL operations, has an area of 16 600 km^2. It forms the eastern portion of a basin extending into Kazakhstan. Several other basins with potential to host sandstone-type uranium deposits are presently being explored in China.

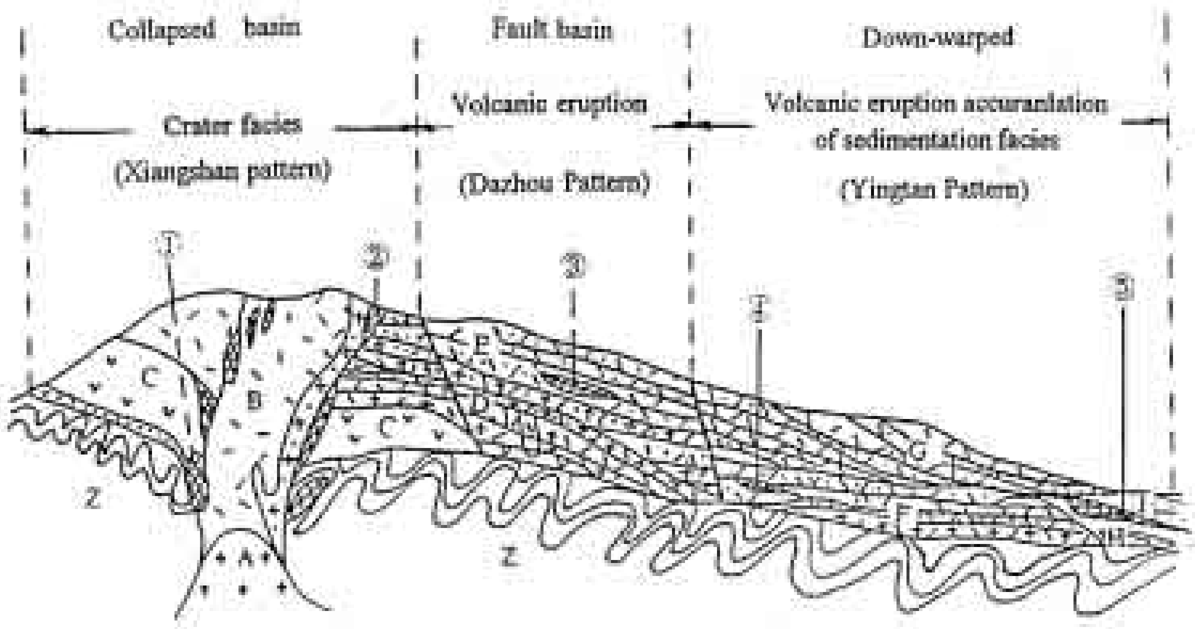
Basins currently under evaluation in central and southeastern Mongolia are less well known. Uranium deposits currently under exploration in Mongolia's Hairhan Depression, occur in a basin 50 to 60 km long by several km wide.

Abukumov describes the roll front uranium deposits of the Chu-Saryssu Basin, Kazakhstan, as winding, often up to 10 to 20 km long [12]. The deposit width varies from several dozens of metres up to 1 to 1.5 km. In cross section the deposits have an asymmetric roll or lens form. The thickness ranges from several metres, up to 15 to 20 metres or more. The uranium deposits are of low grade averaging 0.02 to 0.05% U, or more. In all of the deposits there are ores with a grade of up to 0.1 to 0.3% U, and more rarely up to 1%. The depth of occurrence ranges from a minimum of 80 to 100 m, up to 400 to 600 m. The ore consists of finely dispersed coffinite and nasturan occurring in the clay cement between quartz and feldspar sand grains, in microfractures of grains and as pseudomorphs of organic plant remains.

The organic content of these rocks is low consisting of a few hundredths to a few tenths of a percent carbonaceous material. It is proposed by Shchetochkin and Kislyakov [13] that the low average uranium grade of the ores is controlled by the low concentration of the organic material which forms the geochemical barrier responsible for precipitating the uranium. In other areas such as in Uzbekistan, where the concentration of precipitant such as organic carbon or pyrite is higher, the uranium grades are also higher.

3.2. Volcanic-type deposits

Volcanic-type deposits are the major sources of uranium production in Russia and Mongolia, and are also of importance in China. Volcanic deposits are defined as stratabound and structurebound uranium concentrations occurring in acid volcanic rocks (Figs. 7a and 7b).



A) Magma chamber, B) Rocks filling in crater, C) Dacite, D) Volcanic lava (I), E) Volcanic lava (III), F) Volcanic rock (I), G) Volcanic clastic rock (II), H) Lacustrine facies sediments (I), I) Lacustrine facies sediments (II), Z) Basemental metamorphic rocks.

FIG. 7a. A comprehensive scheme of the relationship between main occurrence pattern and volcanic setting of volcanic rock type uranium deposits in Ganhang belt, China

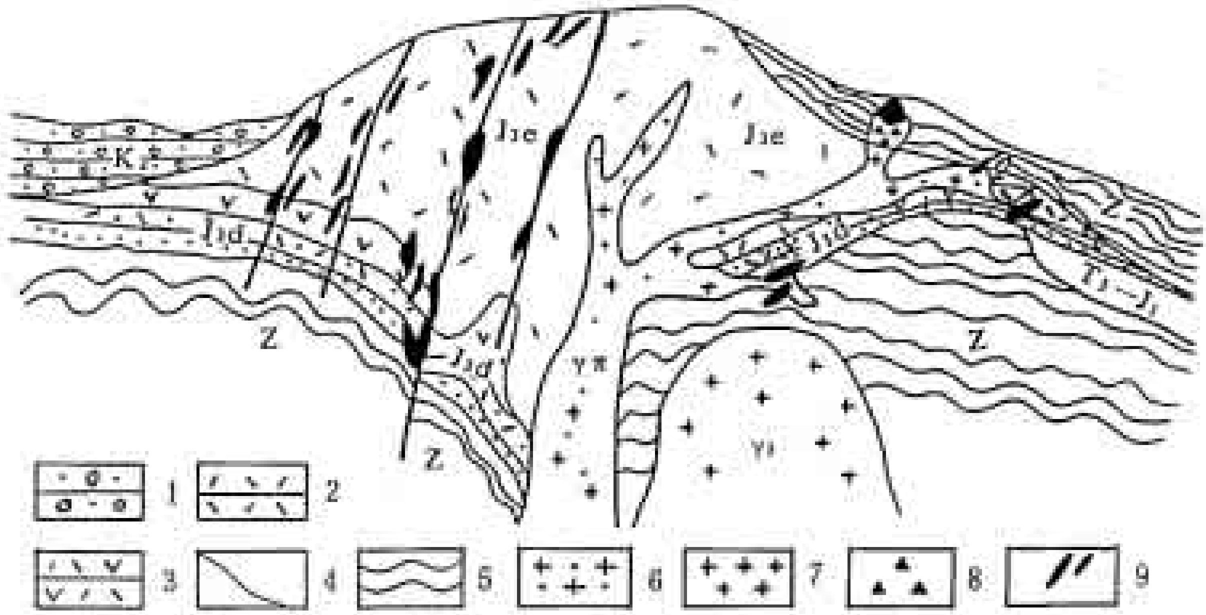
Mining at the Streltsovsky deposits near Krasnokamensk, by Priargun Mining and Chemical Enterprise, produced 97 418 t U from 1968 to 1996, making it a world class uranium district that accounted for nearly 94% of Russia's total production [14]. At Streltsovsk the uranium deposits occur as large scale vein-stockwork deposits of hydrothermal origin within a volcano-tectonic caldera formed by continental volcanism of Late Mesozoic age [15].

The geology of the Xiangshan District deposits located in southeastern China is also attributed to a volcanic caldera environment as described by Chen and He [16]. While the amount of uranium production from the Chinese deposits is not published, this Cretaceous age deposit type is reported to be "one of the most important bases of uranium resources in China".

The Dornot uranium district of northeastern Mongolia is comprised of a similar environment consisting of Mesozoic volcanics and sediments [17]. Open pit mining at this site has contributed all 533 t U produced to-date in Mongolia. It is also the location where preparation for uranium production is presently underway with planned production starting in 1998.

3.3. Other deposit types

Much of the uranium production in Ukraine has come from metasomatite deposits of the alkaline albitite type. It is the major known uranium reserve type in that country. China has for some time relied on production from black schist and granite hosted deposits. China is also currently mining the pegmatite hosted Danfeng deposit near Xian. Exploration for unconformity type deposits has been carried out in China and Russia with no success.



1) Sandy conglomerate, 2) Porphyroclastic lava, 3) Rhyodacite, sandstone, stuff, 4) Sandstone, 5) Schist, 6) Granite, 7) Granite, 8) Granite dyke, 9) Uranium deposit.

FIG. 7b. Metallogenic model scheme of Xiangshan orefield, China.

4. Uranium resources

Table 5 gives a summary of known uranium resources (RAR and EAR-1), producible at \$80/kgU or less, for the CIS and Mongolia [18]. Comparable information is not available for China. Kazakhstan has by far the largest resources in both the \$80/kg U and under, and \$40/kg U and under, classes. Much of these are attributable to its large sandstone hosted resources. Ukraine is notable as it has no resources producable from the \$40/kg U class. All 106 000 t U of Uzbekistan's resources are recoverable, and are producable at \$40/kg U or less. Most of Russia's resources producable at \$40/kg U or less, occur in undeveloped basal channel (valley-type) deposits. Most of remaining resources at Russia's Priargunsky are only producable at \$80 to \$130/kg U. Mongolia has 83 000 t U, with 22 000 t U producable at \$40/kgU or less.

Table V. Known resources (RAR + EAR -1) of the CIS, China, and Mongolia (producable at ≤ $40 and ≤ $80/KgU)

Resources (tU × 1000)	≤ $40/KgU	≤ $80/KgU
China	N.A.	N.A.
Kazakhstan	436*	635*
Mongolia	22*	83*
Russian Federation	83*	181*
Ukraine	0	83*
Uzbekistan	106	106

* As in situ resources.

Most of the resources of the CIS were first evaluated using the Soviet resource reporting system [19]. While the methodology for estimating quantities of uranium were found to be similar to systems used in many other parts of the world, it was found that the Soviet system did not classify resources by the market based cost of production. Furthermore, the resources were reported as "in-situ" or geologic resources, as no allowance was made for mining and milling losses during production. Uniform low grade cutoffs were used for all estimates. A cutoff of 0.01% U was used for ISL amenable resources, while 0.03% U was used for ores to be produced by conventional mining and milling.

Since the breakup of the Soviet Union in 1991, progress has been made in most countries to reevaluate the uranium resources and introduce market based concepts into the classification. This has been difficult for several reasons as changing the system involves revising laws and formal policies that define how all resource estimates were to be made. Recent improvements include Uzbekistan's reevaluation and reporting of recoverable rather than in situ resources. With the exception of Mongolia, most countries have reclassified resources to more closely reflect the cost of production.

5. Production technology

Throughout the CIS, China and Mongolia the uranium industry has been impacted by the increasing need to consider the economics of production. As a result, with the exception of Ukraine, mines with higher production costs have been closed in all of these countries. This in part accounts for the decrease in employment in the uranium production industries of China, Kazakhstan and Mongolia. Progress is also being made by improving the efficiency of existing facilities and/or developing new facilities using lower cost technologies.

Conventional uranium mining and milling technology is expected to continue to play an important role in uranium production in Mongolia, Russia and Ukraine. It may also contribute to production in Kazakhstan and China. However, the widespread distribution of sandstone hosted uranium deposits, together with the potential for low cost production using ISL technology, has greatly increased the interest in use of the technology.

5.1. ISL mining technology

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.*

The technology of leaching ore “in situ” (in place), is the unique part of ISL mining (Fig. 8). Once the uranium is in solution and brought to the surface, the recovery and processing of the uranium is accomplished using conventional uranium processing technology.

The leach solution is prepared by adding chemicals to water pumped from the ore body aquifer. The ground water serves three other functions: it moves the leach solution within the deposit, allows control of the solutions during operation and helps to restore the natural state following leaching.

Sandstone hosted uranium deposits favorable for ISL extraction contain readily leachable uranium minerals, are generally unconsolidated, have a low carbonate content (<2% for acid leaching), and a minimum permeability of 0.5 m/day (0.6 darcy). In highly favorable conditions the permeability will range to 10, or more m/day (≥12 darkest). ISL projects are currently producing from a maximum depth of about 550 m in Kazakhstan. Orebodies at depths up to 500 m have been mined in Uzbekistan. Production costs increase with depth. Excessive depths make otherwise suitable resources uneconomic to mine.

In 1996 ISL mining produced 4750 t U, or 13% of world output, 36 200 t U (Fig. 9). About 40% of the CIS and China's total production of 6830 t U came from ISL mining. The remaining 60% was extracted using conventional mining technology. A significant part of this ore was processed using heap and in-stope leaching, technologies introduced in China and Russia to reduce production costs.

New ISL projects (or expansions) are being developed in China, Kazakhstan, Mongolia, Russian Federation and Uzbekistan. Ukraine has also recently indicated it may develop new projects using ISL technology. Ukraine pioneered the use of ISL technology in 1963 and continued its use to 1983.

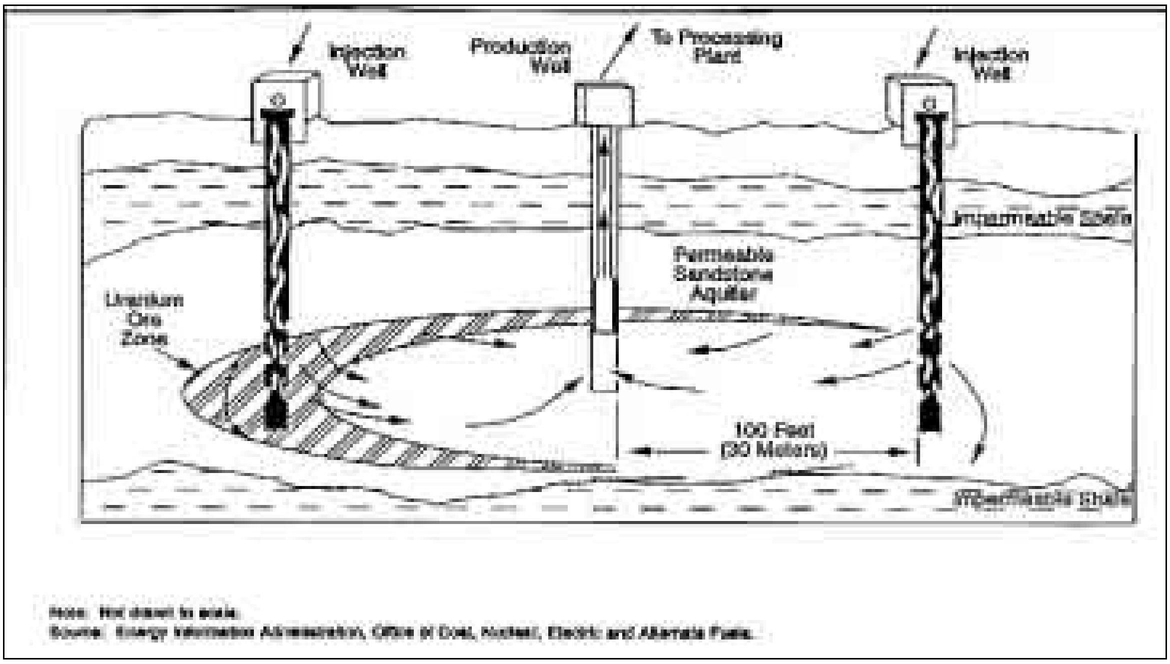


FIG. 8. Cross section of an ISL wellfield.

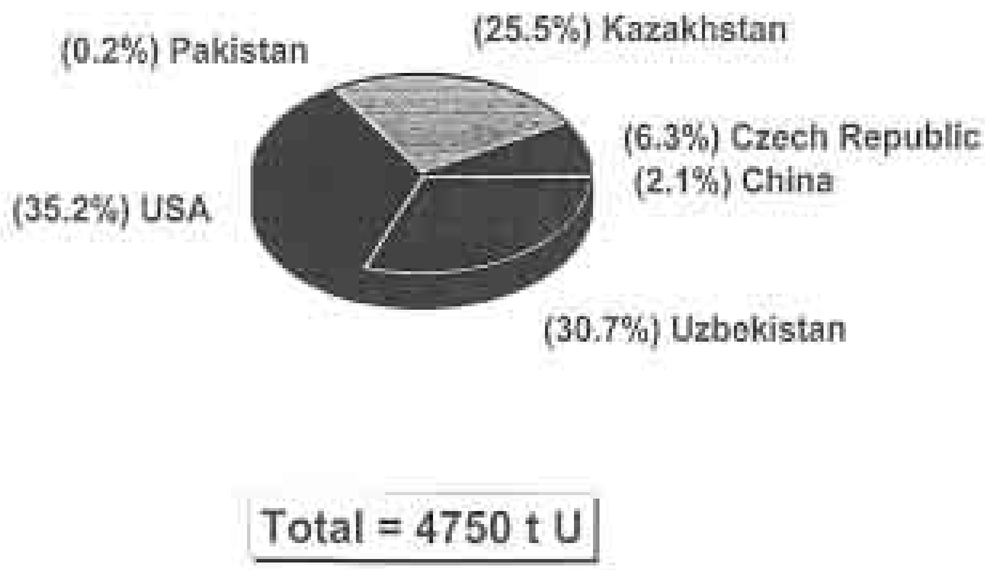


FIG. 9. ISL Uranium production – 1996 (percentage by country).

5.2. *Leaching systems*

Two alternative leaching systems are used in ISL mining. Alkaline systems, using oxygen and carbon dioxide dissolved in ground water have a near neutral pH of about 6.8 to 7.5. The acid system, developed in the former Soviet Union, uses sulfuric acid (containing from 0.3 to 50 milligrams/litre) dissolved in ground water to form a dilute solution with a low pH.

The use of acid leaching in poorly planned uranium projects in eastern Germany and the Czech Republic has resulted in very costly projects to cleanup contaminated groundwater.

While US producers use only alkaline systems for recovering uranium, there are clear indications the use of acid leaching is increasing in several areas of the world. New information is becoming available from central Asia regarding restoration experience involving natural attenuation following leaching. Improvements in the technology used in Uzbekistan are reported to reduce environmental impacts [20]. Acid ISL mining to recover copper has already been approved for use in Arizona, USA, by both the U.S. Environmental Protection Agency and Arizona state regulators. The decisions regarding using acid leaching is expected to be based on the results of environmental impact assessments which take into consideration such factors as project location with respect to population, water use and baseline water quality.

Advantages or disadvantages of each system depend on site specific conditions. Where the carbonate content of the ore is less than about 2%, acid leaching is more effective. At higher levels operating costs increase as excessive amounts of acid are required. The kinetics of acid leaching are favorable with shorter leaching times, higher concentrations of uranium in the leaching stream and a higher proportion of uranium recovered from the ore. These factors all contribute to reducing production costs. However, use of dilute acids requires acid resistant pipes, pumps and materials. Some advantages of alkaline leaching are its selective recovery of uranium with less impact on the host rock and aquifer, and the use of less costly piping, pumps and materials.

6. National reports*

6.1. Commonwealth of Independent States

6.1.1. Republic of Kazakhstan

Kazakhstan should be well positioned to increase uranium production with an established industry and very large resources, most of which are amenable to low cost ISL recovery. Uranium production in Kazakhstan has been decreasing in recent years, apparently because of the lack of capital for materials, supplies and developing new well fields. The uranium resources occur in the very large Chu-Saryssu and Syr-Darya Basins of southern Kazakhstan, as well as in vein-stockwork deposits in the Kokchetau District, northern Kazakhstan.

Uranium production in Kazakhstan is the responsibility of KATEP a subsidiary of KAZATOMPROM. Kazakhstan currently has three active ISL production centres in the southern part of the country: the Stepnoye and Central facilities in the Chu-Saryssu Basin; and the Number 6 Facility in the Syr Darya Basin. About 950 t U of Kazakhstan's 1997 production came from ISL production, with the remaining 140 t from milling stockpiled ore at Stepnogorsk.

Three ventures with foreign mining companies will be capable of supplying development capital, provided acceptable agreement is reached to authorize operation of the respective projects. Joint ventures exist between KAZATOMPROM and both Cameco Corporation and COGEMA. In addition, World Wide Minerals Limited (WWM) entered into an agreement with the Republic of Kazakhstan to acquire a 90% equity interest in the Tselinny Gorno-Khimicheskii Kombinat (TGK) uranium mine-mill complex of northern Kazakhstan [21].

Foreign company ventures in Kazakhstan include the: Inkai ISL Uranium Project (Cameco) KATCO Joint Company, and the TGK venture. The Inkai and KATCO ventures involve ISL production from sandstone hosted deposits in the Chu Saryssu Basin. Before suspension of all activities in August 1997, the TGK Project was focusing its efforts on restarting production at the Stepnogorsk mine-mill complex of northern Kazakhstan.

Production from two Western ISL joint ventures could begin in 1999 to 2000. The Inkai joint venture is scheduled to begin production in 1999 at an initial annual rate of about 390 t U. Production capacity at Inkai may be increased to 1000 t U about 3 year later. The project will have additional expansion potential if market conditions warrant.

Inkai ISL Uranium Project [22]

The Inkai ISL Uranium Project is a joint venture with ownership of 2/3rds Cameco and 1/3rd KAZATOMPROM. The venture was formed to explore for and mine uranium in Kazakhstan, and to export it. Project financing will be in the form of a loan to the joint venture from the Western participant which will be repaid from the profits of the operation.

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* In addition to the references cited, this section of the report includes production information from the 1997 Red Book "Uranium 1997: Resources, Production and Demand", as well as information from the "Critical review of uranium resources and production capability to 2020", IAEA-TECDOC-1033, Vienna, 1998.

The sandstone ore bodies to be developed are named the Inkai and Mynkuduk ore fields. The various ore host sands have favorable high horizontal permeabilities, with the coarse sands having filtration coefficients up to 20 to 30 m/day (23 to 35 Darcies) at Inkai, and of the order of 10 m/day (12 Darcies) at Mynkuduk. The confined Upper Cretaceous aquifers produce artesian conditions. Results of a preliminary feasibility study by the joint venture gave favourable economics for the project.

Substantial exploration was completed in the project area while it was part of the Soviet Union. Proven and probable reserves (category C1 and better) at Inkai total 55 016 t U (143 million lbs U_3O_8) at an average grade of 0.06% U. Proven and probable reserves (category C1 and better) at Mynkuduk total 49 000 t U (127 million lbs U_3O_8) at an average grade of 0.035% U.

KATCO Joint Company [23]

The KATCO Joint Company (COGEMA 45%, KAZATOMPROM 45%, ZAMBEZI Holdings 10%) was registered in May 1996. KATCO is targeting the ISL uranium potential of Muyunkum deposit located in the Chu Saryssu sedimentary basin, south Kazakhstan. The deposits in this area are potentially amenable to ISL production techniques. Confirmation is expected from pilot testing which will lead to completion of a feasibility study. The Turkuduk deposits are of the roll-front type occurring in Eocene age rocks. The value of the filtration capacity (i.e. permeability) is 5 to 10 m/day (6 to 12 Darcies). Yazikov [24] reports the deposits at Mynkuduk occur in sandstones with low carbonate cement content of a few tenths of a percent.

TGK Project [25]

Through the TGK Project, World Wide Minerals Limited assumed responsibility for restructuring and redeveloping the conventional mine-mill complex based on the Stepnogorsk mill in northern Kazakhstan [26]. The TGK Project was developed under a management agreement with the Republic of Kazakhstan. The project involved revising mine plans and reopening the Vostok and Zvezdnoye underground mines at the Mine Management Unit No. 1 (MMU#1) and the Grachevskoye underground mine at MMU#5, and to process the stockpile of previously mined ore. The TGK Project also includes other deposits, such as the Semisby deposit reported to be amenable to ISL mining. Under the agreement the Stepnogorsk Mill was restarted in March 1997 to process stockpiled ore. All activities were terminated in August 1997 when disagreement arose between the Republic of Kazakhstan and the venture partner. Estimated geological resources controlled by TGK are 29 600 t U. At present the project is under litigation.

6.1.2. Russian Federation

For several years Russia's only production has come from the Priargunsky mines in the volcanic hosted Streltsovsk deposit located east of Lake Baikal, Siberia. While this important district will likely continue as a source of uranium, Russia is also planning to develop ISL mines in 3 new districts to increase production (Fig. 10). To continue to be able to meet its substantial commitments Russia has announced plans to increase uranium production to 10 000 t U/annum by 2010 [27].

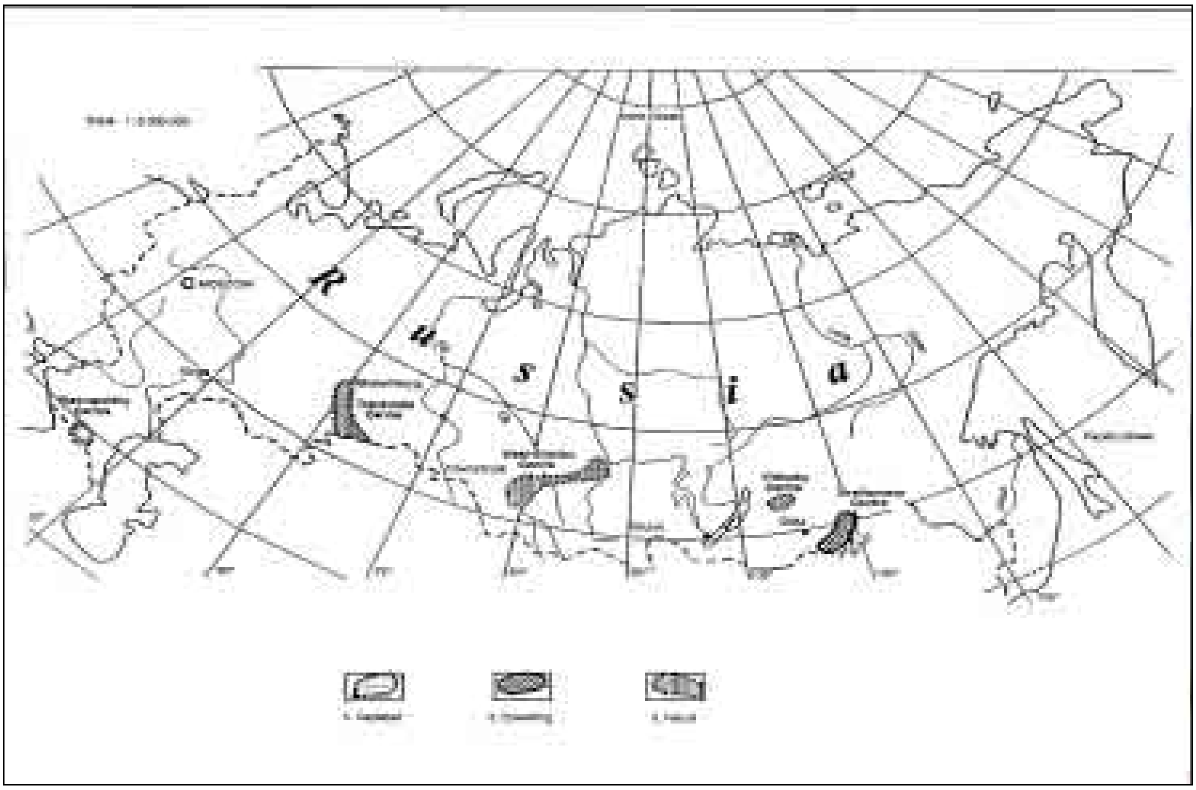

FIG. 10. Uranium production centres of Russia.

For the first time Russia provided an official report of production activities to the 1997 Red Book. Following several years of declining production, the 1996 output of 2605 t U marked a 20% increase over 1995.

Priargunsky Mining and Chemical Enterprise, with 13 000 employees in 1996, operates the only uranium mine and mill complex in Russia. The enterprise is owned 51.4% by MINATOM, the Russian Ministry of Atomic Power, 15% by foreign investors, with the remaining interest held by current and past employees [28]. All other uranium related activities within the country are conducted by the government.

Priargunsky operations include three underground mines and a conventional mill, with an annual production capacity of 3500 t U. Surface heap leaching and underground block or stope leaching are being implemented to lower production costs. Priargunsky is expected to continue as the cornerstone of Russia's production industry for the foreseeable future.

Ore grades are declining, however, and costs are increasing, making the future uncertain. Much of the recent production came from ore with a production cost of $40/kgU or less, while most of the remaining ore has a production cost between $80 and $130/kgU [29]. By the year-2000, annual production is projected to total 3500 t U and to be about equally divided between conventional milling and surface and underground heap leaching.

Russia has been evaluating the potential for ISL extraction of basal channel (valley-type) sandstone deposits in three areas outside the Priargunsky-Streltsovsk Region: Zauralsky; Western Siberia; and Hiagda-Vitimsk. An ISL pilot test has been completed at the Dalmatovsk deposit in the Zauralsky province, with ore depths ranging between 420 and

560 meters and an average grade of approximately 0.043% U. In late 1997 it was announced that MINATOM was providing $30 million to the Malyshev Ore Company to develop the Dalmatovk project using ISL technology. At the time the first stage development was underway. The project was expected to produce about 10% of Russian needs in 1998.

Russia expects to gradually build its ISL production capacity to between 4500 and 5000 t U by the year-2005. It also has announced plans to reach 10 000 t U/year by 2010 with up to 6000 t coming from its ISL operations.

6.1.3. Ukraine

Ukraine's uranium production is derived from 2 underground mines in the Kirovograd Province of central Ukraine. Ninty percent of the ore is produced from the Ingul'skii Mine and 10% from the Vatutinskii Mine. The ore is hauled by rail to the conventional mill in Zheltiye Vody for processing. The mill has an annual capacity of 1000 t U. Ukraine reports that for several years uranium production has been 1000 t U/year.

The uranium production cost for Ukraine is not known. However, Ukraine is the only CIS country that reports no resources in the $40/kgU ($15/lb U_3O_8) or less, category. The production comes from relatively deep deposits extracted using conventional underground mining technology. They have a low average grade (about 0.1% U) and have characteristics indicating they are relatively high cost to mine and mill.

Ukraine's resources (RAR+EAR I) total 131 000 t U, of which 62 600 t are projected to be recoverable at costs of <$80/kgU or less. Ukraine also has minor basal channel sandstone hosted resources that may be amenable to ISL extraction.

Ukraine plans to expand production to meet all of its nuclear fuel requirements with domestic uranium. The annual requirement are projected to be about 2500 t U through 2010. The timing to reach its goal of self sufficiency is uncertain. Becoming self sufficient will require a 2.5 times increase over the current production levels. This presents a formidable challenge as most of Ukraine's resources are associated with deep, low grade deposits, with relatively high production costs.

6.1.4. Uzbekistan

Uzbekistan has an established ISL industry currently producing from sandstone hosted deposits in 3 districts (i.e. Northern, Southern and Number 5) in central Uzbekistan. It has recently entered into a joint venture with COGEMA. Uzbekistan's known resources, producable at $40/kgU or less, of nearly 100 000 t U could supply 30 years of operations at Uzbekistan's target production level of 3000 t U/annum. The uranium production increase of nearly 20% to 1733 t U in 1997 is a reversal of the declining trend of recent years.

Navoi Metallurgical and Chemical Complex (NAVOI) is Uzbekistan's gold and uranium production company responsible for all uranium mining. The company has a substantial cash flow from its operations, including the large Muruntau gold mine, which has recently been producing more than 55 t gold/annum. In recent years NAVOI has acquired new drilling equipment and a factory for manufacturing the PVC casing used for ISL well construction.

While NAVOI's ISL production capacity has been constrained by lack of capital and materials for wellfield development, it has established a annual production goal of 3000 t U by the year–2000. Uzbekistan has the uranium resources and mill capacity to meet this objective. It may also be able to rely on capital from NAVOI's cash flow to maintain and expand its production. However, if this does not occur, the country may have to attract Western capital to expand existing wellfields and to develop new deposits needed for the goal to become a reality. The recently signed joint venture with COGEMA may provide this type of opportunity.

In early 1997 COGEMA and NAVOI formed a joint venture to determine the feasibility of mining the Sugraly Deposit. NAVOI's Chief Engineer indicated the proven resources of Sugraly are 38 000 t U. He further indicated that the company had previously operated the project, but had closed it in 1994 when it was found to be unprofitable.

In contrast to most other sandstone hosted rollfront-type orebodies of Uzbekistan, the Sugraly Deposit is unusual because of the abundance of high-grade uranium (with Mo, Se and Re) ores [30]. These pitchblende-hematite-sulfide and pitchblende-sulfide ores occur at sites along faults which cut the orebody. These zones are complex because of remobilization of the ores by heated fluids from the fault zones. The depth of mineralization is between 260 and 580 m (850 and 1902 feet). The host rocks are fine grained sandstones and have a permeability of about 1 m/day (i.e. 1.2 darcies) and higher.

6.2. The People's Republic of China

The principal objective of China's uranium industry is to meet domestic reactor needs. Current requirements are 300 t U/annum. China has also been exporting up to 1000 t U/year for sales. China's has the fastest growing nuclear programme in the world. Reactor requirements are projected to be 600 t U in 2000, increasing to between 3200 and 4000 t U in 2015. To supply these levels, production must expand by up to 8 times over current estimated levels. Details of both uranium resources and production are a state secret [31]. China's annual uranium production is estimated to have averaged about 500 t U in the last few years [32].

In recent years China has made major efforts to lower the cost of its uranium production by closing high cost production facilities, reducing manpower and adopting more effective technology at existing mines. New mines have been brought into production based on improved technology. The uranium production cost at new facilities is 30 to 50% below that of the recently closed sites [33].

During the last decade China shifted its main exploration efforts from small, low-grade granite, volcanic and black schist hosted uranium deposits in southeastern China, to the large Mesozoic-Cenozoic continental basins in northwestern and northern China. These basins host rollfront and stratiform type uranium deposits (Fig. 11). The sandstone deposits are of large scale and may be mined using ISL technology. The most important deposits have been delineated in the Yili Basin of Xinjiang Autonomous Region.

In 1996 about 260 t U reportedly came from 3 new mines: Yining ISL facilities in the Yili Basin, Xinjiang Autonomous Region, northwest China; the conventional Benxi mine/heap leach operation in northeast China; and the conventional Lantian mine/heap leach operation near Xian, central China. Conventional mines continue to operate in south China. In 1996 heap and stope leaching, together with ISL mining, provided two-thirds of China's output.

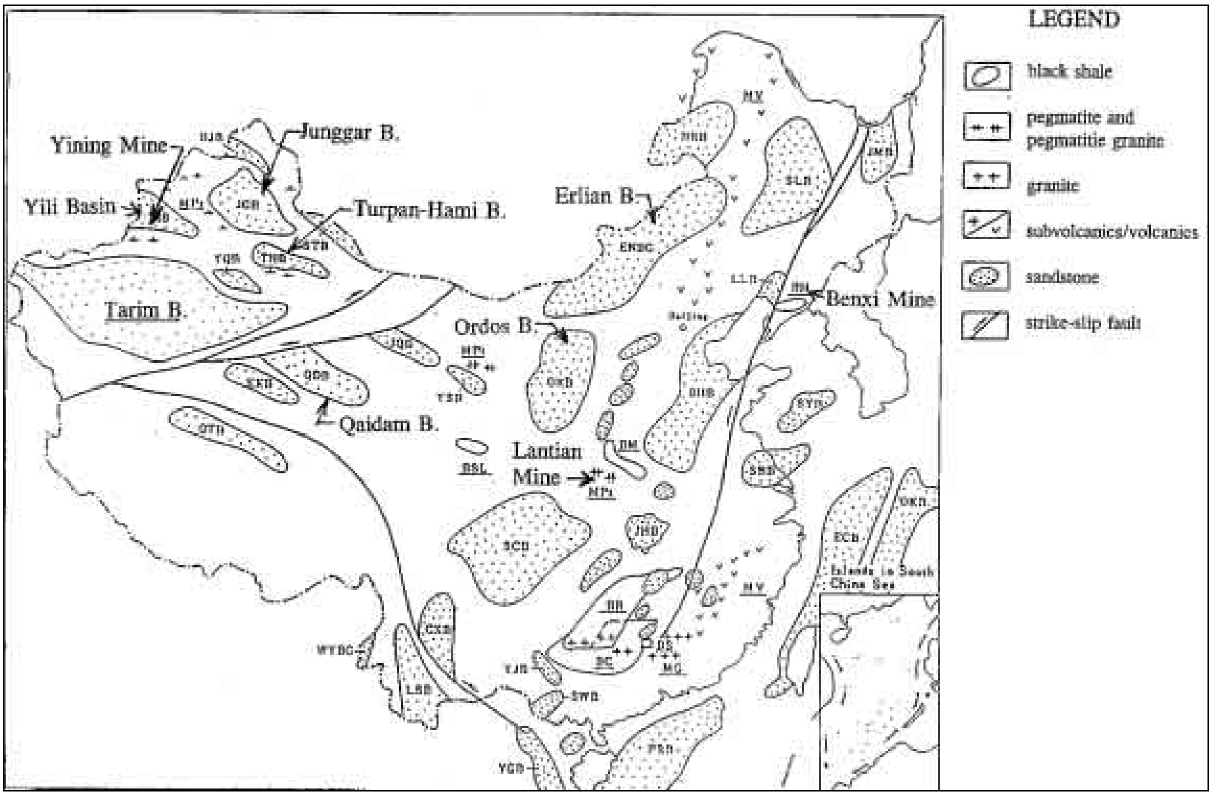

FIG. 11. Distribution of uranium host rock formations, major sandstone basin and new mines in China.

The Yining ISL facility produced 100 t U in 1996. Expansion is planned to 400 t U by 2000 and 600 to 1000 t U/annum in later years. China has been evaluating other basins for ISL amenable sandstone deposits and is expected to increase capacity using this technology.

While resources of only 64 000 t U are reported in the Red Book, China reports that requirements beyond the short term will have to be met by uranium resources that have not yet been discovered. China's large exploration programme is conducted by the Bureau of Geology (BOG) of the China National Nuclear Corporation. The BOG, with 5 district offices, has a total staff of 45 000, including 14 000 technical personnel. China's only uranium related joint venture activities with PNC of Japan are scheduled to end in 1998.

6.3. Mongolia

Mining is important to Mongolia's economy, which contributed 56% of foreign earnings in 1997 and 58% of the country's industrial output [34]. In contrast, uranium mining has played only a minor role with total production of 533 t U from 1988 to 1994. The uranium geology of Mongolia is however, relatively well known through the results of an extensive uranium exploration programme carried out under bilateral agreement with the former Soviet Union from 1970 until 1990.

Extensive mine development was previously completed at 2 deposits in the Dornod district of northern Mongolia. The mining was conducted at the Mardai open pit by ERDES Mining Enterprise, a joint venture of Mongolia and Russian Federation (Fig. 12). Ore from the Mardai operation was hauled 485 km by rail to the Priargunsky mill in Russia for processing.

Extensive mine development has been completed in Ore Body No. 7 of the Gurvangulag deposit complex, but the mine was never put into production because of lack of capital.

The country's potential has attracted interest from western companies which resulted in 3 uranium joint ventures being formed. The joint ventures with the Mongolian Government are: Central Asia Uranium Company (with World Wide Minerals Limited and a Russian Government organization), COGEGOBI Joint Company (with COGEMA), and Gurvan Saihan Joint Venture (GSJV) (with International Uranium Corporation and a Russian Government organization).

The Central Asia Uranium Company (CAUC) is focusing its efforts on restarting production in the Dornod district in 1998, while the other programmes are involved in exploration and evaluation of sandstone-type deposits in southern Mongolia. CAUC is planning to mine 3000 \ t U over 6 years, with plans for expansion if market conditions warrant.

Since its inception in 1994, the GSJV programme has involved exploration drilling and conducting pilot ISL tests. Drilling to date comprises about 94 000 metres with an additional 50 000 metres planned for 1998. In 1994 a small acid ISL test was performed at the Haraat Deposit, followed by an acid ISL pilot test in 1996. The results confirmed favourability for acid leaching. Drilling through 1997 identified about 4200 t U (10.8 million lbs U_3O_8) of measured and indicated resources [35].

The COGEGOBI JV, formed in early 1997, is evaluating its targets by drilling, geologic and geophysical surveys.

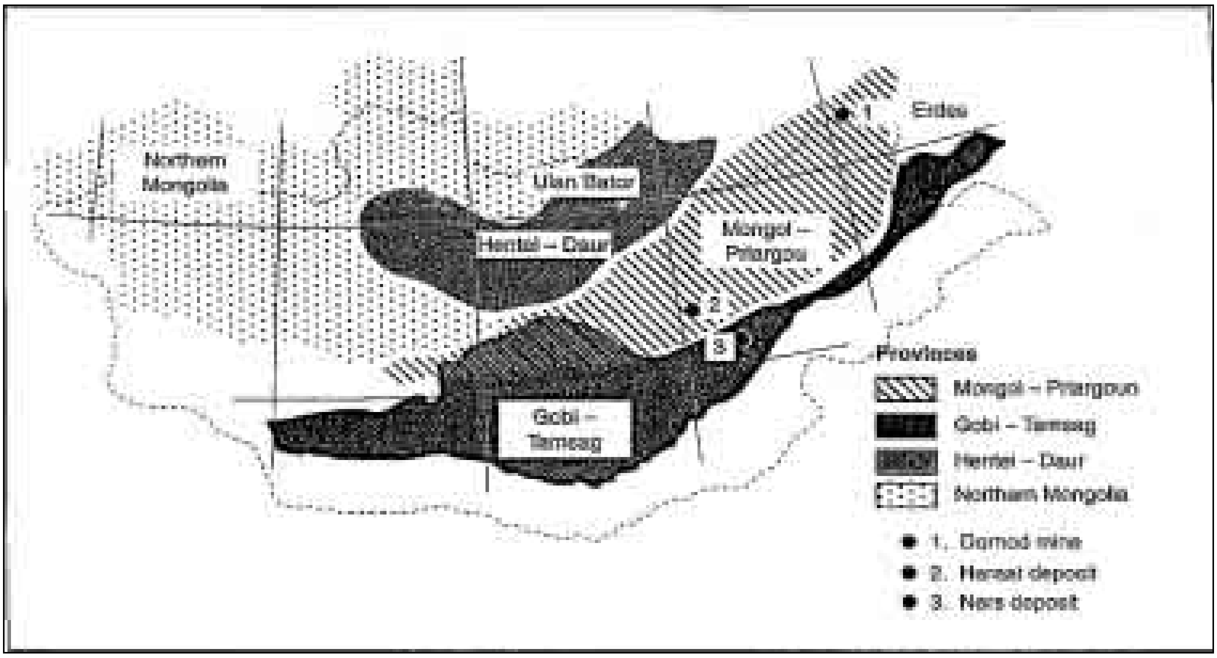

FIG. 12. Uranium metallogenic provinces and deposits of Mongolia.

7. Conclusions

Over the next 10 to 15 years total annual uranium output is expected to increase over recent levels for the CIS, China and Mongolia. The 1996 production for the group was about

6 835 t U. It is unlikely, however, that all of the expansion objectives announced for each country will be achieved. Countries lacking low cost uranium resources and investment capital for new facilities are not likely to meet their production objectives.

The main increase is expected in those countries with large uranium resources producible using low cost ISL technology. The greatest potential for low cost uranium production is in Kazakhstan and Uzbekistan. Mongolia also appears to have significant potential for low cost ISL production.

China is expected to increase production using ISL amenable resources. At present, however, there are insufficient known resources to meet production objectives through 2015. Russia and Ukraine have set expansion goals involving large production increases that may be difficult to achieve with presently known uranium resources and available investment capital.

Taking all of these factors into consideration, and given favorable market conditions, the combined annual uranium production in the CIS, China and Mongolia could increase by 100% or more over the next 15 years.

Business ventures with foreign mining companies are expected to make a significant contribution to the development of the new production facilities. The ventures bring together the necessary capital, improved management and western technology, with low cost uranium resources, proven acid ISL technology and the experienced staff and manpower to operate the facilities. These ventures will, however, only be successful in those countries with a stable legal and administrative business environment. They will also require uranium market prices that will provide an acceptable return on investment.

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Future development of Russian uranium industry

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Abstract. Priargunsk Mining-Chemical Production Enterprise (PPGHO) is the only active uranium producing centre in Russia. Its nominal annual capacity is 3500 t U. To increase annual uranium production in Russia, three new ISL production centres are planned to come into operation: Transural (Kurgan region), West Siberian (Kemerovo and Novosibirsk regions), Vitim (Republic Buryatiya). New exploration activities are focused on deposits of sandstone and unconformity type discovery.

The policy of Russia in uranium production is reviewed in the "Red Book 1997" and did not changed significantly since that time.

For the present moment there is only one enterprise in Russia that is engaged in uranium ores mining and processing - "Priargun mining - chemical manufacturing association", that is located in Krasnokamensk, Chita region. The most part of ores is processed at hydrometallurgical plant, with the nominal capacity of about 3500 t/y. About 90 tonnes of uranium is mined by In Situ Leaching (ISL) method and about 500 tonnes - by heap leaching method. It is planning that the role of heap leaching method will be steadily growing.

In order to increase uranium production in Russia there have been planning to start 3 additional uranium production centres: Transurals (Kurgan region), West-Siberian (Kemerovo and Novosibirsk regions) and Vitimsky (Buryatiya). At these deposits uranium will be mined by in-situ leaching method through wells (Fig. 1).

One of the deposits (Dolmatovskoye) in ***Transurals region*** (Fig. 2) has been fully explored. Preliminary prospecting jobs are carrying out at the second deposit - Dobrovolskoye. The third deposit - Khohlovskoye -is at the stage of estimation. The speculative resources of these three deposits is about 40 000 tonnes of uranium. There are quite positive capabilities for increasing the mineral potential of the region up to 80 000-100 000 tonnes.

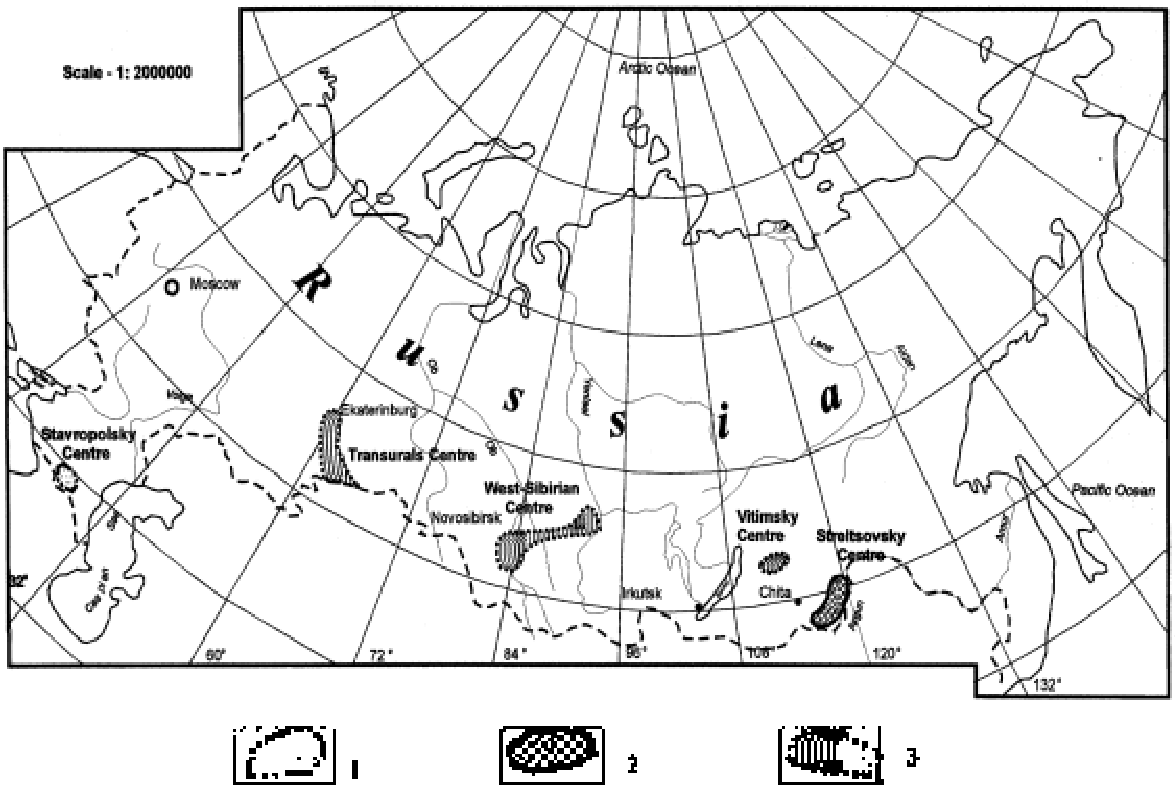
The installation for ISL production has been completed. The starting annual production will be 100 m tU. The stand by processing plant has been restored and wellfield unit is prepared for leaching.

The production volume of Transurals region could be increased within the period of 5-7 years up to 700 tonnes of uranium. In Transurals region Dolmatovskoye deposit could be considered as the most prospected one.

The deposit is bedded mainly in the cut of West-Siberian platform in sedimentary cover paleovalley formed by Middle-Upper-Jurassic alluvial sediments. The uranium injection is controlled by the border of bed oxidizing zone in water-bearing sand-gravely sediments (Fig. 3).

Orebodies are located in paleovalley and its tributary. The total length of uranium injection is about 25 km at a width of 1.5 km. The ore deposit depth is 360-500 m (Fig. 4). In drawing the orebodies has stripe shapes, often telescoped vertically and divided by water packer. In the cross-section it is the set of ore lenses, sometimes multilevel, rarely it is common rolls with clearly distinguished sack part.

The ore mineralization is introduced by coffinite and pitchblende. Uranium average content is 0.039%. At high concentrations in ores there could be scandium, molybdenum, rhenium and REE.



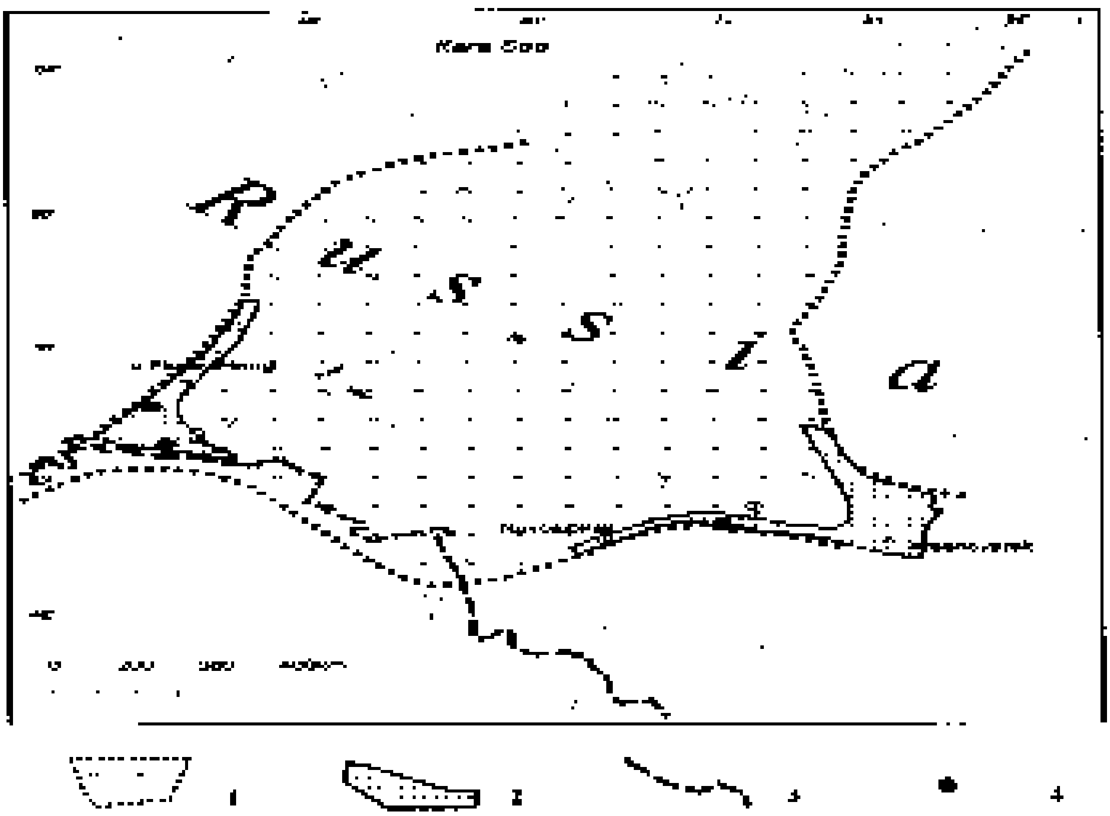
1) Depleted centre; 2) Modern centre; 3) Future centres.

FIG. 1. Uranium production centres of Russia.

West Siberia ore region is introduced by uranium deposits of infiltration genesis type, located in platform deposition of Late Jurassic-Early Cretaceous age (Fig. 2). Only at one of these deposits - Malinovskoye - there were carried out the prospecting and evaluation jobs. It is located in paleovalley (Fig. 5) cut into Paleozoic foundation rocks. The thickness of Mesozoic-Cenozoic depositions in paleovalley is about 300 in average. Bed type uranium orebodies are located in Bazhenovsky horizon (J_3 - K_1) with the thickness of about 70-120 in (Fig. 6). It is composed of sands with different grains size, gravel and boulder-pebble depositions of bed fractions that contain carbonoficated vegetable residuals even in the form of brown coal thin layers (0.1-0.5 m).

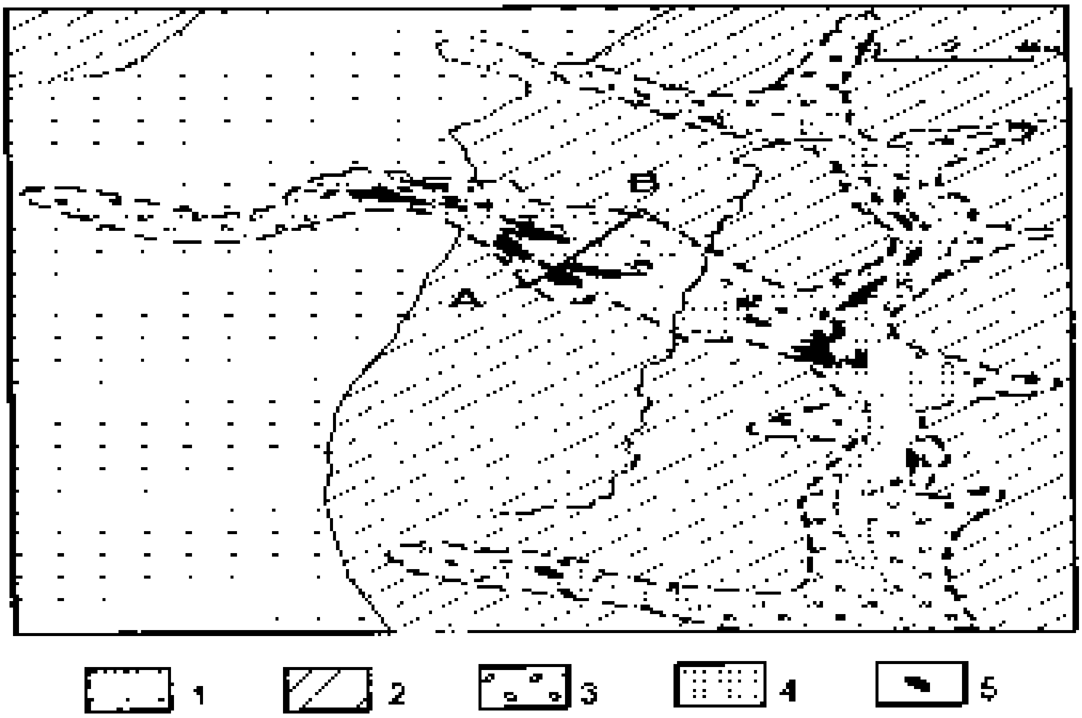
The bed type deposition is about of 50 m of thickness, its length is 2.5 km., width is 100 – 300 m, uranium content is about 0.013 – 0.139%. The basic uranium minerals are coffinite and pitchblende.

The experimental tests for ISL are carried out at the present time. The results will be the base for evaluation of the future production center capacity. The resources of Malinovskoye deposit are estimated as 20 000 tonnes of uranium while the total West Siberia resources make about 180 000 tonnes of uranium.



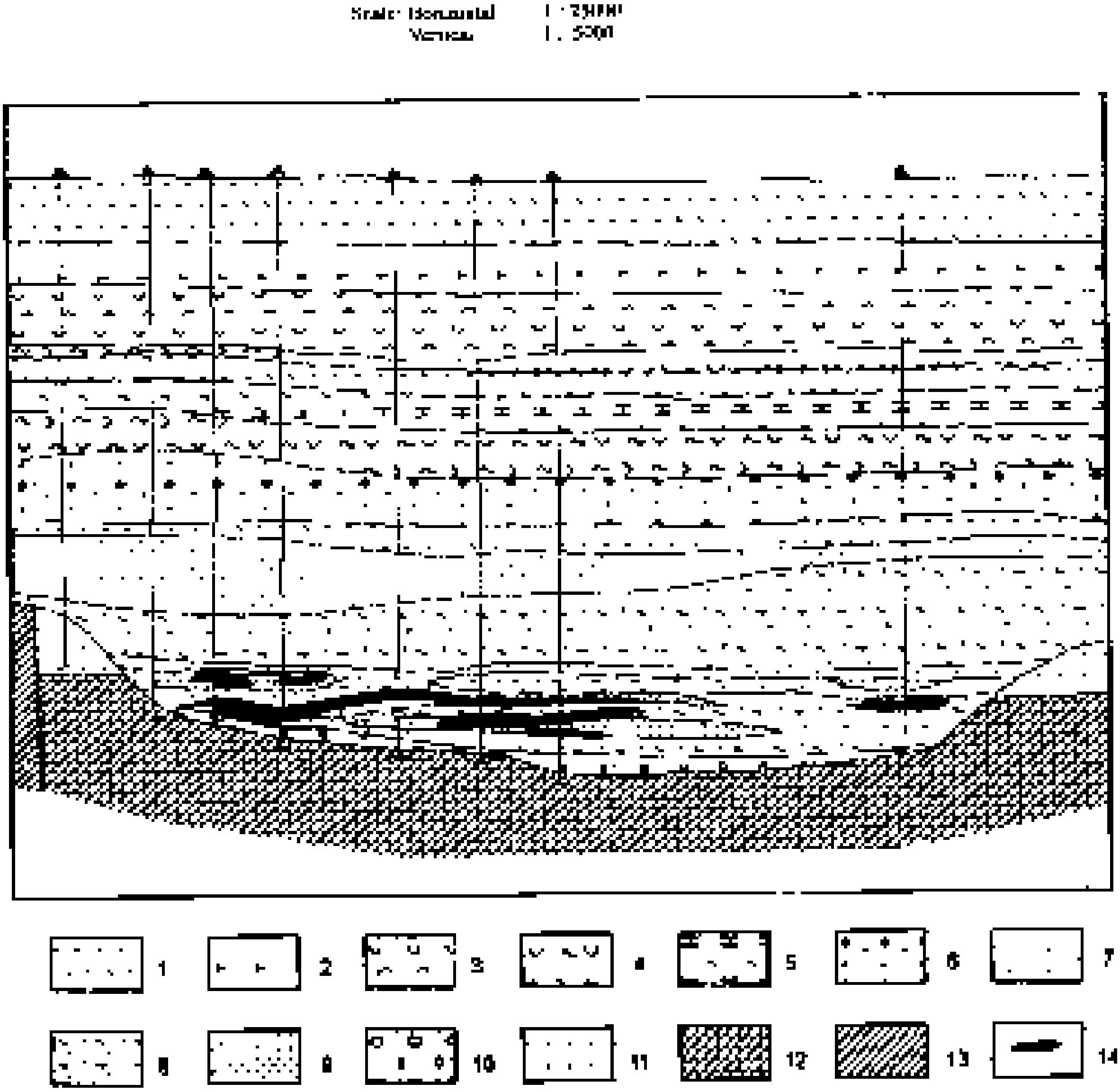
1) West Siberian platform; 2) Uranium-bearing regions; 3) Boundary of Russia; 4) Uranium deposits: 1) Dolmatovskoye, 2) Dobrovolnoye, 3) Malinovskoye.

FIG. 2. Position of valley-type uranium deposits on West Siberian platform.



1-2) Folded complex (Pz) of basement: 1-liparites, tuffs, carbonaceous and siliceous shales; 2) Basalts, tuffs, limestones; 3) Platform complex ($J_{(2-3)}$) filling up paleovalley; 4) Content of uranium >0.01%; 5) Uranium orebodies (>0.08m%); A-B Line of cross-section.

FIG. 3. Dolmatvosky uranium-bearing area.

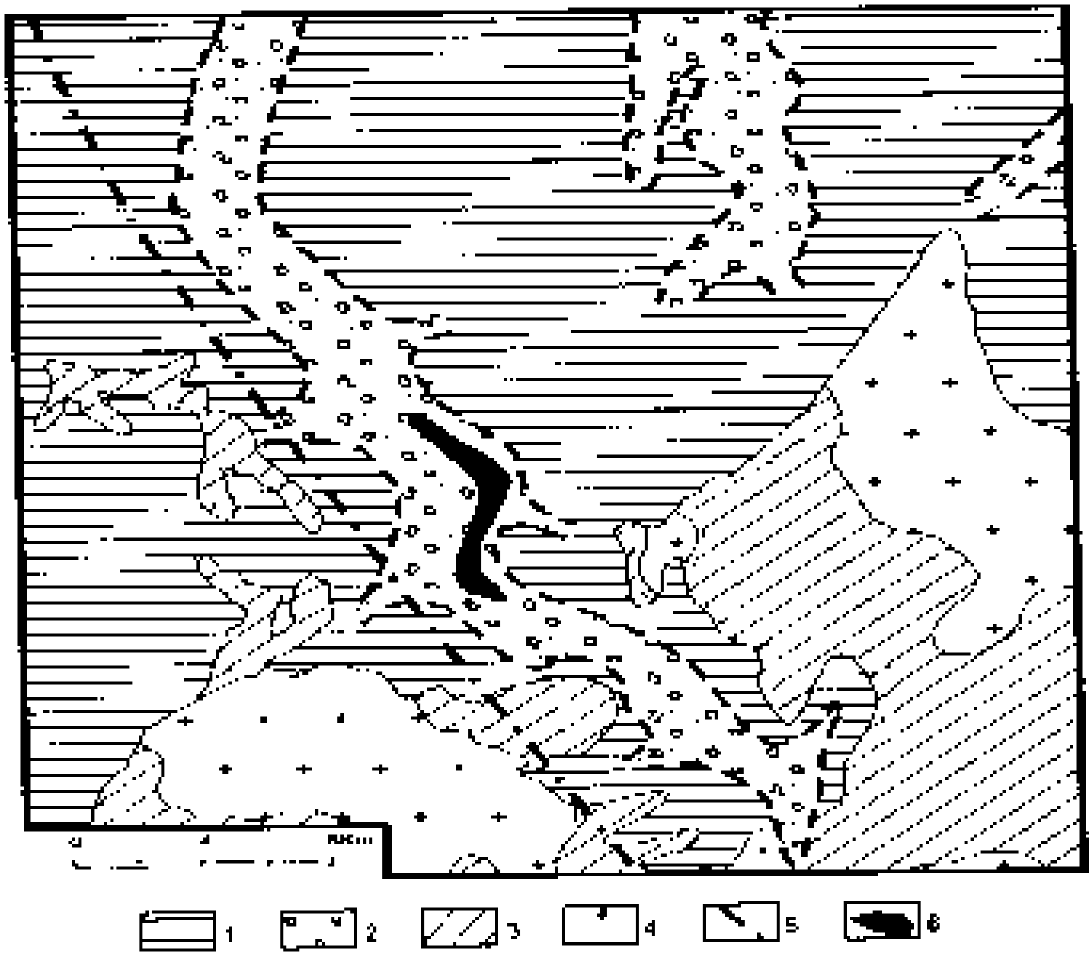


1) Clay; 2) Diatomite; 3) Opoka; 4) Opoka with clay lenses; 5) Chalky clay; 6) Quartz-glauconitic sand; 7) Quartz-feldspathic sand; 8) Drift Clay; 9) Coarse sand; 10) Boulder sand; 11) Basalt; 12) Limestone; 13) Shale; 14) Orebody.

FIG. 4. Geological cross-section of Dolmatvoskoye deposit.

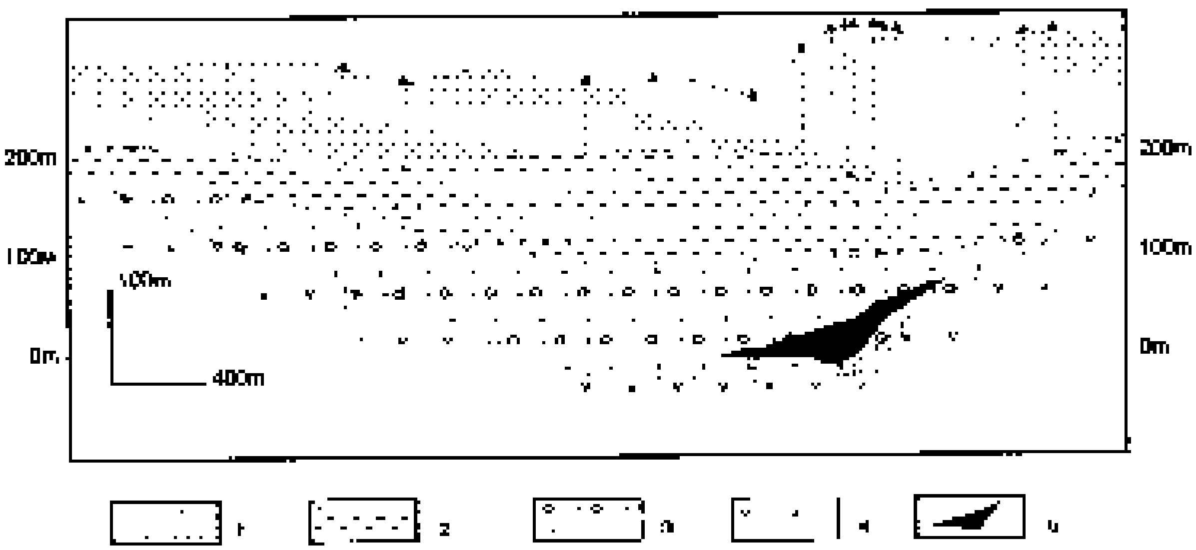
Vitimsky region is located 140 km to the North of Chita in the borders of Amalatsky Plato, between Vitim river and its left tributary - Amalat. The uranium injection is timed to paleovalleys of side tributaries of two large paleorivers (Fig. 7). Paleovalley is made of alluvial-prolluvial depositions of Miocene, introduced by clay-sand rocks, clays, tuff, sands and sandstones. Sediments are enriched by organic substances and includes lignites interlayer. The thickness of these depositions is about several dozens of meters. They are overlapped by Quarterly basalt of 250 m of thickness.

Uranium injections are located in lower layers of sediments at a depth of 150-200 m (Fig. 8). Orebodies are of stripe shape. The length of the deposition is first kilometers, width is hundreds of meters, thickness is first dozens of meters. Uranium content is about 0.05%. All in all there have been found 11 deposits.



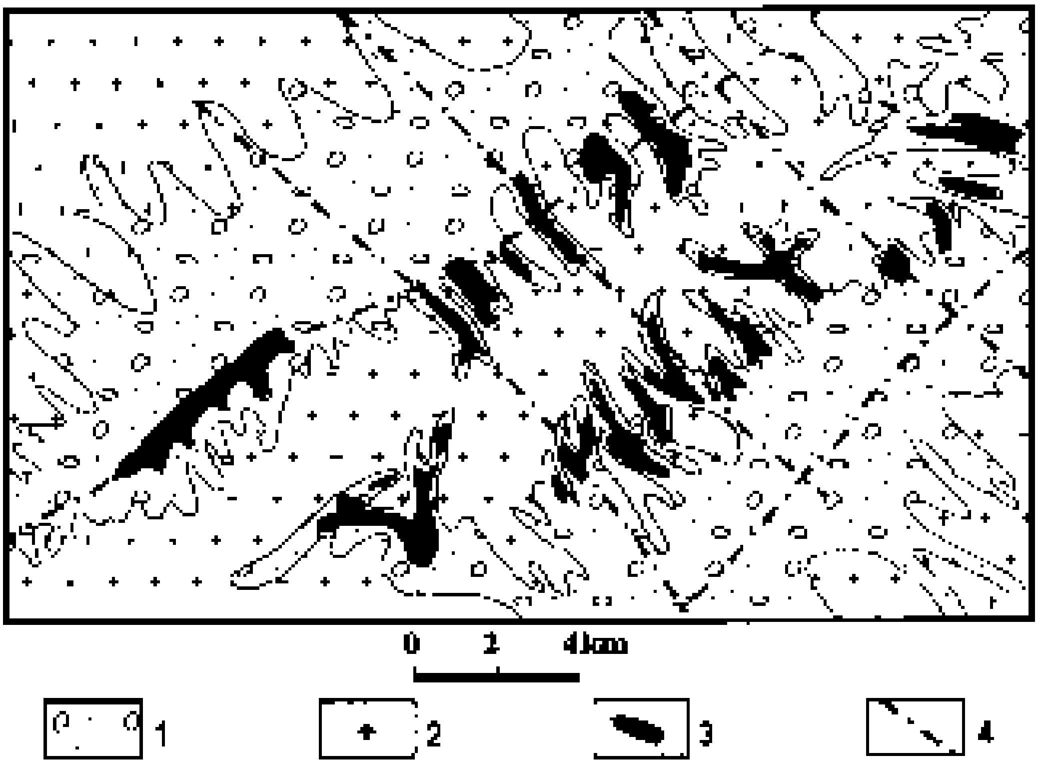
1) Upper level platform complex; 2) Alluvial depositions of paleovalleys (J_3-K_1); 3) Lower level platform complex; 4) Granitoids; 5) Faults; 6) Malinovskoye deposit.

FIG. 5. Malinovsky uranium-bearing region.



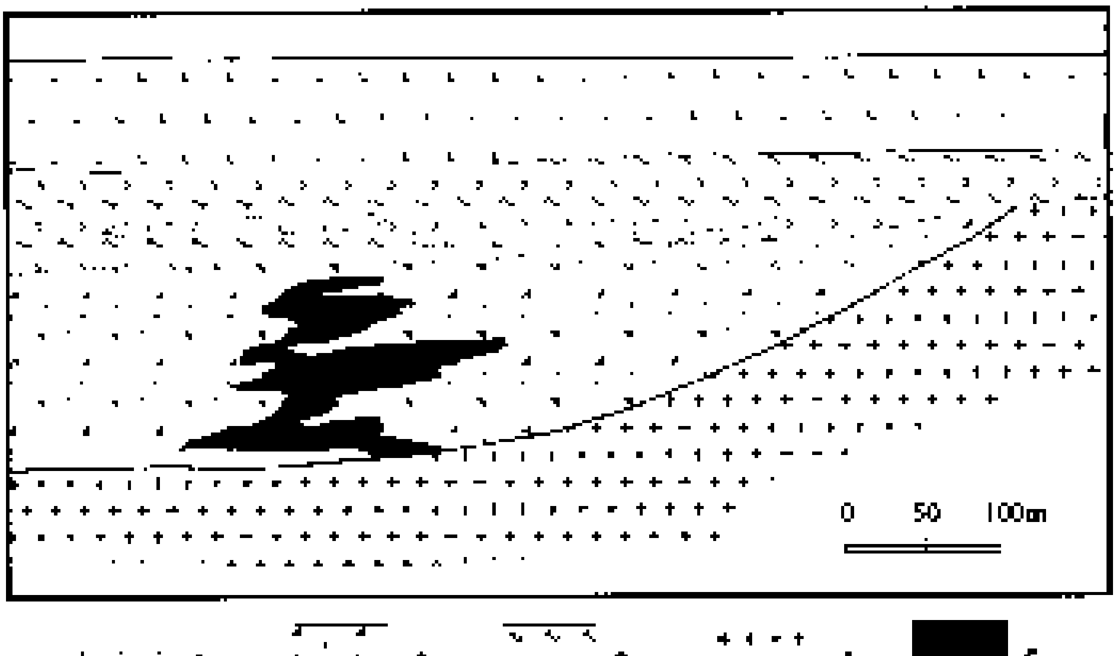
1) Clays, sands (K_2); 2) Clays (K_1); 3) Alluvial depositions (K_1-J_3); 4) Rocks of basement; 5) Orebody.

FIG. 6. Geological cross-section of Malinovskoye deposit.



1) Alluvial depositions of paleovalleys (Miocene); 2) Rocks of basement; 3) Orebodies; 4) Faults.

FIG. 7. Vitimsky uranium-bearing region.



1) Basalts; 2-3) Alluvial depositions; 3) Lower level; 3) Upper level; 4) Rocks of basement; 5) Orebody.

FIG. 8. Geological cross-section of a typical deposit.

The prospected resources of Vitimsky region are estimated as 52 000 tonnes of uranium. The largest deposit, Khiagda, has about 15 500 tonnes of uranium resources at an average uranium content of about 0.05%. The speculative resources of the region make about 100 000 tonnes of uranium. It is possible to construct a new enterprise with the output more 1000 tonnes of uranium on the base of prospected deposits.

The experimental ISL working has been started at Khiagda deposit.

Basel channel (valley-type) sandstone type Sheglovskoye deposit with 8000 mt U EAR2 resources has been discovered in 1998. Its evaluation is in progress.

The Uranium Exploration in Russia is carried out in limited volume. It focused mainly on the discovery of deposits of two types:

- Sandstone-type, which are amenable for ISL,
- Unconformity type with high grade ores.

The geological prerequisites for unconformity type deposit are in the Karelia-Kola region of Baltic shield and in the south-eastern part of Aldan shield. This exploration will be developed further at the all territory of Russia. The most favorable areas are situated in the Voronezh massif, Aldan and Anabar shields and in Altai-Sayan fold belt.

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Status and perspective developments of uranium production in Ukraine

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Abstract. Atomic energy industry is one of the most important branches of Ukrainian economy. Due to the specific economic situation of Ukraine at present, its dependence on foreign energy-carriers, the role played by nuclear energy in future will be increased according to the Ukrainian National Energy Programme. This report has been prepared based on materials from archives of State Committee on Atomic Energy, Ministry of Energy of Ukraine, State Enterprise “Kirovgeology”. The source of raw uranium materials of Ukraine has formed over a long period of time. Basically it consists of deposits genetically depending on process of alkaline metasomatite types. At present Ukraine decides on the problem to discover more non-deficient uranium deposits with cost ranges < $ 40/kg U. Uranium stocks is practically absent in Ukraine. The uranium concentrate is completely dispatched to Russia in exchange for reactor nuclear fuel heat producing elements. Existing state owned production centers still do not assure requirements in nuclear fuel for atomic electric power stations of Ukraine. Deficit uranium part for production of heat-producing elements is buying in Russia. In such a contingency the Ukrainian geological enterprises have to intensify their exploration works and existing production centers have, in a short brief space of time, to enlarge the production capacity of existing mines and exploitation of new explored uranium deposits in order to provide Ukrainian nuclear power stations with their own uranium.

1. Uranium exploration in Ukraine

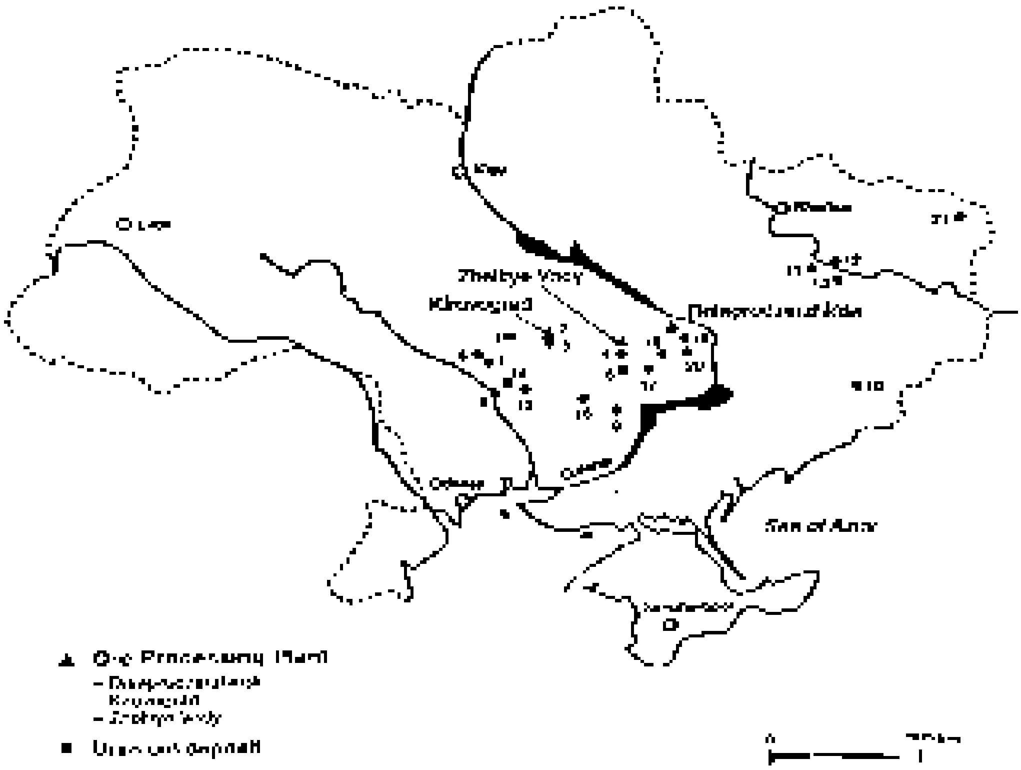
The exploration for the commercial uranium deposits (Fig. 1) was started in Ukraine in 1944. As a result, Pervomayskoye deposit was discovered in 1945 and Zheltorechenskoye deposit was discovered in 1946. They were associated with alkaline metasomatism of the ferruginous rocks of the Krivoi Rog region.

The first commercial uranium deposit (Michurinskoye) was discovered in 1964. It was associated with alkaline metasomatism and crush zones in granite-gneiss complex of the Ukrainian Shield (USh). Further exploration for this new type of deposit led to the discovery of the Kirovograd uranium-ore region. Its deposits are mined by the Eastern Mining and Dressing Combine. Uranium contents in ores of these deposits are not exceeded 0.2% too. Special radiometric, general geophysical, radiohydrogeological methods and drilling were used for uranium exploration.

As it was reported previously, uranium exploration and development for mining in Ukraine are conducted by the State Geological Enterprise “Kirovgeology” submitting to the State Committee of Ukraine for Geology and Utilization of Mineral Resources. Uranium mining and processing are conducted by the State Association “Vostochny Integrated Mining and Concentrating Plant” (“VostGOK”) submitting to the Ministry of Energy of Ukraine with main office located in Zhovti Vody town.

Providing of uranium mining enterprises with explored uranium reserves is sufficient to plan mining for the nearest future. The base of uranium resources of Ukraine is presented by the Kirovograd ore region deposits associated with uranium-bearing albitite formation in zones of deep faults of the Ukrainian Shield (USh). Their origin is associated with sodium metasomatism superimposed on granite-gneiss basement within an area of tectono-magmatic protoactivization occurred at the end of the Ukrainian Shield orogenesis. The uranium ore formation was 1.8–1.7 billion years ago and followed regional potassium granitization

(2000 ± 100 mln. years). Uranium minerals are presented by oxides (uraninite, nasturan), silicates (uranophane, boltwoodite, betauranotile, coffinite), titanates (brannerite, davidite). Furthermore, albitite always contains hematite, magnetite, apatite, malacone, rutile.



1. Vatutinskoye
2. Severinskoye
3. Michurinskoye
4. Zheltorechenskoye
5. Pervomaysskoye
6. Lozovatskoye
7. Kallnovskoye
8. Yuzhnoye
9. Nikolokozelskoye
10. Nikolayevskoye
11. Berekskoye
12. Krasnooskolskoye
13. Adamovskoye
14. Sadovokonstantinovskoye
15. Bratskoye
16. Safonovskoye
17. Devladovskoye
18. Novoguryevskoye
19. Surskoye
20. Chervonoyarskoye
21. Markovskoye

FIG. 1. Uranium deposits of Ukraine.

Besides uranium deposits in albitites, commercial uranium deposits confined to coaly-sand sediments in sedimentary cover of the Ukrainian Shield are discovered. VostGOK mined out two deposits (Deviadovskoye and Bratskoye) by ISL method. Other similar deposits were not involved into exploitation till present time. Deposits of other types discovered in Ukraine until now can hardly be profitable taking into account market prices.

Total assessment of uranium resources of Ukraine is without changes and makes up 366 000 tU in situ including: 81 000 tU RAR; 50 000 tU EAR-I; 3900 tU EAR-II; 231 100 tU SR. There are no resources with the cost lower than $40/kg U in the total 131 000 tU RAR & EAR-I with the cost cheaper than $130/kg U. 62 600 tU RAR & EAR-I with the cost lower than $80/kg U are concentrated in the albitite-type Vatutinskoye (25 500 tU) and

Michurinskoye (27 000 tU) deposits and in small deposits (10 100 tU) within sedimentary cover of the Ukrainian shield which can be mined by ISL method. Remained 68 400 tU RAR & EAR-I with the cost of $130/kg U or less are concentrated in the albitite-type Severinskoye deposit (50 000 tU), in the pegmatite-type Yuzhnoye, Kalinovskoye and Lozovatskoye deposits (15 000 tU) and in the Adamovskoye, Krasnooskol'skoye and Berekskoye deposits (3400 tU) in bitumens.

The area of alkali metasomatites developed between the Vatutinskoye deposit in the west and the Michurinskoye deposit in the east is the most perspective to explore new commercial albitite-type deposits.

The NW slope of the Ukrainian Shield is very perspective to discover high-grade uranium deposits (unconformity-related deposits) as well as the Zapadno-Inguletskaya tectonic zone located westerly from the Krivoy Rog iron-ore basin is perspective to discover vein and vein-impregnated uranium deposits.

The development of these areas for further exploration is limited by insufficient and unstable funding of exploration activity.

1.1. Uranium deposits in Ukraine

Commercial uranium deposits in Ukraine, situated in two ore-bearing regions, Krivoy Rog and Kirovograd ones, belong to the uraniferous albitite formation. Their origin was related to processes of alkali metasomatism superimposed on a granite-metamorphic substratum in areas of protoactivation that took place at the late orogenic stage of formation of the Ukrainian shield. The deposits are localized in volume cataclasis zones formed at the intersection of differently oriented deep fractures. Structural-morphologic features, are largely defined by premetasomatic folding, heterogeneity of ferruginous-slaty and granite-gneissic beds, protoclastic and directional structures of granite massifs and morphology of small granite bodies. Albitization is developed on ferruginous quartzites, slates, granites, gneisses, migmatites with formation of albitites, egyrinites, riebeckitic meta-somatites. Uranium mineralization is superimposed on cataclased metasomatites, forming a fine impregnation together with late albite, rhodusite, chlorite, phlogopite, carbonate and hematite. Secondary silicates and uranium hydroxides are widespread.

Uranium deposits in Ukraine are situated in two ore-bearing regions, Krivoy Rog and Kirovograd ones. The Krivoy Rog region contains Pervomajskoe and Zheltorechenskoe deposits, mined out by the present time, as well as non-commercial Annovskoe and Kremenchugskoe ones. In addition, the non-commercial Nikolo-Kozel'skoe deposit in sandstones and conglomerates of the lower suite of the Krivorozhian series is known here.

The Kirovograd ore-bearing region contains Severinskoe, Michurinskoe, and Vatutinskoe deposits as well as a number of ore shows. Apart from albitite-type deposits, several small ones associated with processes of potassium metasomatism and close in the age to the regional granitization (Yuzhnoe, Kalinovskoe, Lozovatskoe) are known here.

In both ore-bearing regions there are a number of small uranium deposits of a sedimentary-infiltration type in continental sandy-clay Paleogene deposits, which perform paleodepressions of a crystalline foundation.

The commercial deposits belong to the uraniferous albitite formation. Their origin was related to processes of alkali metasomatism that superimposed on a granite-gneissic substratum in areas of tectono-magmatic pro to activation that took place at the end of the orogenio stage of formation of the Ukrainian Shield (USh). Formation of uranium ores (1.8–1.7 Ga) followed in time the regional granitization stage (2 Ga), but was close to the time of formation of rapakivi-granite massifs.

Uranium-ore regions and deposits

The Krivoy Rog region is one of the largest mining areas. At its center is the town of Zheltye Vody where the Vostochnyj integrated ore concentrating works is situated, which processes uranium ores from the Krivoy Rog and adjacent Kirovograd ore bearing regions.

Uranium deposits are situated within the Krivorozhsko-Kremenchugskaya metallogenic zone, formed by low Proterozoio sedimentary-volcanogenic and ferruginous-siliceous formations of the Krivorozhskaya series, which is traced in the submeridional direction in the form of a narrow strip of intensely folded rocks and separates blocks of the early Proterozoic and the late Archean stabilization.

The Zheltorechenskoe deposit is situated within a syncline of the same name, consisting of two adjacent isoclinal folds with subvertical bends, the Zheltorechenskaya proper and the Danilovskaya one, separated by a compressed anticline. The folds are divided into several wedge-shaped blocks by a system of subconcordant and transverse fractures with vertical displacement amplitudes of first hundreds of meters. The lower (Skelevatian) suite is represented by quartzites. The middle (Saksaganskian) one consists of interlayered horizons of quartz-micaceous and amphibolic slates and three horizons of ferruginous quartzites. The upper (Gleevatian-Gdantsean) suite occurs on, deposits of the middle suite without a visible discordance, forms the core of the Zheltorechenskaya syncline, and is divided into a lower, dolomite-quartzitic, subsuite and an upper, slate, one.

The axial surface of the Zheltorechenskaya syncline is vertical. The bend of the fold subsides at an angle of 62–70° and has a reversed dip at a depth of 1.2–1.5 km.

Formation of uranium and ferruginous ores was closely associated with magnesian-ferruginous, sodium carbonate, late-alkali, and sulfide-nasturan stages of hydrothermal-metasomatic processes.

Most widespread is the magnesian-ferruginous metasomatism, which extends far beyond the boundaries of uranium mineralization. Rich iron ores are formed in schistosity, compression, and crushing zones. The carbonate-sodium metasomatism is more locally in the western wing of the Zheltorechenskaya syncline. Products of the sodium metasomatism are represented by albitites, egyrinites, and riebeckitized magnetite-amphibolic slates. Albitites at upper horizons of the deposit incorporate the aluminosilicate ores with uraninite, brannerite, and nenadkevite-type uranium silicates. Magnetite riebeckitic metasomatisms contain small deposits of uranium ores.

The carbonate metasomatism is most markedly pronounced in middle horizons of the deposit by iron ores, ferruginous quartzites, and magnetite-amphibolic slates. Main large commercial deposits of uranium iron-carbonate ores are associated with the carbonate metasomatism at depths below 600 m, the basic uranium mineral there is uraninite. The sulfide-nasturanian mineralization fills in cracks that dissect sodium-carbonate metasomatites and rocks not affected by metasomatism, formation of vein-type uranium ores is associated with this stage.

Layerwise linear ore zones are developed in rocks of the upper part of the section of the middle suite of the Krivorozhskaya series, within wings of the syncline and its sharp carinate joint. They contain deposits of both uranium and iron ores. Saddle-shaped (annular) ore zones are developed in the topmost horizon of the middle suite arid in rocks of the upper suite; transverse ones, in deposits of both suites. The saddle-shaped and transverse zones carry only the uranium mineralization.

Ore deposits have stratum and lenticular shapes, and in periclinal parts of folds and flexures, the shape of ore pillars. The deposits are large both in the strike and thickness and are traced to depths of 1000–1500 m.

Three main types of uranium ores distinguished are alumino-silicate, iron-carbonate, and carbonate. Aluminosilicate uranium ores consist of 70–90% of albite, amphiboles, egyrine, hydronicas, and chlorite: hematite, magnetite, and accessory minerals account for 10-20%. The uranium mineralization is represented by uraninite, nenadkivite, brannerite, coffinite, nasturan, and hydroxides. Malacone, sphene, and apatite are encountered.

Iron-carbonate uranium ores are formed by magnetite, hematite, martite, carbonate (mainly dolomite), talc, egyrine, actinolite, alkaline amphiboles, garnet, and impregnated uraninite.

Carbonate uranium ores are developed only in rocks of the upper suite and consist of dolomite, calcite, albite, actinolite, alkaline amphiboles, and iron sulfides. Accessory minerals include malacone, anthraxolite-like substance, and graphite. Uranium minerals are represented by nasturan, coffinite, and hydroxides.

A characteristic feature of the Zheltorechenskoe deposit is presence of uranium-vanadium-rare earth-scandium ores, localized in sodium-carbonate metasomatites developed on diopsidic quartzites, actinolitic slates, and dolomites of the upper suite.

Ore deposits with rich scandium ores are situated in areas of conjugation of layered vertically dipping rupture disturbances with a gently sloping dolomite zone. Two natural types are distinguished: malacone-apatite (uranium-rare earth) and vanadium-scandium, ores. The two varieties form both united and independent orebodies. Malacone-apatite ores are 30–40% leaner in scandium and vanadium as compared with vanadium-scandium ores, but are rich in uranium, thorium, phosphorus, rare earths of yttrium and cerium groups. Most of scandium and vanadium is concentrated in vanadium egyrinacmite, and of uranium, yttrium and rare earths of yttrium group in apatite.

The Pervomajskoe deposit lies in the Pervomajskaya syncline, formed by a change in the course of the Krivorozhskaya iron-ore strip from north-eastern to north-western, which has the form of a transverse fold open to the west. The axial surface of the fold has a sublatitudinal strike and a steep dip towards the north or north-west. The bend of the fold steeply inclines towards the south-west in upper parts of the deposit, acquiring at its lower horizons a north-eastern inclination at an angle of 70–80°.

The plicated structure of the deposit is complicated by numerous rupture disturbances mainly of a north-western strike, which break up the ore field into a number of blocks and produce a characteristic mosaic-block structure of the ore field. In the north-western part of the deposit, at the intersection of the submeridional zone of crushing of rocks of the Saksaganskian thrust fault with a system of north-western disturbances of the Pervomajskoe ore field, a zone of breccias is developed in the torn of a cone-shaped body which has been named “breccia pipe”. The “pipe” is formed by two types of breccias, which are tectonic and eruptive.

Superposition of metasomatic processes on volcanogenic-sedimentary metamorphic rocks of the Krivorozhskaya series resulted in formation of extensive zones of metasomatism, iron-ore and uranium bodies, whose composition and shape are determined by features of this process, type of the rocks having been substituted, fold and rupture deformations.

Hydrothermal-metasomatic processes manifested themselves during several successive stages: magnesian-ferruginous (iron-ore), sodium (alkaline), carbonate, and late-alkaline ones. Every next stage developed in an ever more narrow areal with respect to the preceding one.

Ore deposits are situated within the Pervomajskaya tectonic zone, which extends parallel to the northern wing of the fold and is a system of rupture disturbances of various orders. The main iron ore deposit was formed in the process of ferruginous metasomatism developing on cummingtonite-magnetite quartzites of the sixth ferruginous horizon. Together with uranium ores contained in it, it represents a large tectonic block, broken up by numerous disturbances into separate chumps. Main uranium orebodies do not extend under loose rocks and are “blind”. The same structural position is occupied by small iron-ore and uranium bodies of the south-eastern part of the deposit, which are developed near the surface.

The bulk of commercial uranium ores is associated with manifestation of the carbonate stage, superimposed, on riebeckitized and egyrinized rich magnetite iron ores, and is represented by the iron-carbonate type. As a result of this process, iron ores are hematitized, enriched in dolomite, ankerite, siderite, calcite, uraninite, nasturan, chlorite, and hydromica. All uranium and iron-orebodies have mainly tectonic boundaries and are parts of once united deposit.

Uranium ores associated with the late stage of alkali metasomatosism, which manifested itself after postmineral block displacements, are less widespread. These ores are localized in tectonic zones, which confine or intersect bodies of carbonate-uranium ores. The main uranium mineral of ores of this type is coffinite, which associates with albite, alkaline amphibole of the crossite type, and hydromicas. The age of mineralization is of 750 and 920 Ma. A vein sulfide-nasturan mineralization of an age of 220 Ma, having no independent commercial importance, is encountered occasionally.

The Kirovograd uranium ore region is situated in the central part of the USh within the Central axial uplift of the Korsun’-Novoukrainskij anticlinorium. The region is elongated in the latitudinal direction with a general meridional orientation of granite-gneissic plicated structures and uranium ore fields. It is bounded on the north by the Subbotsko-Koshorinskij latitudinal fault and on the east and west by the Kirovogradskaja and Zvenigorodsko-Annovskaja tectono-metasomatic zones; at the south it has no distinct structural boundary. As found by complex seismic studies, this uranium-ore region is disposed in a latitudinal-strike earth crust block with a distinct northern boundary along the Subbotsko-Moshorinskij fault, characterized by a relatively greater thickness of the earth crust (45 km) and the greatest depth (20 km) of occurrence of palingenetic granitoids.

Uranium ore fields are disposed symmetrically with respect to the axis of the central uplift of the Korsun'-Novoukrainskij anti-clinorium and controlled by meridional tectono-metasomatic zones: the Leiekovskoe and Michurinskoe fields, by the Kirovogradskaya eastern boundary zone, the Vatutinskoe field, by the Zvenigorodsko-Annovskaya western boundary zone.

On the whole, the structural position of the ore fields is determined by areas of complications of submeridional tectono-metasomatic zones. Two structural situations controlling the spatial position of deposits in the ore fields are distinguished. The first of them includes areas of complication of submeridional tectono-metasomatic zones by north-western strike faults. Such a structural position is typical for deposits localized in zones that bound the ore region: the Michurinskoe and Vatutinskoe ones. The second structural situation, exemplified by the geologic position of the Northern part of the Michurinskoe deposit is characterized by formation of a complex structural unit where faults of all directions participate. Structural traps of deposits duplicate at a higher level the positions of ore fields; they are particular structural units.

Sodium metasomatites are developed through all petrographic varieties of rocks in the region. Metasomatic transformations occurred with retention of texture-structural features of the rocks having been substituted, including prealbititic tectonites. In accordance with substituted rocks, albitites are subdivided into apogneissic, apomigmatitic, apogranitic, apopegmatitic, etc.

Among dark-color minerals, predominating in albitites, including ore ones, the following are distinguished: chlorite-epidotic, riebeckite-chlorite-epidotic, riebeckite-egyrinic, egyrinic, hydromica-phlogopitic, and carbonate-hematitic. Egyrinic albitites are disposed in zones of the most intensive manifestation of the sodium metasomatism. Hydromica-phlogopitic and carbonate-chlorite-hematitic albitites form independent parageneses with partial or complete substitution of alkali dark-color minerals. In late super-imposed parageneses the content of carbonates increases to 10% and occasionally to 25% (in early parageneses it is of 1–3%, sometimes of 4–5%), and of hematite to 15%.

Uranium minerals in ores are represented by oxides: nasturan, uraninite, hydronasturan, uranium blacks; silicates: uranophane, boltwoodite, beta-uranotile, kasolite, coffinite; titanates: brannerite, davidite, and leucoxene-like uranium-titanium minerals of the urgite type, as well as uranium sorptions on iron hydroxides and clay minerals.

The deposits are characterized by absence of zoning in distribution of uranium minerals. Primary and secondary uranium minerals are developed at one and the same depth levels. Secondary minerals in ores occur down to depths of 1000 m and more, and at the Severinskoe deposit, yellow silicates in albitites were found at a depth of 2900 m from the surface.

The uranium mineralization is superimposed and has the form of microveins and separate impregnations in small fissures of rocks, intergranular space, structural defects of minerals, it tends to accumulations of dark-color minerals.

Albitite bodies in deposits are traced along the strike for first hundreds of meters and up to 2 km at a width from tens of meters and up to 800 m. The depth of occurrence of albitites and orebodies in deposits is comparable with their length on the strike, reaches 1300–1500 m and depends on the erosion shear showing up at the deposit.

Ore controlling structures in the Kirovograd region with respect to the erosion surface of Precambrian rocks are open, since albitites and a part of orebodies at all deposits extend under sedimentary rocks of the platform cover, which overlap them. At the same time the orebodies containing the main resources of deposits are “blind”, only at the Michurinskoe deposit, according to available data, they are half eroded.

The Lelekovskoe and Michurinskoe ore fields are disposed in the eastern exocontact of the Novoukrainskij granite massif in the complex-structure Kirovogradskaya zone of faults of a submeridional strike with a predominantly steep ($0–60°) eastern and north-eastern dip. The Lelekovskoe ore field with the Severinskoe uranium deposit is in the northern part of the exocontact zone, while the Michurinskoe ore field with the deposit of the same name and several noncommercial shows is in the southern part of the zone. The eastern boundary of the ore fields over their whole length is the Kirovogradskij fault, whose fragments have been named (from the north to the south) Rodnikovskij, Vostochnyj (Eastern), and Glavnyj (Main) Michurinskij.

At the Severinskoe uranium deposit the ore-controlling fault of a varying strike (from submeridional to north-western) with a steep (55–75°) north-eastern dip extends in the zone of transition from Lelekovskian medium-grained granites through banded injection migmatites to porphyroblastic migmatites. The major part of albitites and orebodies is disposed in the lying side of the fault. Along with subconcordant elements of tectonics (in the form of mylonites and oataclasites), which have developed in banded migmatites of the upper part of the deposit, the basic plane of the mylonite joint of the Severinskij fault occupies in plan and sectional views an acute transverse position relative to non uniformly layered migmatites, with the result that the geologic position and morphology of albitite and orebodies are determined by a combined wedge-shaped structure formed by no north-western-strike tectonic structures, subconcordant with migmatites, and the main surface of the submeridional Severinskij fault.

At upper horizons of the deposit, within a depth range of 180–600 m (most of bodies do not emerge to the surface of crystal-line rocks), there are numerous small size orebodies, controlled by tectonic elements subconcordant with banded migmatites. Here also layered tectonites control the position of the main orebody of the deposit. After conjugation within a depth range of 600-850 m of the layered tectonics with the plane of steeper-dipping mylonite joint of the Severinskij fault, the position of the main orebody over the depth range of 600–1100 m is controlled by tectonites of the Severinskij fault. At the depth of 1100–1200 m the basic plane of the Severinskij fault flattens out again, occupying a layered position in banded migmatites, and the orebody passes from the plane of steeply dipping tectonites of the fault to albitites of its hanging side. This orebody, the largest in the deposit, is morphologically an ore column sizing 400 m on the strike and more than 1000 m on the dip. Three main bodies, spatially close to one another, at the deposit contain 90% of uranium resources.

The eastern part of the Severinskoe deposit is in a united ore block. The position of albitites and orebodies is controlled by tectonites of the Vostochnyj (Eastern) fault of a north-western strike and submeridional fissure-cataclastic structures of the Podgajtsevskij fault, having an eastern dip at an angle of 50–60°, concordant with the dip of a 500 m non-uniformly-layered rock mass of alternating granites, pegmatites, gneisses, and migmatites, extending in the field of porphyroblastic nigmatites. The position of orebodies of the Southern group is controlled by meridional structures of the Podgajtsevskij fault, concentrated within a depth range of 500–900 m and traced over a length of 800 m on the dip. The Central group of orebodies is disposed at the tectonic joint of the north-western Vostochnyj fault. The bodies are situated within a depth range of 300–1500 m and extend for 300 m on the strike.

A characteristic feature of the Eastern zone of faults is an intensive volume development (of tens and first hundreds of meters on the strike and dip) of zones of quartzification and quartz breccias with fragments of ore albitites. In the process of postmineral quartzification there occurred a complete change of the morphology and structure of the Eastern zone of faults, and its linear tectonites (in the form of mylonites and cataclasites, sometimes with metasomatites) have been preserved as fragments among swells and apophyses of quartz breccias and branching quartzification zones. Possibly, some of orebodies that had been in ore-controlling structures of the Eastern fault were exterminated in the process of quartzification.

Several albitite varieties in the mineral composition are distinguished at the Severinskoe deposit. Of them, hematite-carbonate-chloritic albitites, which have been classified as an independent Severinskij type of ores, are dominating among commercial ores.

The Michurinskoe uranium deposit: The Northern part of the deposit, disposed in a strip of medium-porphyroblastic migmatites, is bounded on the west by southern apophyses of a massif of Lelekovian granites and on the east by gneisses of the Zavadovskaya syncline. Heterogeneity of the ore-formation medium is determined by numerous monadnocks of gneisses of a north-western strike and submeridional bodies of fine-and-medium-grained granites.

Tectonites of the Kushchevskij fault are developed in the zone of contact of migmatites and gneisses. In the northern part of the deposit they have a north-western strike and a dip to the north-east at an angle of 55–65º, and in the southern part, a sub-meridional strike and a steep, 65–75º, dip to the east. At 0.8–1 km to the west of the Xushchevskij fault there extends a series of tectonic joints of the Western fault, which have a varying (from north-western to meridional) strike and an eastern dip of 45–65º. In the submeridional block of migmatites, bounded on the east and west by longitudinal faults, there is a series of alternating (like ladder veins) fissure-cataclastic structures of the latitudinal fault with a varying strike (270–300º) and a dip towards the north and north-east at 60–75º. All systems of tectonites are ore-controlling and ore-enclosing.

Two ore zones, the Eastern, sublatitudinal, and the Western, submeridional, separated from each other, differently oriented, and with different depth levels of distribution of mineralization are disposed within a limited area.

The Eastern ore zone, with a mineralization occurrence depth of 150–550 m, forms in the plan view, for 1200 m on the strike, a flexure-shaped structure. Gneisses end mylonite joints of the Kushchevskij fault contain orebodies of a north-western strike with rich ores in apogneissic albitites. At its passage into migmatites the ore zone acquires a sublatitudinal strike.

With respect to the Western submeridional-strike ore zone the system of latitudinal fissure-cataclastic structures occupies a position of transverse ore-controlling structures separating the zone into blocks with different ore saturations. Orebodies of the Western ore zone are concentrated within a block sizing 350 m on the strike and are disposed levelwise over a depth range of 350–650 m. The orebodies are situated in the lying side of the main joint of the Western fault of 20–30 m in thickness, and in cataclastic structures parallel to it. Ore-controlling submeridional tectonites in the ore block have an arcuate bend, open to the east, in the places where the ore block is bounded on the north and south by latitudinal transverse structures. Ores, not emerging to the surface of crystalline rocks, extend in the form of steeply dipping column-like bodies along tectonic joints for 1000 m on the dip. Albinites with a poor uranium mineralization are traced on the dip for 600 m to the north of the ore block along the main tectonic joint of the Western fault.

In the Eastern and Western ore zones of the Northern part of the Michurinskoe deposit, ore albitites of two paragenetic associations are abundant: of primary riebeckitic, riebeckite-egyrinic and secondary phlogopite-magnetitic and chlorite-hematitic ones with elevated contents of carbonates, the superimposed paragenetic association (phlogopite-hematite-carbonate) being substituted by the next one (chlorite-hematite-carbonate).

The Southern part of the Michurinskoe deposit has in the plan view the structure of a half-open fan, formed by the Glavnyj (Main). Michurinskij fault of a meridional strike with a dip to the east at an angle of 70º and a system of north-western fissure-cataclastic structures with a north-eastern dip at 55–60º, extending from the fault. A thick (up to 20 m) quartzified joint of the Main Michurinskij fault and its overlying gneisses served as a screening plane, because of which metasomatites and mineralization in the hanging wing of the fault acquired no development. Directly under the Main Michurinskij fault is a large orebody in apogneissic albitites with body elements subordinated to the mylonitic joint. The system of north-western ore-enclosing fissure-cataclastic structures extending from the Main fault forms in plan and sectional views a wedge-shaped structure. North-western structures, enveloping small bodies of "mine" granites, control a series of orebodies in apogranitic albitites along 800 m on the strike. At the south of the deposit, at the place of convergence of differently directed faults, a latitudinal blocking structure, the Zavadovskij fault is traced. The deposit is considerably eroded: all orebodies emerge to the erosion surface of crystalline rocks while tapering out at a depth of 500 m. Characteristic of the Michurinskoe uranium deposit are ore albitites of primary paragenetic association riebeckitic, riebeckite-egyrinic; ore albitites of a phlogopite-carbonate and partly hematite-chlorite-carbonate mineralogic association are developed moderately.

The Novoukrainskoe albitite field is situated in the north-western endocontact of the massif of the same name, formed by porphyroblastic, trachytoidic biotitic, and also garnet-biotitic granites, hyperstene-containing charnockite-like granites and monzonites. Vein- and dike-like bodies of aplite-pegmatoidic, fine-grained aplite- and gneiss-like granites are encountered. Granitoids are broken-through by dikes of basic rocks, represented by diabases, diabasio porphyrites, lamprophyres, and picrites. The strike of dikes is north-western (320–350º).

The albitite field is of a block structure, formed by intersection of the submeridional Novoukrainiskij fault with the north-western Andreevsko-Anikeevskij fault and north-eastern Zlynkovskij fault. The intersection and conjugation of faults of orthogonal and diagonal systems in their combination with planar-parallel structures of the protoclasis of porphyroblastic and trachytoidic granites define the structural position of uraniferous albitites.

Albitites are disposed in a plate-like block of a submeridional strike, bounded on the west by the Central, and on the east, by the Eastern (Vostochnyj) meridional fault, with a dip to the east at 40–50º. The tectonic block, 1 km wide in the plan view, is diagonally (from south-east to north-west) divided into two wedge-shaped structures by the diagonal fault having a north-eastern dip at an angle of 40–50º. Upthrust-sheer displacements at the Eastern and Central faults, bounding the block, formed in the latter sub-horizontal extension (breakoff) structures, the most continuous of which is at the upper contact of a dike of fine-grained granites, gently dipping to the west.

The morphology of the gently dipping structure, named the Dike fault, is complicated by the Diagonal and Central faults, where upthrust-shear displacements of the dike of fine-grained granites with an amplitude of 20–50 m have occurred. Uraniferous albitites are disposed on a vertical at three levels: upper, middle, and lower.

The upper ore level is represented by the largest body of albitites, disposed over the dike of fine-grained granites in the zone of the Dike fault. Uraniferous albitites in the eastern part of the area emerge to the surface of crystalline rocks and at the west submerge to a depth of 190 m from the day surface. Their strike is submeridional and the dip is western at an angle of 5–20º. The length of the albitite body is of 770 m on the strike and from 100 to 630 m on the dip.

In the middle ore level the albitite bodies are at depths of 130–185 m from the day surface in the hanging and lying sides of the Diagonal fault they are lenticular, sizing not over 200×150 m. Thickness of the bodies vary from 1 to 77 m.

The third ore level is supposedly at isolated intersections at depths of 500-800 m in albitites of the Central fault. Albitites with uranium mineralization are represented by riebeckite-egyrinic, egyrinic, phologopite-carbonate, and phlogopite-andraditic mineral associations.

In the Vatutinskoe ore field represented by the uranium deposit of the same name and several uranium ore shows, there occurs chiefly a gneiss-granite complex or rocks, forming gneiss-granite domes and gneissic synclines. At the Vatutinskoe uranium deposit the ore-controlling wedge-shaped volume structure, open to the north, is formed by the plane of the Main Western fault of a north-western strike, dipping to the south-west at angles of 60–70º. At its hanging side there is a strip of gneisses, playing together with tectonites of the fault the role of a screen, and at its lying side layered and branched injection migmatites of a "thin-layered horizon" (alternation of medium-grained granites, gneisses, pegmatites, and migmatites) with a submeridional strike and a dip to the west at 50–55º. The Main Western fault, intersecting the rocks of the "thin-layered" horizon at an acute angle, in plan and sectional views forms a structure where orebodies of the upper part of the deposit are associated with fissure-cataclastic zones developed in the schistosity of rocks of the "thin-layered" horizon, while with depth at the approach to the Main Western fault the orebodies become more compact, steeply dipping, and are controlled by the tectonites and main mylonitic joint of this fault. They taper out at a depth of 800 m. On the east the structure of the Vatutinskoe deposit is bounded by the submeridional Eastern fault, dipping to the west at an angle of 60–70º. It affects the position of a compact orebody with rich ores, disposed directly along mylonitic and cataclasitic joints of this fault.

Ores of the Vatutinskoe uranium deposit are characterized by a chiefly riebeckite-egyrinic and egyrinic mineral composition of albitites and sporadically phlogopite-carbonate one. Uranium oxides prevail in ores of the deposit.

Thus, commercial uranium deposits in Ukraine are associated with manifestations of processes of an alkali postgranitizational metasomatism in zones of large tectonic faults. Some geologists assign, them to ultrametamorphic ones, formed under the action of hydrothermal solutions ascending from deep-seated zones of ultra-metamorphism. The participation of juvenile subcrustal sources of solutions and ore matter is also not excluded.

The uranium deposits are situated in two ore regions, Krivoj Rog and Kirovograd ones. The position of deposits in the Krivoj Rog region is controlled by the Krivorozhsko-Kremenchugskij deep-seated interblock fault, and in the Kirovograd region, by the Kirovogradskij, Zvenigorodsko-Annovskij, and Novoukrainskij deep-seated interblock faults. Within the deep-seated faults the deposits are disposed in local structural units formed by joints of folded and differently oriented rupture disturbances of high orders, among which there are distinguished ancient ones, formed at the stage of folding, and late ones, close in the time to albitization and ore formation. Flexural bends of rupture disturbances on the strike and dip have as well an ore-controlling importance. Structural and morphologic features of the deposits are greatly determined by the premetasomatic folding, heterogeneity of ferruginous-slaty and granite-gneissic masses, protoclastic and directional structures of granite massifs, and morphology of small granite bodies.

The uranium mineralization is closely associated with sodium metasomatites. Albitization is developed on ferruginous quartzites, slates, granites, gneisses, and migmatites with formation of albitiles, egyrinites, and ribekitic metasomatites. The uranium mineralization (uraninite, nasturan, brannerite, uranium and titanium silicates) is superimposed on cataclased metasomatites, forming a fine impregnation together with late albite, chlorite, phlogopite, carbonate, and hematite. Secondary uranium silicates and hydroxides are widespread. Orebodies tend to central parts of bodies of sodium metasomatites and are bed-, lens-, and column-shaped.

At present the major uranium ore resources are concentrated in the Kirovograd region, which is a reliable source of raw material for operating mines of the Eastern integrated ore-concentrating works.

1.2. Classification of the uranium and mineral reserves and resources

The Ukrainian Government has approved the mineral reserves and resources National Classification, which embraces all kinds of minerals and has adapted for market principles of resources utilization.

The principles of mineral reserves and resources dividing into groups and classes are in harmony with the United Nations International Framework for solid fuel mineral Reserve/Resource Classification (1997), IAEA Uranium Resources Classification. Clauses of the United Nations International Mineral Resources Classification (1979) were taken into account too.

The new Classification has three basic definition of mineral reserve/resource dividing: in accordance with economic efficiency, stages of feasibility study, and exploration. Market economic principles need the introduction of these classifying definitions since a potential investor is interested in the capital investment guaranteed efficiency and minimum economic risk.

Under the Classification the technical and economic feasibility study envisages increasing requirements to complete the following definition items: detailed mining and technical, geographical and economic, socio-economic and environmental, other necessary conditions of mineability assessment and subsequent development of deposits, ore processing as well marketing grounds for favorable mineral commodities supplying.

In fact, the feasibility study is directed first of all at the definitions of influence factors on mineral commodities cost: organizational, technical, economic, financial and other solutions.

The mineral reserves and resources are classified by the relationship of the industrial importance, technical- economic- and geological study stages and subdivided into classes identifying with a help of the international three figures code (Table I).

Table I. Technical, economic and geological study stages, international three figures code

The industrial (commercial) importance	The technical and economic feasibility study level	The geological study level	The class code
1. Balance reserves	GEO-1	Explored reserves	111 assured
	GEO-2 GEO-2		121 estimated
		Preliminary explored	122
2. Conditionally balance and outbalance reserves	GEO-1	Explored reserves	211
	GEO-2 GEO-2		221
		Preliminary explored reserves	222
3. The industrial importance is not defined	GEO-3 GEO-3 GEO-3		332
		Perspective resources	332
		Prognosticated resources	334

The class under code “111” pools explored and detailed evaluated reserves which shall be mined with an economic efficiency. These reserves, in accordance with the International Classification, are related to assured reserves (Proved mineral reserves).

The classes under codes “121” and “122” includes balance explored and preliminary explored that are preliminary evaluated belong to estimated reserves of the United Nations Classification (Probable mineral reserves).

The new Classification of the mineral reserves and resources is also the framework. The using of the Classification for minerals, technogenical including, is regulated by the instructions of the State Committee on Reserves (DKZ) of Ukraine.

Now there is elaborated and will be approved soon the Instruction of the Classification using for uranium ore deposits. This Classification determines groups of uranium deposits according to their geological and industrial types, dividing of reserves value and uranium content in ore, geological structure complication, dividing principles of uranium reserves regarding their industrial importance and technical-economic-geological study stages, level of their commercial knowledge, reserves evaluation and readiness to the exploitation.

In particular the dividing categories of uranium deposits according to their geological-industrial types have basis of a typification introduced by the IAEA (International Atomic Energy Agency). There are 15 main types of uranium deposits, which are presented as stable uranium supplier to the world market. Side by side with uranium reserves subdividing, accordingly to their industrial importance, into balance, conditionally balance and outbalance reserves, the instruction will content cost groups of production and ore processing into the consumer good: to $40/kg, $80/kg, $130/kg and above.

In that way Ukraine approving the new Classification of the mineral reserves and resources and elaborating the instruction of its using for uranium deposits takes the next step to the system development of the geological-economic assessment and state registration of raw materials adapted for internationally recognized schemes and market economic principles.

2. Environmental protection on uranium sites

Zhovty Vody Site (Fig. 2)

The industrial site Zhovty Vody is the main one in the system of VostGOK Industrial Company. There are mining and supporting enterprises: "Olkhovskaya" and "Novaya" mines; the uranium mixes ores processing plant (GMZ); the sulphuric acid plant (SKZ) and some other facilities necessary for the normal activity of the town, on the site. The Company's headquarter is on the site too.

From the very beginning of Zhovty Vody's mining a two quarries (named Gabayevsky and Veseloivanovsky) were formed on the territory of the site. Besides the above mentioned three tailings: "KBZh", "Sch" and "R" were formed too.

The mining activity performed on the Novaya mine and Olkhovskaya mine led to a large quantity of waste dumps with total volume of 550 thousands of m^3. The affected territory with the total area of 968 hectares consisted of the following:

— Dumps (19.1 hectares),
— Depressions (17 hectares),
— Quarries (50.6 hectares),
— Tailings (644.6 hectares),
— Others (34 hectares).

The Olkhovskaya mine was closed in 1980.

The waste and under conditioned rocks from Novaya mine are directed into a depression now. The tails from hydrometallurgical plant and iron ore enrichment plant are stored in tailings. The "KBZh" tailing is in 3 km from the northern border of the town within a sanitary-protective zone of hydrometallurgical plant. The closed limonite quarry was used as a receptacle for tailing. The water surface is 55 hectares. The quarry's volume was almost completely filled up with tails in 1987 and now after partial upgrading it is used as a reserve storage for emergency out flow from the hydrometallurgical plant. The tailing is filled up with leached uranium ores' pulp with the content of uranium about 0.007%. The tails quantity is 19.34 million tons. The 222-Radon's exhalation from the tailing's surface varies from 0.05 to 3.0 Bq /m^2 sec.

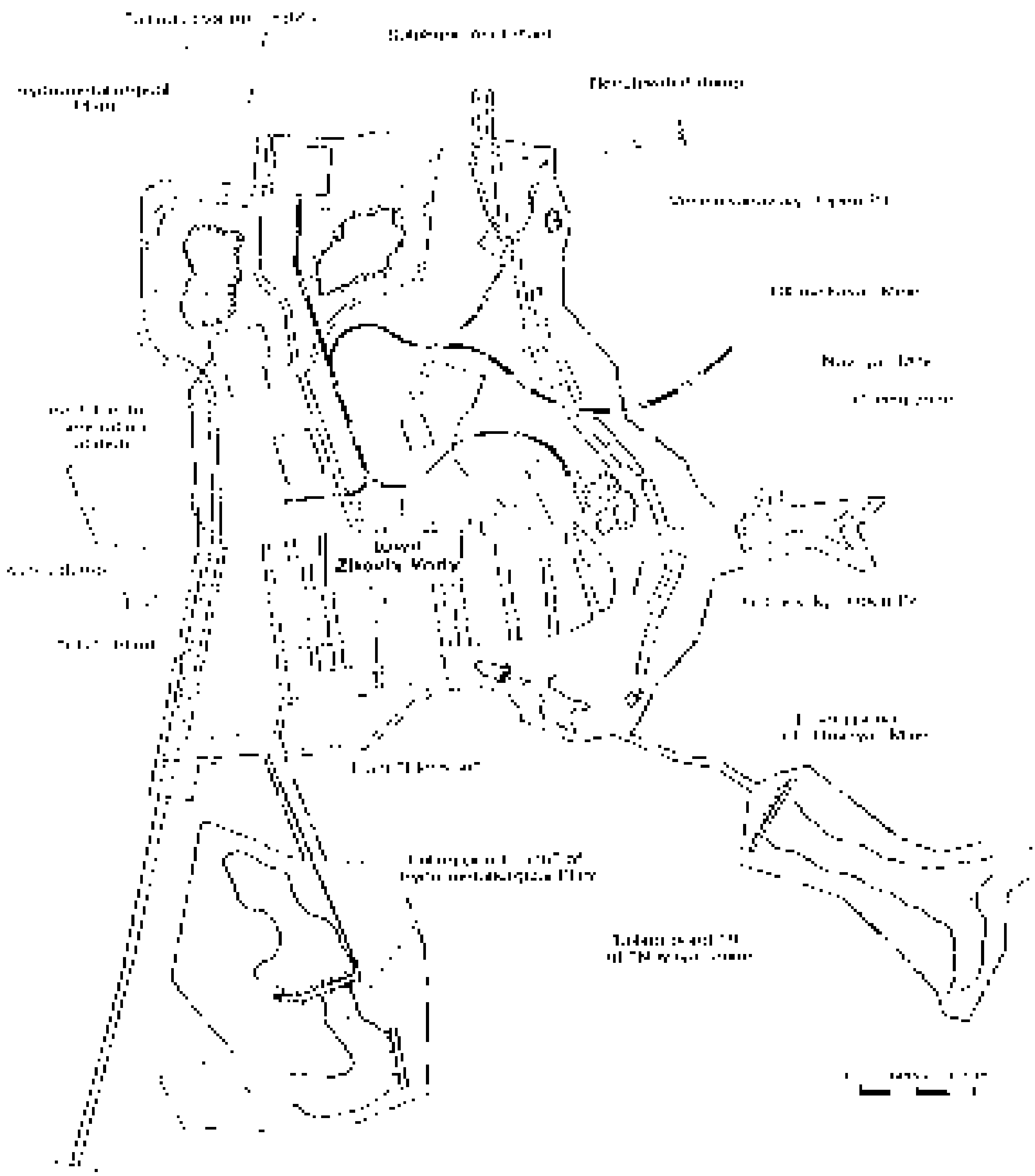


FIG. 2. VostGOK, Scheme of the Zhovty Vody industrial site.

The “She” tailing is located 1.5 km to the south from the town within the borders of Scherbakovskaya gorge and has been exploited from 1977. The area of the storage is 250 hectares. The tail’s stored volume is of 43.54 millions of tons. The leached uranium ore’s pulp has a content of uranium about 0.007%. The 222-Rn exhalation from the tailings area varies from 0.5 to 2.0 Bq/m^{2}s.

The stored tails total activity is 1.8 10 + 15 Bq. The “R” tailing is located on the left side of river Zholtaya’s valley within the “Razbery” - gorge. It is exploited from 1969 as storage for iron ores’ waste from “Novaya” mine enrichment facility. The tailing’s area is 230 ha.

The mine waters with radionuclides content are directed after the treatment to natural water system. The effluents volume is 2.4 million m^3 per year.

The site of Ingulskaya mine

The site is located in south neighborhood of Kirovograd city. The deposit is open with three shafts and is developed to a depth of 700 meters. The mined ore has been preliminary sorted and divided into ore for sale, under conditioned ore or waste rock. Last two types are directed to dump. The total area of dumps is 44.7 ha. The stored rocks volume is about 2.4 million m^3.

The Ra-226 content in the dumps varies from 843 to 1389 Bq/kg. All radionuclides of uranium family are presented in dump rocks. The density of Rn-222 flow in atmosphere from the dump's surface is from 0.85 to 1.28 Bq/m^2s with average value of 1.07 Bq/m^2s.

After the treatment the mine waters are directed into a hydrographic net with annual volume of 2.6 million m^3.

The site of Smolino mine

The site is located in Kirovograd region 3 km away from miners' town of Smolino. The site allows the underground mining of Vatutinskoye deposit at a depth of 500 m. It also has facilities for crushing, sorting, inventory and shipping the ores. The deposit is open with 4 shafts.

There is a waste rocks dump on the site with basis area of 5.3 ha and stored volume of 1.06 million m^3. The dosimetric survey shows the surface contamination with radionuclides is concentrated on the site and in the area of solid waste dumps.

The underground mine waters are directed to mine water clearing unit and after the treatment into natural hydrosystem.

In situ leaching (ISL) sites

In situ leaching (ISL) of uranium was carried out on Deviadovo, Bratskoye and Safonovka Deposits by VostGOK. The Deviadovo Site is located in Dnipropetrovsk region 30 km to south-east from Zhovty Vody.

The ISL methods were practiced on industrial scale from 1966 up to 1983. The chemicals used were sulphuric and nitric acids.

The area of the site is 12 ha, the orebody area is about 218 ha, the area for underground storage is of 120 ha. The deposit coincides with uranium bearing coal-and-clay Paleogen sands.

As a result of ISL mining the underground water were contaminated at a depth of 80 m. The halo of residual solution was distributed on the 1.7 km distance along the underground waters flow and for 0.35 km against the flow. The nearest locality at the underground flow direction is in 4 km. The volume of residual solutions after the ISL mining of uranium in buchak aquifer is 7.09 million m^3.

The volume of water in tailing ponds is 1 million m^3 and the volume of a contaminated silt in ponds-collectors is about 40 thousands m^3. Leakages from pipelines caused the contamination of soils and ground. The volume of contaminated soils is about 50 thousands m^3. The Bratskoye ISL site is located in Nikolayev region 200 km to the South from Zhovty Vody. The deposit of uranium is located in Paleogen sediments.

The industrial mining of uranium took place there from 1971 to 1984. The orebody area is 95.5 ha. The sulphuric acid and nitric acid were used as chemicals for working solution preparation.

After the finishing the development of the deposit all the working solution presented in a volume of orebody on the moment of the end of operation were left unremoved. The volume is of 5.2 million m^3. The halo of residual solutions was distributed for 3 km along the underground waters' flow and for 1.2 km across the flow to a depth of 50 meters.

The Safonovka Site is located in Nikolayev region too. The deposit of uranium relates to uranium - beaming coalclay sands. The mining of uranium there took place during the period from 1982 to 1993. The surface technological structure took the square of 5 ha.

"PChZ" site

The Pridneprovsky Chemical Plant (PChZ) is situated on the right bank of river Dnipro in a frame of Dniprodzierzhynsk city of Dnipropetrovsk region.

The enterprise is performing its activity on two sites, e.g.:

- The site of the plant,
- The site of "S" tailing-pond and reloading station ("S"-base) that are located 10 km to the south-east from the plant.

South-east from the plant, the temporarily closed "D" tailings storage on right beach of Dnipro-river is located at a 300 m distance from the plant's site. All the above mentioned sites were used for storage of radioactive waste. The characteristics of the sites are presented in Table II.

Table II. The characteristics of the waste and contaminated territories from PChZ

Sites (time of operation)	Quantity, million tons	Volume, Million m^3	Area, ha	Total activity, TBq	Dose rate, μSv/Hour
Industrial Site (1949–1957)	1.0		6	313	3-60
"S" tailing:			78	970	0.32–9.0
I part (1968–1983)	19.065	8.55			
II part (1983–now)	9.6	4.4			
Reloading station "S"			35		0.3–48
"D" tailing (1957–1968)	22.0		73	1500	0.08–0.18

The experience of remediation of affected territories

From many of projects proposed for the remediation of affected territories the following are realized in Ukraine:

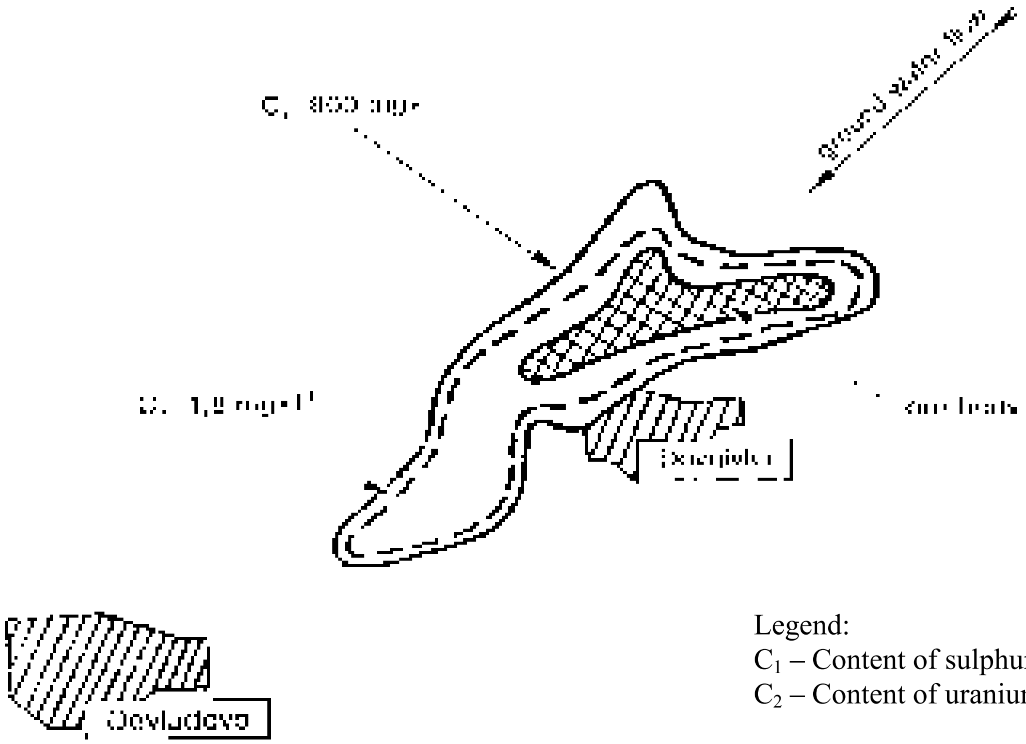
- The restoration of the "Devladovo" and "Bratskoye" ISL sites after finishing the operation,
- The rehabilitation of the territory adjoining the "Olkhovskaya" mine,
- The "KBZh" tailing's restoration,
- The decontamination of the Mukachevo reloading station of Lviv railroad.

The "Devladovo" and "Bratskoye" ISL sites rehabilitation (Fig. 3)

The very first site of in-situ leaching of uranium in the former Soviet Union was "Devladovo" plot. The plot was used for the testing and improvement of ISL-technology. The tests led to the considerable surface contamination by the acids and the radionuclides as well. In the 1973-1975 the most contaminated part of the site's territory was rehabilitated for the first time in former Soviet Union. The technology of rehabilitation consisted of replacement of an affected ground either from in between the rows of the working holes or from the spots after the split solution with clear ground and further deep up to 50 cm from surface ploughing of it with trenching plough. Then after liming of the soils and completing the sanitarian expertise the site was handed out to the agricultural enterprise.

For years after, the site was used mainly for growing the industrial and forage crops. The rehabilitation of entire territory of the site was finished up to the end of eighties. The results of an investigation on the state of ISL site's territory in 15 years period after recultivation are shown on.

The same technology was applied for the rehabilitation of "Bratskoye" site. The whole territory of this site was recultivated in 1991. Up to the moment the grounds of the "Bratskoye" site returned into agricultural operation grounds are used for growing the graincrops.



Legend:
C_1 – Content of sulphuric-ion;
C_2 – Content of uranium.

FIG.3. Scheme of ground waters pollution of "Devladovo" site.

The restoration of the grounds adjoining the Oikhovskaya mine

The restoration was performed during the period from 1979 to 1982. The technology included the selective deconstruction of a pit heap, waste rocks dumps and under conditioned ores. Partially the rocks were transported to Hydrometallurgical Plant for processing. The other part was used in tailing pond dump construction. But the largest part was stored in a nearest quarry.

The total amount of removed and utilized rocks was about 550 thousand m^3. The contaminated soil under the dumps was removed up to deep of 1m and transported to the quarry again. The total area of the remedied territory made about 15 ha. The equivalent Y-dose- rate on the site was about 0.10–0.22 mSv/hour. The recultivated territory was used partially for the construction of a garage, partially for mechanical enterprise construction and for the gardening.

The tailing "KBZh" restoration

The rehabilitative works were started in 1991 and have been continued up to the present time. Nevertheless, now about 85% of the tailing's territory is covered with the loam 0.4 m depth, that preventing the dusting of tail material. The tailing area is 55 ha.

The project foresees the construction of the multilayer protective cover. The structure consist of 0.4 m of loam, 0.4 m of waste rocks, 3.5 m of layer by layer compressed loam, 0.3 m of black soils. It is planned to use the recovered territory after the rehabilitation as an agricultural pasture.

The project for waste rocks dumps' rehabilitation on the sites of "Ingulskoye" mining enterprise

One of the possible ways to decrease the impact uranium mining waste on environment is to use them for filling up the gorges and ravines. The amount of mining waste to be stored in ravines is about 500 thousands of cubic meters. The specific alpha-activity of the rocks varies from 370 to 39 000 Bq/kg and this fact characterizes them as a mixture of low activity radioactive rocks. The results from the simulation showed the absence of underground waters' contamination with the natural radionuclides during the period of 1000 years. The radon exhalation from rehabilitated territory will not exceed the values of the background level for the given territory. The restored territory is planned to be used for gardening.

3. Creation of nuclear fuel cycle in Ukraine

After the disintegration and collapse of the former USSR, Ukraine has had 15 units of nuclear power reactors in operation and 5 under construction and the Ukrainian nuclear industry has consisted of the East Integrated Mining and Concentration Mill (VostGOK) is operating to mine and process the uranium ore and the Pridnieprovskiy Chemical Plant. Hence nuclear power plants of Ukraine have found themselves without a scientific-research of NFC support, without an enterprise of nuclear fuel fabrication and an away from reactor storage (AFR), spent fuel management, processing technology and safety. The atomic energy and industry of Ukraine, as a separate branch from the beginning of main task definition to this day is operating with stability and dynamically that is confirmed by quantitative and qualitative indices, see the table below.

Electricity supplied by reactors in	1993	1994	1995	1996	1998
TW (e).h	75.2	68.9	70.5	79.5	79.4
% of total	32.7	34.0	36.4	43.8	44.6

This means in spite of stagnation of general industrial activities in Ukraine, the atomic branch has increased electricity generation and basic funds, keep skilled engineers and trained workers as well as builders are capable to increase the basic funds.

From the side of assessment of different energy sources for electricity generation in Ukraine, the country is supplying electricity with utilization of:

— Nuclear fuel (uranium) – 44.6%,
— Coal – 26.1%,
— Gas – 21.1%,
— Oil - 2.6%,
— Hydro (water) – 4.9% and

Following the National Programme on energy development after 2000 Ukraine is planning to supply 35.5% by nuclear power plants (NPPs) of total electricity generation, with installed capacity of NPPs – 22.7% for comparative assessment of different energy sources of total electricity generation in Ukraine, that means a predomination of the coefficient of installed capacity use of nuclear power plants ($C_{u.i.c.}$) under $C_{u.i.c.}$ of thermal power stations in 1.8 times.

Today the industrial capacity intended for nuclear fuel cycle of atomic energy meets the requirements of total nuclear fuel fabrication resources 10% only:

- Natural uranium production (VostGOK) meets 30% of the reactors demand of NPPs in Ukraine,
- Ionic-exchange-resin production for uranium concentrate fabrication (Pridnieprovskiy Chemical Plant) meets complete demand,
- Zirconium concentrate production (Verkhnednieprovskiy mining-metallurgical combine): full demand satisfaction.

The rest 90% of nuclear fuel components is supplying today from Russian Federation and Kazakhstan.

Taking into account of a specific volume of atomic energy in the energy/electric sector of the country, the national security reasons determine a necessity of the creation of own nuclear fuel cycle. Even during the creation of the national nuclear fuel cycle, Ukraine is planning to reduce permanent dependence on foreign sources. There are such opportunities and facilities in the uranium- and zirconium- fields, in the demesne of up-to-date technology and scientific/technical potential. The analysis of nuclear fuel components (NFCIS) shows that the uranium enrichment in the ^{235}U isotope is a more expansive stage of the fuel fabrication (45%). But for Ukraine, taking into account the national conditions, the task of the enrichment of U is non-realistic to do it independently. As it is notorious that the state-owners of the nuclear weapons (USA, Russia, England, France, China) have only enrichment plants are financing additionally from programmes of nuclear armament.

Therefore, looking into the reduction of supplying of foreign nuclear fuel in Ukraine at present, it is possible to carry out this reduction up to 45% of demand satisfaction. Ukraine can liquidate the supply of foreign nuclear fuel only under condition of possible implementation of the heavy water cooled and moderated reactor (CANDU). This task of reduction of dependence on foreign nuclear countries from 90% to 45% is resolving by Goskomatom, ministries and departments of the country.

The composite programme of the nuclear fuel cycle creation of Ukraine consists of five separate programmes:

The 1st programme: “Mining and processing of uranium ore”.
The 2nd programme: “The pigs production of zirconium alloy”.
The 3rd programme: “The rolled zirconium production”.
The 4th programme: “The heat-eradiated fuel assemblies production”.
The 5th programme: “The scientific and design-technological maintenance”.

The 1st programme: Mining and processing of uranium ore.

The aim of this programme is to establish facilities to satisfy the reactor related requirements of NPPs with natural uranium.

This programme foresees:

— The exploration and development surface drilling in favor of non-deficient/economical uranium deposits,
— The further operation and development of the Vatutinskoye and Michurinskoye uranium deposits,
— The industrial development of new uranium deposits,
— The reconstruction of the hydrometallurgical plant,
— The widening of new facilities and technical approaches, procedures and guidelines to increase an output and safety of the dump,
— The modernization of machinery and equipment manufacturing plants,
— The establishment of enterprises of goods production to meet the infrastructure requirements of mines and processing plants.

4. Conclusion

Atomic energy has perspective development in Ukraine. Potential of necessary uranium and zirconium resources is enough to provide atomic energy industry minimum up to 100 years. Measures to strengthen atomic energy industry are backed by the programme of creating nuclear fuel cycle in the country.

Uranium resource processing: Secondary resources, India

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Abstract. While the primary resources of uranium are the main contributors to the industrial uranium production, the secondary resources are becoming important from the viewpoint of eco-friendliness and resource conservation. The secondary resources include uraniferous phosphates processed by the fertiliser industry monazite, which is processed for rare earths elements, uraniferous carbonaceous materials and ultimately seawater. A significant advantage of the secondary resources is that the major cost of mining and processing is borne by the parent valuable content and only the incremental cost of uranium recovery needs to be considered. A second major advantage results from the radiation safety requirements. The primary sources, because of higher uranium content, are associated with higher levels of radioactive daughter products of uranium, which leads to imposition of strict radiological safety norms to mining and processing personnel, industry and environment. Secondary resources, by contrast, require very little additional safety engineering features to be incorporated.

Secondary uranium resources: Phosphates, Monazite, Carbonaceous Materials, River and Seawater

1. Uranium recovery from phosphates

Rock phosphate is a vital input for increased food grain production, required to feed the growing populations of the developing countries. India has a number of fertilizer plants, which process the rock phosphate into fertilizer, mostly by the sulphuric acid process. In addition there are two plants using the sulphuric acid process to produce industrial phosphates required for applications as detergent and water softening agents. Two plants also process phosphates by nitric acid route for fertilizer.

Uranium is known to occur in phosphates. The potential for recovery of uranium from the phosphates is substantial. It is available as a by-product of an industry, which is well established and stable. Unlike the conventional sources of uranium such as the mined ore, the phosphatic uranium is amenable for rapid exploitation.

As an energy source, if uranium contained in phosphates is not recovered, it is lost irretrievably with the fertilizers. Besides the spread with fertilizer is of environmental concern due to the radioactive hazards involved. The radioactivity levels in the fertilizers exceed the new levels prescribed in the revised international standards for safe use of radioactive materials. It is imperative therefore that uranium separation from phosphates is carried out.

The recovery process consists of basic steps shown in Figure 1. The phosphate ore, as mined, is accompanied by waste rock. Hence upgradation by ore dressing techniques is carried out. Typical results on a sample from a uraniferous Indian phosphate deposit show that subjecting an ore containing P_2O_5 = 29.6% and U_3O_8 = 0.043% to the operations of calcination, magnetic separation and froth flotation yields a high acid-grade concentrate fit for fertiliser purpose, containing P_2O_5 = 36.3% and U_3O_8 = 0.046%. The bulk of uranium values (~75%) are intimately associated in the phosphate mineral and no selective upgradation or leaching is feasible.

The next step in the process is acid dissolution of the rock phosphate. There are several methods of acidulation, but the most common one is the process involving the use of sulphuric acid to reject the calcium in the rock phosphate as “dihydrate” gypsum, while yielding phosphoric acid containing 27–32% P_2O_5 - which is called the “wet process phosphoric acid” (WPA).

During acidulation, uranium present in the rock reports to the WPA as the operation is carried out under oxidizing conditions. This is generally the case since air-cooling or flash-cooling of the acid is adopted for removal of the heat produced in the dissolution reaction. If required the operation can be deliberately controlled by monitoring the redox potential, or the e.m.f.

Uranium recovery from WPA involves these steps: (i) phosphoric acid pre- treatment, (ii) uranium extraction, (iii) uranium purification by re-extraction, (iv) product recovery, and (v) post - treatment of uranium depleted acid.

Prior to uranium extraction, WPA must undergo several pre-treatment steps. These include cooling to an optimum processing temperature, clarification to remove both the suspended solids and the organic material present in the acid (called as “humates”), and adjustment of uranium valency. Depending upon the solvent, uranium is extracted from the acid, after pre-treatment, either in the +4 or +6 oxidation state by solvent extraction. The uranium is recovered from the solvent by another contact with an acid strip solution.

The uranium in the acid strip solution may be precipitated but needs to be purified before conversion to the final product. Purification is accomplished by re-extracting the uranium with a second organic solvent. The uranium loaded organic in the second circuit is scrubbed to remove the impurities. The pure uranium is stripped from the solvent and precipitated. This precipitated “yellowcake”, is dried or calcined, packaged and transferred to uranium fuel conversion facilities. The uranium-barren phosphoric acid, called “raffinate”, is sent to a clean-up step to remove traces of entrained organic before being returned to the fertilizer plant.

Detailed techno-economic studies, based on the scale-up data from our pilot plant, for industrial plants capable of producing 50 – 300 TPY uranium show that the process is viable in the Indian context.

2. Uranium recovery from monazite

Isolation of thorium (and uranium) from bulk of the rare earths (RE) and the gangue involves two stages of processing: opening of monazite by chemical decomposition and the separation of thorium concentrate. Monazite is highly refractory. The RE, U etc. are closely bound to its crystal structure. Drastic chemical attack is required to destroy the monazite structure. Digestion with sulphuric acid or with caustic soda can be used for the “attack” reaction. In the alkali process, adopted industrially in India, finely ground monazite is digested with sodium hydroxide (30–45% NaOH in reaction slurry) producing insoluble hydrous oxides of Th & RE, uranate and soluble trisodium phosphate (TSP). Over 95% of Th & RE and 99% of U in monazite is converted. The slurry is diluted and the hydrous oxides are separated by filtration from the solution containing TSP and excess caustic. The cake is dissolved in conc. HCI and solution is diluted (~8 gm ThO_2/lit.). Treatment with NaOH at pH 5.8–6.0 precipitates thorium and uranium as hydroxide. Filtration and drying gives thorium concentrate. Thorium recovery in precipitation is 99%. The concentrates have about 2.5% of total rare earth. Thoria content of the concentrate is about 55%. Levels of other elements on thorium basis is: U 2.5%, RE 20%, Fe 10%, Ti 15%, P 5%, Cl 30%, approximately. Phosphate/sulphate are low. Uranium is more strongly extractable than thorium and nuclear grade tolerates only a few ppm. Two types of solvent extraction flow sheets both with TBP-Nitrate system are possible, depending upon the philosophy of uranium thorium separation. These are:

— Separate extraction of uranium and thorium, uranium in solvent with low (5–10%) TBP concentration and then thorium in high (30–40%) TBP concentration from the raffinate of uranium extraction,
— Co-extraction of uranium and thorium in high TBP solvent and selective stripping of thorium and uranium with 0.5N nitric acid and acidulated water (0.02N HNO_3) respectively.

The two solvent processes have been found to yield acceptable performance. The process flow sheet is shown in Figure 2.

3. Recovery of uranium from seawater

Seawater containing 3.34 mg/m^3 uranium is a vast potential source of uranium. Several separation processes like ion flotation, co-precipitation, solvent extraction, bio-sorption and adsorption on solid substrate have been considered. Although solvent extraction is a highly selective feasible process, it is uneconomical in view of the solvent losses due to solubility and entrainment involved in handling large volume of extremely dilute solutions. Thus a test rig of 300 m^3/hr containing ~1 g/hr uranium would have solvent loss 1500 times higher even assuming a low loss of 5 ppm. Adsorption on solid substrates overcomes this limitation. Hydrated titanium oxide (HTO) has been investigated world wide as an adsorber material. It has good specific adsorption capacity. At pH 8 it behaves as cation exchanger. At the acidic surface of the HTO, the carbonate complex of uranium gets ionized into UO_2^{2+} and HCO_3^- species. The uranyl ions are adsorbed on the surface of HTO. The physico-chemical properties of HTO need to be optimized by a suitable synthesis process. The HTO processes developed and tested at BARC include:

(a) Beneficiated ilmenite,
(b) Titanium Impregnated Charcoal Granules,
(c) Composite Granules of HTO and activated carbon Powder,
(d) Titanium Silicate Granules.

Coastal belts of Kerala, Tamilnadu and Orissa contain vast amounts of mineral ilmenite, which is 65%TiO_2 and 35% FeO. Carbon reduction of iron oxide to metallic iron followed by acid leaching yields beneficiated ilmenite. Beneficiated ilmenite is a porous hard titanium compound with high surface area. Tests showed that this product had uranium saturation loading of 0.7 mg/g adsorbent. But the material is very fine and continuous columnar operation requires careful plant design. While charcoal based products had low life, the synthetic product found most suitable was titanium silicate granules. Co-precipitated TiO_2 and SiO_2 gel in the 1:1 ratio has a high cation exchange capacity. Tests showed uranium adsorption was faster than with HTO. Elution could be carried out either with 0.01–1 M H_2SO_4 or with 0.05–1 M $(NH_4)_2CO_3$. Dissolution of titanium in eluate was negligible. Repeated cycles of adsorption and elution did not show any reduction in capacity. A test flowsheet is shown in Figure 3. Detailed engineering and preliminary techno-economic evaluation is under progress.

4. Recovery of uranium from carbonaceous matter

Fly ash obtained from combustion of uraniferous coals by thermal power reactors contains significant levels of uranium. The energy content of the uranium in fly ash exceeds the energy of the thermal plant producing the ash. Uranium is dispersed and no discrete minerals have been identified. The matrix consists of quartz, sericite, micas, haematite-geothite etc. Chemically Al and Fe are ~10% while V, Ti are present up to 250 ppm. The uranium content varies from 300–1500 ppm, depending on the source. Bulk of the uranium is present in refractory form as the combustion process generates temperatures ~1200°C, The uranium recovery process tested involves chemical leaching at 75°C with a sulphuric acid concentration of >300 kg H_2SO_4/t. No oxidant has been found necessary, unlike the case with conventional acid leaching of ores. The bulk of uranium (~80%) gets dissolved with high selectivity and dissolution of other inorganic impurities is low. Besides uranium, many other ions, especially iron, vanadium, aluminum, magnesium, potassium and titanium are obtained in the solution. The choice of the acid concentration and the temperature of leaching are based on techno-economic considerations. Higher temperature and acid concentration leads to more uranium recovery but the more refractory matrix materials also get decomposed and impurity level also increases. The impure solution from the leaching operation is processed by ion exchange and the sulphate complex in anionic form is adsorbed. Elution has been carried by chloride/sulphate solutions. The barren solution, after the recovery of uranium, is treated with lime for neutralization and precipitation of cationic elements to comply with effluent control norms. The neutral slurry is pumped to the dump for the solid leach residue where the precipitate is retained. The clear effluent solution free of polluting metals is pumped for disposal. The pregnant eluate is processed by solvent extraction and uranium precipitated by hydrogen peroxide.

The various types of leach systems have been considered: agitation leaching of finely ground material followed by solid-liquid separation through filtration or sedimentation, or percolation leaching in sumps with filter bottom. Based on techno-economic considerations, the percolation leach is selected. The slimy character of the fine material leads to somewhat slow filtration and sedimentation performance and hence static leach is preferred. In addition the residue is self-draining and not as difficult to dispose as is the thixotropic slurry from conventional CCD. The static leach has the disadvantage of minor loss of uranium. The material of construction for the corrosive solutions include acid-proof lining, impervious graphite and plastics including PVC, PTFE and nylon braided hoses.

Although the cost of uranium is higher than the recovery from conventional ores, its impact on the unit energy cost of the electricity produced is not high considering the three-phase nuclear power cycle of the country. Significant cost reductions is possible by scrubbing the sulphur dioxide from the thermal plant flue gases to produce sulphuric acid solution for leaching. The overall ecological impact of the process is benign.

5. Conclusion

Uranium recovery from secondary sources such as phosphates, monazite, carbonaceous matter and seawater is a technically feasible and eco-friendly option. For a country with limited energy resources and for long-term energy security, the processes need favourable consideration.

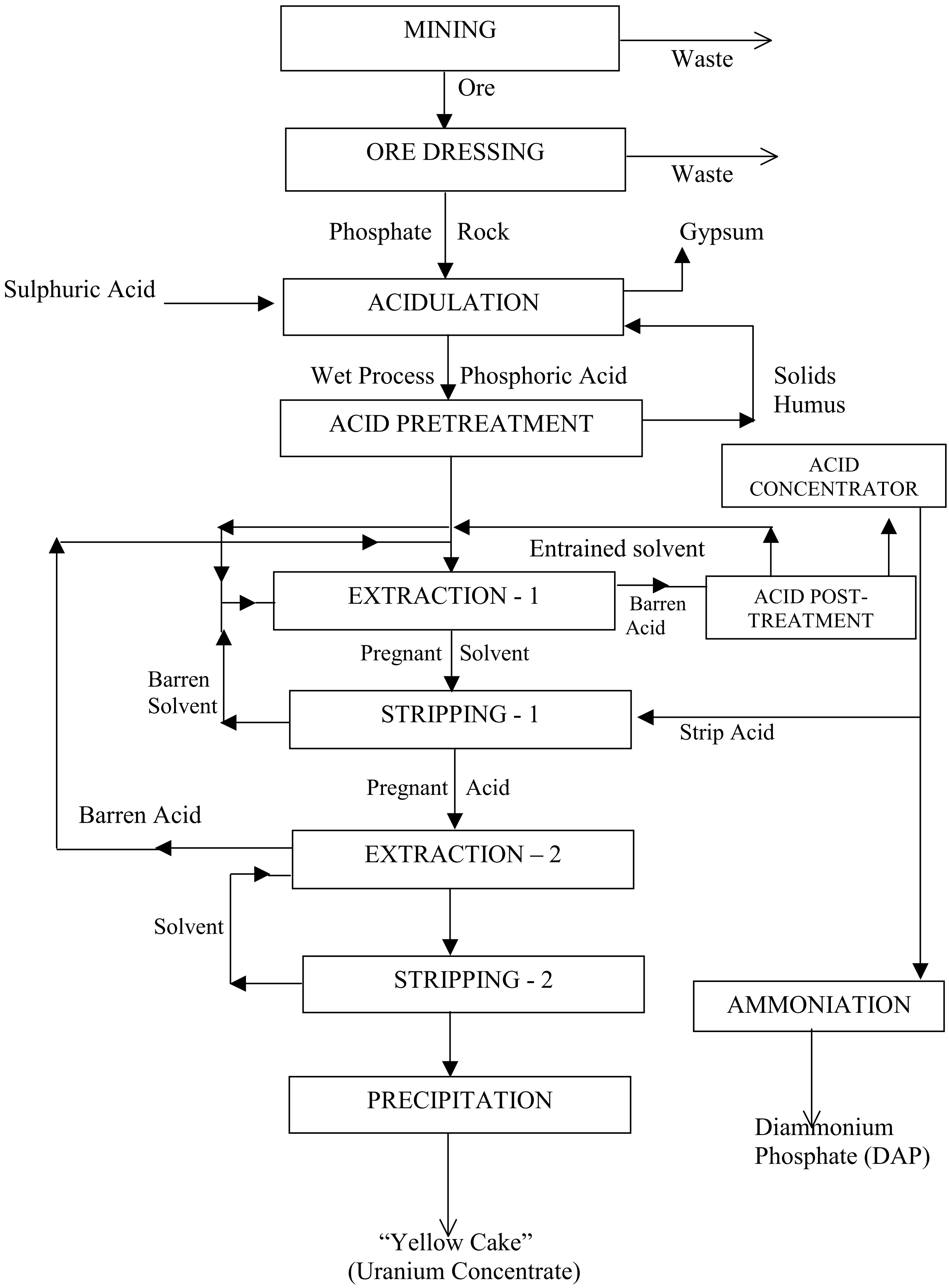

FIG. 1. Process schematic for uranium recovery from Phosphoric acid.

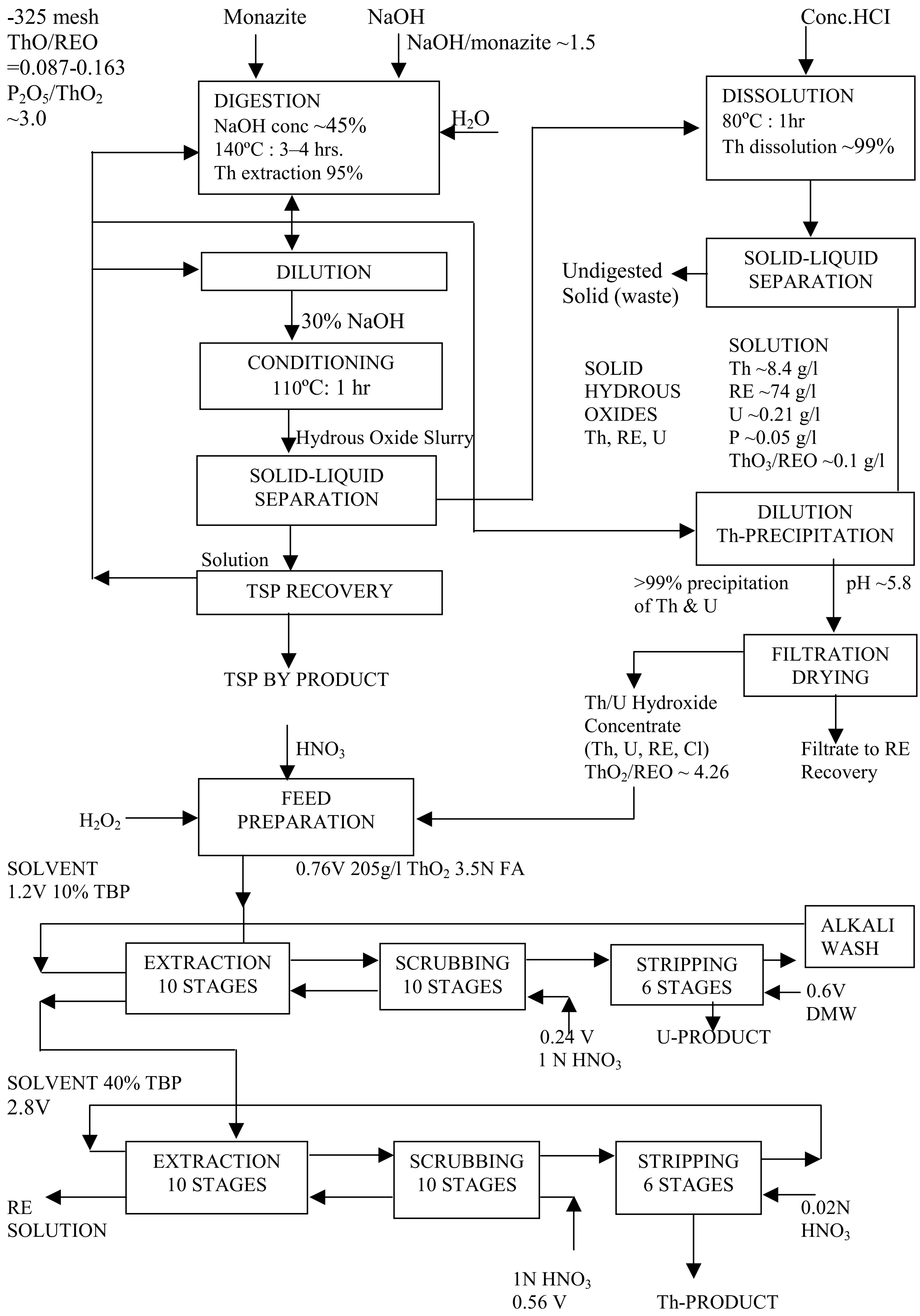

FIG. 2. Uranium and thorium recovery from Monazite.
TSP: Trisodium phosphate REO: Rare Earths Oxide RE: Rare Earths

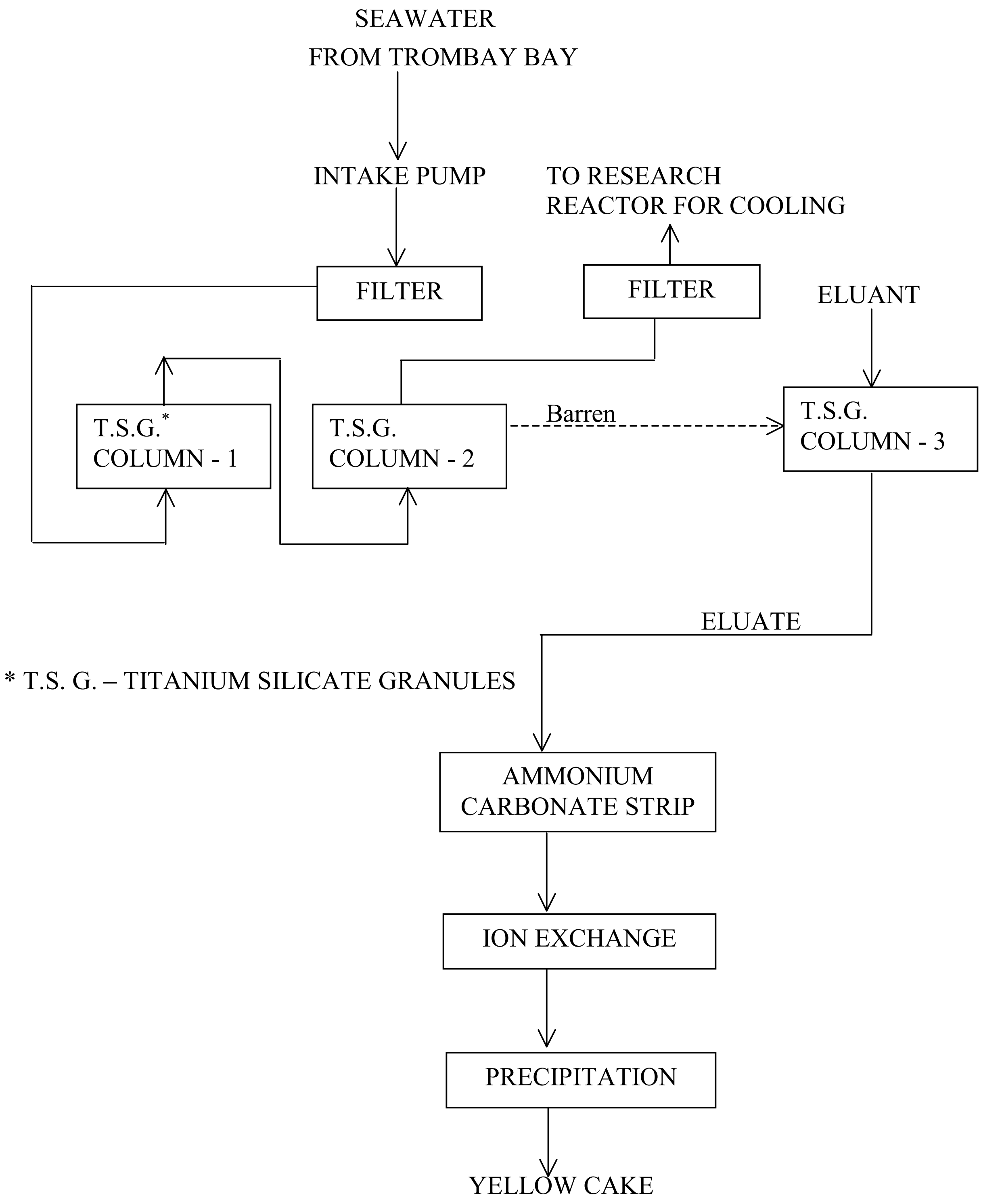

FIG. 3. Seawater uranium recovery by ion adsorption ("SURIA").

Uranium exploration in the Proterozoic Basins in India — Present status and future strategy, India

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Abstract. Proterozoic rocks of India as elsewhere in the world are the most favorable targets for uranium exploration. In the Peninsular India, these are well developed in the mobile belts or as peri/ intra-cratonic basins of early to late Proterozoic age and are called as Bhima, Cuddapah-Kurnool, Kaladgi, Chattisgarh, Vindhyan, Abujhmar, Delhi, Bijawar and Aravalli etc. Conceptual modelling and sustained multi-disciplinary, multi-faceted and comprehensive uranium exploration activities including remote sensing, aerial surveys, exploration geophysics, regional hydrogeochemical sampling, ground radiometry, exploratory drilling, and gamma-ray logging of borewells drilled for water during the last few decades have led to the identification of promising areas, besides establishing sizeable medium to large tonnage and low to medium-grade deposits of uranium. Proterozoic rocks exhibit diverse geological set-up as well as well known types of uranium mineralisation, right from Archaean-Proterozoic Quartz-Pebble Conglomerate-type in Karnataka to disseminated hydrothermal type in Singhbhum, where uranium mining is in progress. Of late, the major thrust of uranium exploration in India is directed on the structurally/fault controlled hydro-epithermal types in Bhima Basin, unconformity and fracture controlled type in Cuddapah-Chattisgarh basin. Besides, the albitite related mineralisation in Delhi fold belt and hydrothermal mineralization in the carbon phyllites and calcareous sediments of the Umra-Udaisagar area of the Aravalli region of Rajasthan are being relooked to locate commercially viable deposits. The current strategy of uranium exploration in India is to look for blind, high-grade deposits in analogy with those in the Athabasca basin, Canada, to achieve the goal of self-sufficiency for envisaged nuclear power generation programme of the country.

1. Introduction

Proterozoic basins of Peninsular India fall into two broad categories - (i) late Archaean -early Proterozoic surrounding the Archaean protocontinents and, (ii) middle to late Proterozoic basins, often called as "Purana basins" [1,2] formed largely on the continental anorogenic basement of Archaean to early Proterozoic granitoids, metasediments and metavolcanics as epi/peri/intracratonic basins. Exploration for uranium in India in the first category [3,4,5] was targetted to look for early Proterozoic Quartz Pebble Conglomerate type as in Karnataka, Bihar and Central India along the margins of Archean cratons or hydrothermal disseminated polymetallic vein type mainly in the Singhbhum province of eastern India [6] (where presently 3 uranium mines and a mill are located) or in the dolomitic limestone of the Umra area of Aravalli Supergroup, Rajasthan [4,5] which fall within the mobile belts. With the discovery of high-grade, large-tonnage unconformity-related deposits in the middle to late Proterozoic basins of Canada which constitute over a third of world uranium reserves, the Purana basins, such as Cuddapah-Kurnool, Bhima, Kaladgi, Chattisgarh, Indravati, Abujhmar, Vindhyan and others (Fig. 1) became the first order target for the uranium exploration in India [7,8,9]. Renewed exploration activities, based on conceptual modeling and the application of different techniques right from remote sensing, aerial survey followed by ground radiometric survey, regional hydrogeochemical sampling, ground geophysics, exploratory drilling and gamma-ray logging of borewells drilled for drinking water were taken up. During the last two decades this have led to identification of promising areas besides establishing sizable medium to large tonnage, low to medium grade deposits of uranium. Of late, the major thrust of uranium exploration in India is concentrated in the following basins to look for commercially viable deposits.

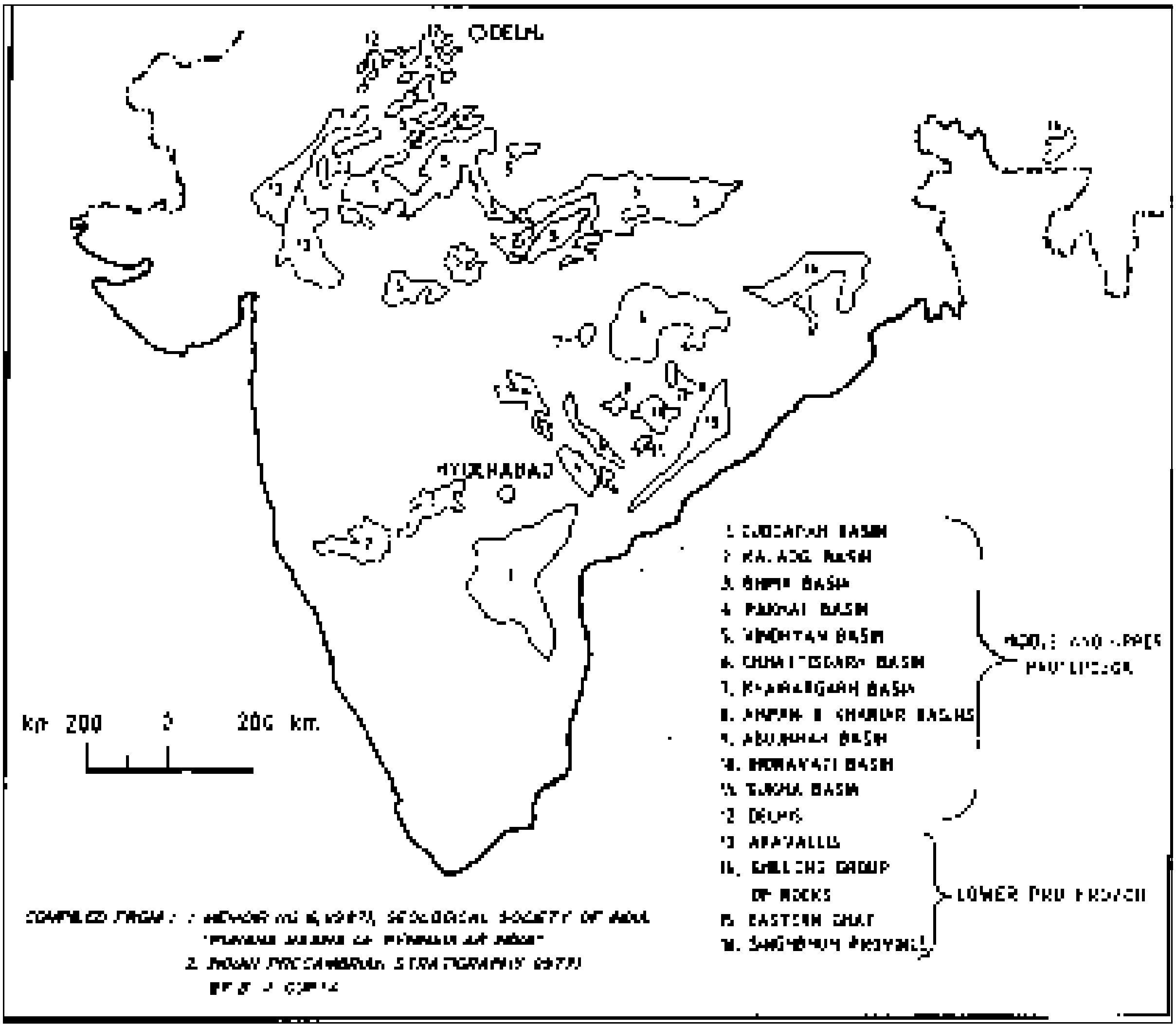

FIG. 1. Proterozoics of Peninsular India.

2. Structurally (fault) controlled U-mineralization in the Bhima Basin

In the southern Peninsular India, the Neoproterozoic Bhima basin assumes immense significance in view of its fertile provenance and structures dissecting both the sediments and basement crystallines (Fig. 2). Sustained exploration efforts, following the location of radioactive phosphatic limestone near the village Ukinal [10] based on remote sensing studies and gamma-ray logging of drinking water borewells led to the identification of potential and prospective medium to high grade uranium mineralized zone associated with brecciated limestone as well as underlying basement granitoid in the Gogi area, Gulbarga district, Karnataka [11,12].

Gogi area lies almost at the middle of the E-W trending Gogi-Kurlagere fault along the southern margin of the Bhima basin. Exposures of brecciated grey limestone of the Shahabad formation underlain by thin but fairly continuous bands of arenite and shale (Rabanapalli clastics) rests over the pink, coarse grained granite with marked unconformity. The dip of the shale bed is usually steep towards the granite basement indicating stratigraphic reversals. The adjacent limestone beds, as confirmed by drilling, also display similar dip along with brecciation indicating reverse nature of the fault. The non-conformity contact, also representing the reverse fault zone, trends E-W with a swerve towards N40°E and again swings back to E-W trend at NE of Gogi village. The present subsurface exploration is continuing in this area. So far, 28 boreholes have been completed, of which, a few intercepted steeply dipping and thick mineralized bands. Surface manifestation of the mineralization is scanty. The medium to high grade and large thickness of the mineralized bands intercepted in the boreholes is quite contrary to the lean and scanty surface occurrences [13].

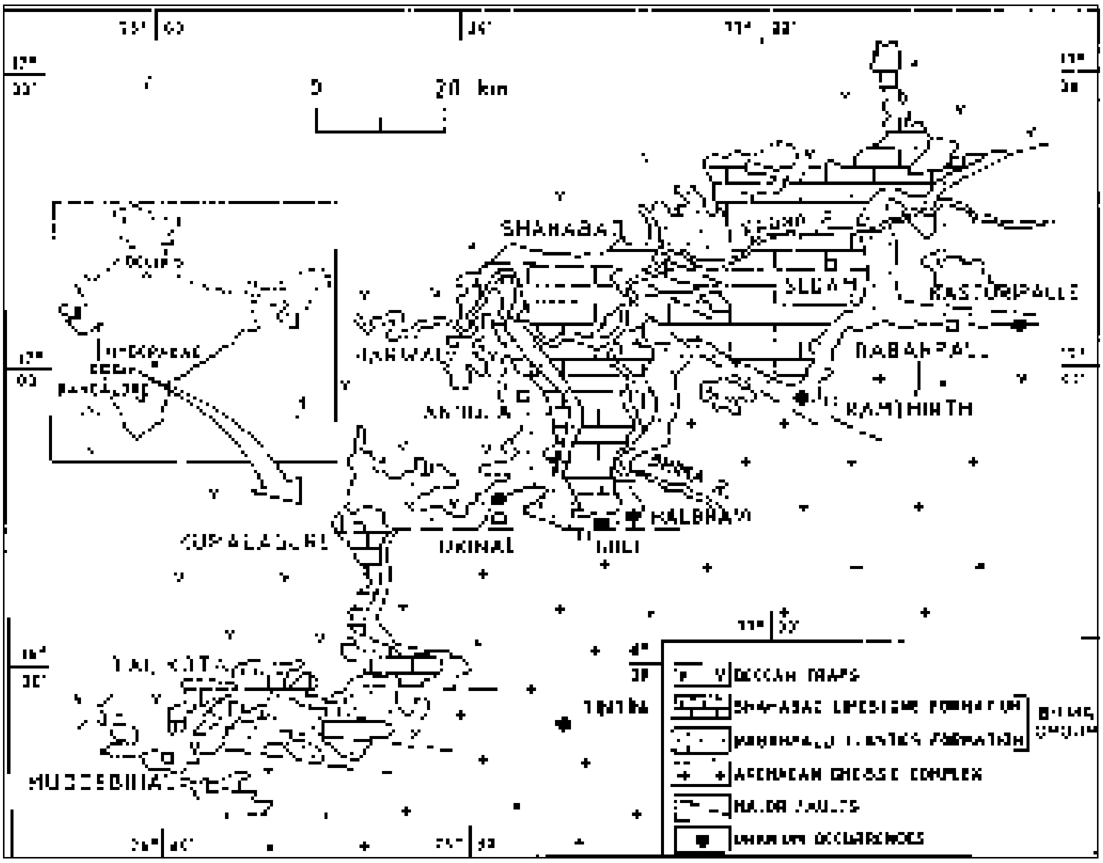

FIG. 2. Geological map of Bhima Basin showing uranium occurrences.

The mineralization has been established over a strike length of 600 m up to a vertical depth of 150 m. The mineralized intercepts vary between 0.10 and 1% U_3O_8 with thickness ranging from a few meters to tens of meters (Fig. 3). Proving the strike continuity and depth extension is underway and estimation of reserves is yet to be taken up.

Studies carried out so far indicate that the structurally-controlled, hydro (epi)-thermal vein type (veins and stringers) mineralization is confined to the intensely brecciated limestone ubiquitously rich in carbonaceous matter and/or sulphides within a moderately altered zone. Association of veins of pink and white calcite and silicification is an important feature. Main radioactive phases identified are coffinite and pitchblende. Uranium is also associated with organic matter, U-Ti complex and in adsorbed state. Coffinite is present as globular aggregates in close association with organic matter where it rims the borders of the latter with pyrite and galena. Pitchblende occurs as veins and it replaces pyrite and coffinite along margins and fractures. Other opaques are marcasite and chalcopyrite. Based on Electron Microporbe (EMP) studies, including computed chemical ages using UO_2, ThO_2 and PbO, more than two episodes of inter-related coffinite-pitchblende pyrite association are inferred. Low content of ThO_2 and RE_2O_3 (Total) in pitchblende and coffinite points to a low-temperature origin in an open system [13].

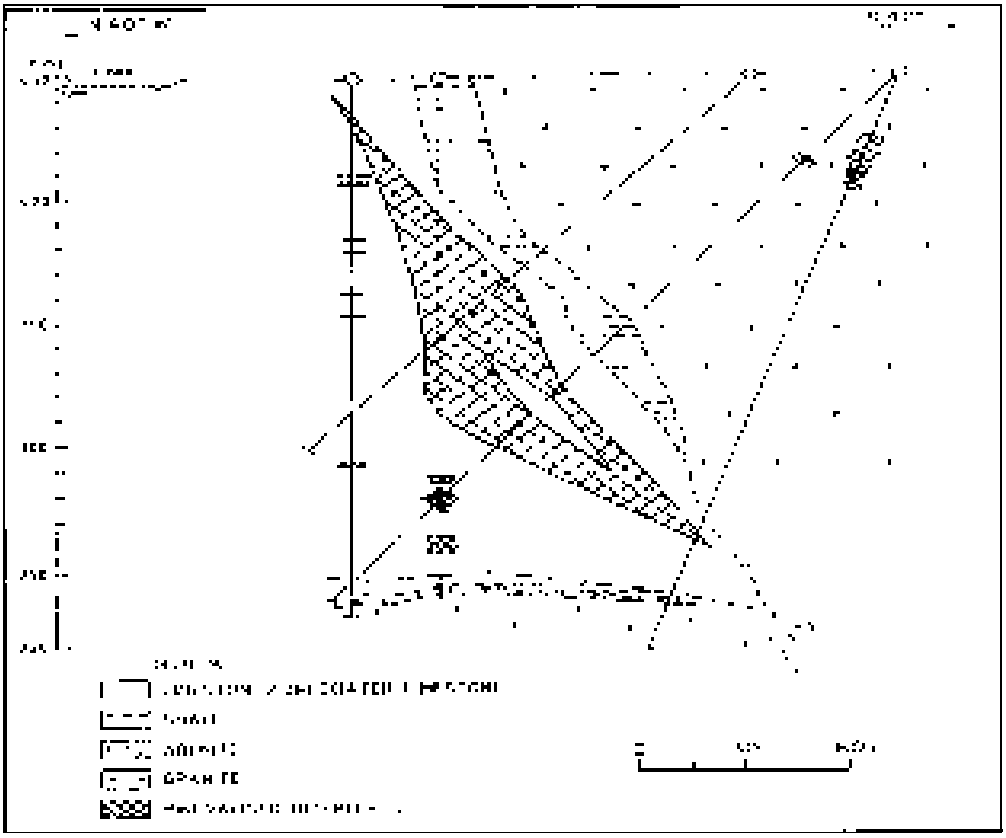

FIG. 3. Geological section across Gogi uranium occurrence.

Flotation tests were carried out on the Gogi ores to float the sulphides, carbonates and silicates separately. The tests did not indicate any marked enrichment of uranium values in any fraction or reduction of acid consuming gangue. However, two-stage sulphide flotation on -100# sample yielded sulphide float of 5.30% by weight analysing 20-40 ppm of silver. Alkali leaching conducted on -100 mesh size feed gave 87-90% leachability by using 25 kg Na_2CO_3/te, 10 kg $NaHCO_3$/te and 5 kg $KMnO_2$/te at 50°C over a contact period of 8 hours. This indicates the possibility of commercial extraction through alkaline route supported by sulphide production for by-product recovery, if the proved reserves are adequate and the deposit is viable for commercial mining [14].

Ground radiometric survey has resulted in locating uranium shows at several places along the unconformity contact in Bhima basin. In analogy of the Gogi occurrence, future strategy is planned to zero upon similar hidden deposits by widespread exploratory drilling along favourable contact (fault) zones. A number of uraniferous phosphatized limestone invariably located near the fault zones all along the basin margin will also be test drilled to know if the primary mineralized zones are occurring at depth.

3. Strata-bound and unconformity type uranium deposits in Cuddapah basin

The crescent-shaped middle to late Proterozoic Cuddapah basin is well known for a variety of mineral reserves [11]. Exploration for uranium in this basin was initiated during 1950s to explore quartz-pebble conglomerate type of uranium mineralization at the base of Cuddapah sediments. This phase of the investigations indicated basal Gulcheru Conglomerates as essentially thoriferous, therefore the surveys were discontinued in Cuddapah basin. Exploration for uranium was revived in 1984 following the discovery of uranium in the Vempalle Formation of Papaghni Group. These exploration efforts led to the identification of three distinct types of uranium mineralization. They are:

(A) Impure dolostone hosted stratabound uranium mineralization in the Vempalle Formation (Tummalapalle-Gadankipalle) Cuddapah district, Andhra Pradesh [15,16,17,18,19,20].
(B) Unconformity-type uranium mineralization in the brecciated basement granite and the unconformity interface with overlying Srisailam Quartzite (Lambapur-Peddagattu and Chitrial) of Cuddapah Supergroup and in the Banganapalle Quartzite (Koppunuru) of Kurnool Group, Nalgonda and Guntur districts, Andhra Pradesh [21,22,23,24,25,26].
(C) Biotite granite hosted, fracture controlled mineralization associated with cataclasites, mylonites and breccia zones, proximal to the basin margin (Lakkireddipalle Mulapalle), Cuddapah district, Andhra Pradesh [21,22,23,24].

3.1. Stratabound type

In the western and southwestern part of the Cuddapah basin, stratabound uranium mineralization considered unique in the world, is hosted by impure dolostone of the Vempalle Formation of Papaghni Group. A large number of surface exposures and high hydrogeochemical anomalies are located over an arcuate belt of 160 km from Maddimadugu near Cuddapah in the east to Chenchelumpalle near Dhone in the west (Fig. 4). Limited stretches of these have been explored by drilling in the early 1990s of which the best explored areas in the southern part were Tummalapalle - Rachakuntapalle where low dipping orebodies are fairly consistent, both strikewise and in depth, but does not exceed the grade range of 0.04 to 0.05% U_3O_8. The uranium mineralization is in the form of ultrafine pitchblende with pyrite as dissemination in collophane rich parts with minor phases of coffinite and U-Ti complex. The other associated sulphides are molybdenite, chalcopyrite, bornite, digenite and covellite. Over the 160 km belt, the uranium mineralization, though confined to the lower part of the Vempalle dolostone, is found at different stratigraphic levels with respect to the marker shale horizon and unconformity surface with basement. Low content of P_2O_5 (0.20 to 0.95%) and higher copper content (up to 0.40%) characterize the uraniferous horizon in the north in contrast to higher P_2O_5 (1.5 to 15%) and richer Mo (200 to 1260 ppm) and V (100 to 400 ppm) in the southern part.

In spite of a large tonnage of 15.000 tonnes of U_3O_8 contained in 29 million tonnes of ore at Tummalapalle with significant quantity of molybdenum, poor leachability (70%) through alkaline route and ultrafine size of pitchblende being unfavourable for physical beneficiation, the cost of extraction of uranium from this deposit is beyond the present day economics. As such, further inputs for subsurface exploration have been restricted and regional hydrogeochemical sampling northward in the basin is being continued.

In the exploration strategy earlier followed, the target horizon was the dolomitic limestone as mentioned and due to limitations of drilling, the unconformity surface below was not probed as the Gulcheru Quartzite was known to be thoriferous. However considering the success in locating unconformity type deposits in northern part and so much of U having moved in the basin from the highly uraniferous (Mahaboobnagar) basement granites, the current strategy is to test drill at few places the unconformity surface below the quartzites.

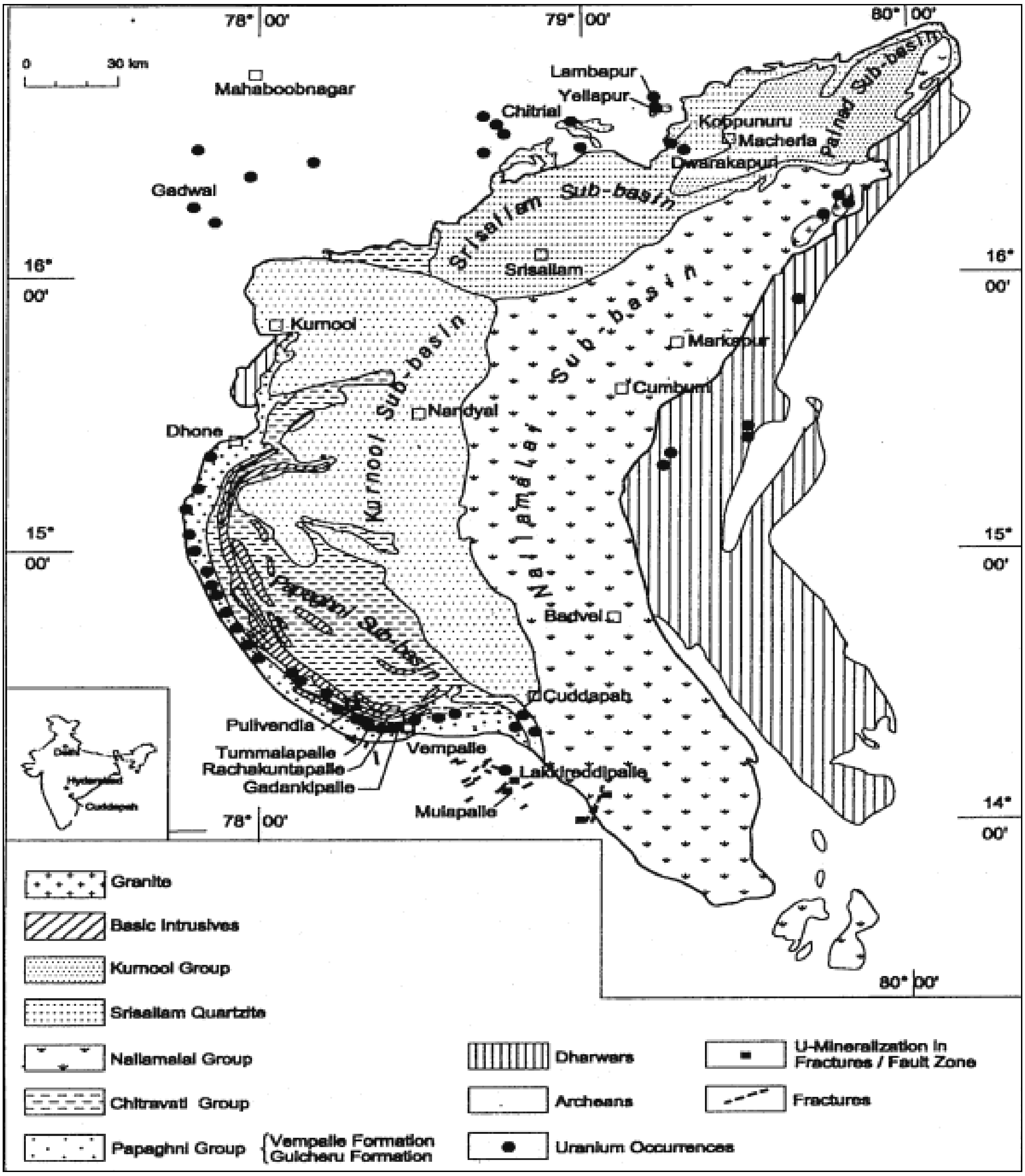

FIG. 4. Geological map of Cuddapah Basin.

3.2. Unconformity type

In the northwestern part of the Cuddapah basin, the youngest member of the Cuddapah Supergroup namely Srisailam Quartzite rests non-conformably over the basement of Archaean gneisses and lower Proterozoic younger granites (Mahaboobnagar granite), with ages of the latter ranging from 2268 ± 32 Ma to 2482 ± 70 Ma [23]. The main plateau (3000 sq km) has been dissected in a number of outliers and the radioactivity was first located in one such outlier at Lambapur. Exploration history, geology, structure, nature of orebody and controls of mineralization at Lambapur have already been described in detail [25] (Fig. 4). Medium grade uranium mineralization (as pitchblende/uraninite with galena, chalcopyrite and pyrite) of the order of 0.10% U_3O_8 is confined very close to the unconformity both in the quartzite and in granite within 40-60 m from the surface. Subsequently, conceptual drilling in the environs of

Lambapur has delineated two more consistent and promising mineralized blocks of Peddagattu-Yellapur outlier with significant reserves. The ores from both Lambapur and Yellapur are amenable to conventional hot agitation leaching by sulfuric acid. As the southern continuity of these blocks extends into the outer core of a "Tiger Sanctuary" area, environmental considerations put limitations for exploitation of the ore.

Further south-west, continued ground radiometric survey around Chitrial outlier (Fig. 4) in the Nalgonda district during the last two years has brought to light presence of similar high order mineralized horizon exposed intermittently all along the 7 km stretch in the basement granite just below the unconformity. Surface samples show both primary uranium minerals (uraninite/pitchblende and coffinite) as well as secondary minerals like uranophane, phosphuranylite and masuyite. The most striking feature of these granites is high content of Pb (more than 200 ppm) and their major and minor trace elemental data point out that they are of a low Ca-type [27]. As this outlier, though larger in aerial extent as compared to the other two blocks, also falls within the outer core of the "Tiger Sanctuary", drilling and mining activities are prohibited here under the Wild Life Act, though it holds a larger potential of uranium reserves and possibly better grades.

Keeping in mind these environmental constraints and to look for new grounds, based on satellite imagery and conceptual modelling uranium investigations were extended in the past few years to the Palnad sub-basin in the northern part where Kurnool Group of sediments (Banganapalle Quartzite and Nargi Limestone) rest either over the Srisailam quartzite or directly on the basement. Uranium mineralization in the current-bedded Banganapalle Quartzite was first reported at Koppunuru, a few meters above the unconformity surface unlike that at Lambapur. Exploratory drilling to test the depth continuity revealed the presence of another significant mineralized band with grades around 0.10% U_3O_8 just below the unconformity surface in the deeper part of the basin in addition to parallel zones both in the younger metasediments and along fractures in older basement. A large part of the Kurnool sediments has been upthrown along faults and the discovery of such unconformity-type mineralized zones outside the sanctuary limit has opened up vast areas for exploration in this late Proterozoic basin [27]. Further thrust for exploration of uranium in India will be in these geologically favorable environments.

3.3 Fracture-controlled, low-grade, hydrothermal type in the basement

In the southern part of the Cuddapah basin, the Archaean basement complex consists of older metamorphic rocks, gneisses and younger intrusive granites. The basement granite is subjected to intense dislocation metamorphism resulting in the formation of breccia, mylonites, cataclasite, and significant alterations along a number of shear zones, some of which are also occupied by quartz reef. Such fracture zones abut against the Cuddapah basin and are partially covered by metasediments (Narji Quartzite and Shale) dipping low towards the basin (Fig. 4). Uranium mineralization is seen in about 60 such fracture zones spread over an area of 50 sq km, prominent of which are at Mulapalle, Burjupalle, Payalopalle, etc. [28,29,30,31]. The major uranium minerals are brannerite and U-Ti complex with minor uraninite and pitchblende as well as coloured secondary uranium minerals. The uranium enrichment is envisaged by the scavanging of the fertile granitoid basement by hot aquous solutions and precipitation along the pathways provided by the fracture zones. Considering the existence of a predominently higher hydrogeochemical anomaly zone (>500 ppb) [24] and in analogy with such exploitable deposits elsewhere in the world, e.g., Romania, [32] some of these fracture zones have been drilled recently in India.

Geophysical survey has revealed that these fracture zones continue below the cover rocks. Limited areas are being tested by exploratory drilling through the sedimentary cover to look for blind deposit in anticipation of mobilization and further concentration along the unconformity surface where reductants could be present in the basement in analogy with pleasant surprises in the northern part of the Cuddapah basin.

4. Chattisgarh basin

The Chattisgarh basin, occupying an area of 33.000 sq km, is located in the central Indian shield and spreads over the states of Madhya Pradesh and Orissa. Integrated lithostructural analyses of satellite data, photo interpretation and critical appraisal of aero-radiometric data followed by ground radiometric survey helped in locating significant radioactivity in the following three distinct types of rocks in the Bargarh district of Orissa and Raigarh district of Madhya Pradesh (Fig. 5).

(a) Predominantly thoriferous activity in the basal conglomerate of Chandrapur Group along the eastern margin of the Chattisgarh basin (Samardhara - Khajuria tract) [33],

(b) Mainly uraniferous in the feldspathic grit with intercalated grey cherty members of Singhora Group near Juba [35,36,37],

(c) Uranium mineralization in quartzofeldspathic breccia/granite cataclasite occurring as linear outcrops (NNE-SSW) within the basement crystallines Sambalpur granite (2380 ±45 Ma) at Kasipali area, Bargarh district, Orissa.

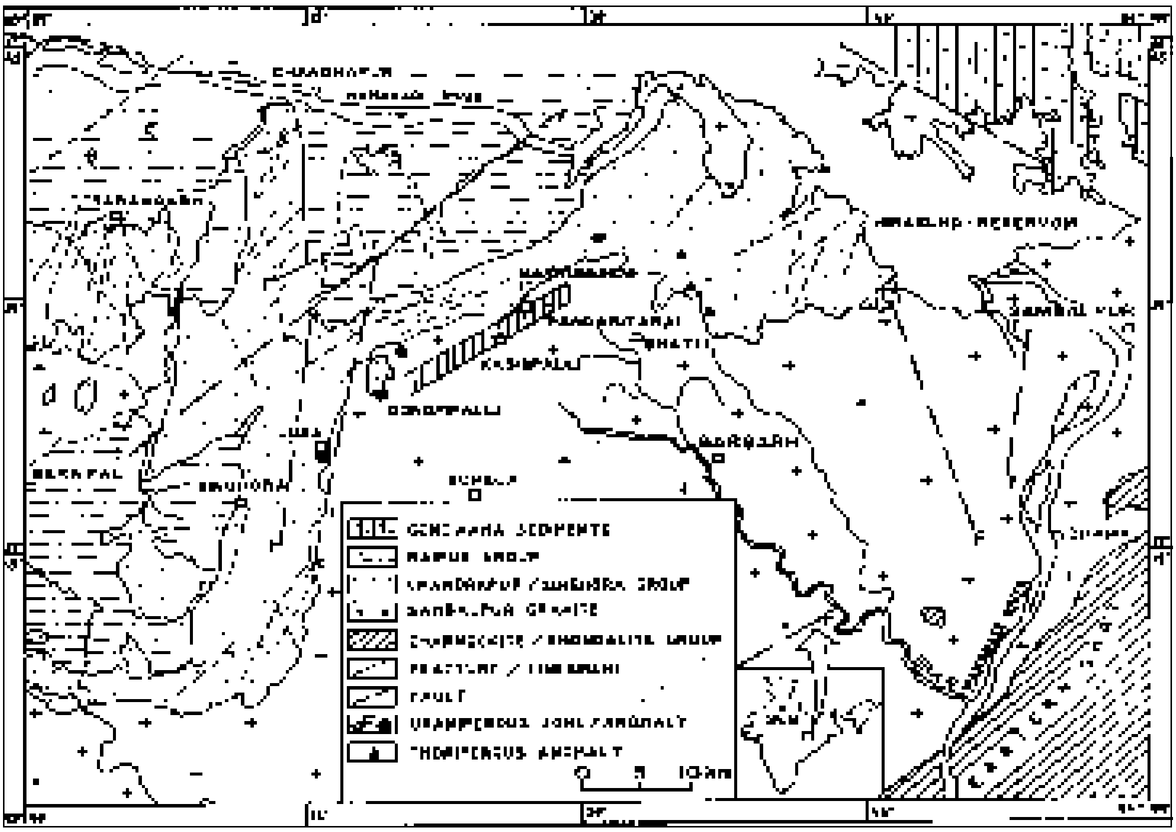

FIG. 5. Geological map of Eastern margin of Chattisgarh Basin, parts of Orissa and Madhya Pradesh.

Significant high-order uranium mineralisation was located in the brecciated granite (peraluminous type with A/CNK of >1.1 in mylonites, in quartzofeldspathic breccia as well as in sheared basic rock extending over considerable length (Kasipali, Makrumunda, Ghoghara) [34]. Primary uranium minerals, viz., uraninite, pitchblende and coffinite, and secondary uranium minerals like secondary brannerite, kasolite, uranophane and beta-uranophane are reported. Some of these NNE-SSW trending fracture zones continue upto the flanks of the Chattisgarh basin where 6 m thick paleosol has been reported [38].

Adjacent to Kasipali in the Sambalpur granitoid, in Raigarh district of Madhya Pradesh, similar uraniferous quartzofeldspathic cataclasites are known in Dongripalle area [37] where the altered cataclasite is extensively pervaded by ferruginous matter and radioactivity is attributed to brannerite, U-Ti-Fe complex and uranium adsorbed on ferruginous matter. This type of mineralization, replicating a geological set-up found adjacent to the Cuddapah basin, demands subsurface exploration, which has been just started in both the areas to look for uranium concentration at depth in the basement rock as well as below the sedimentary cover.

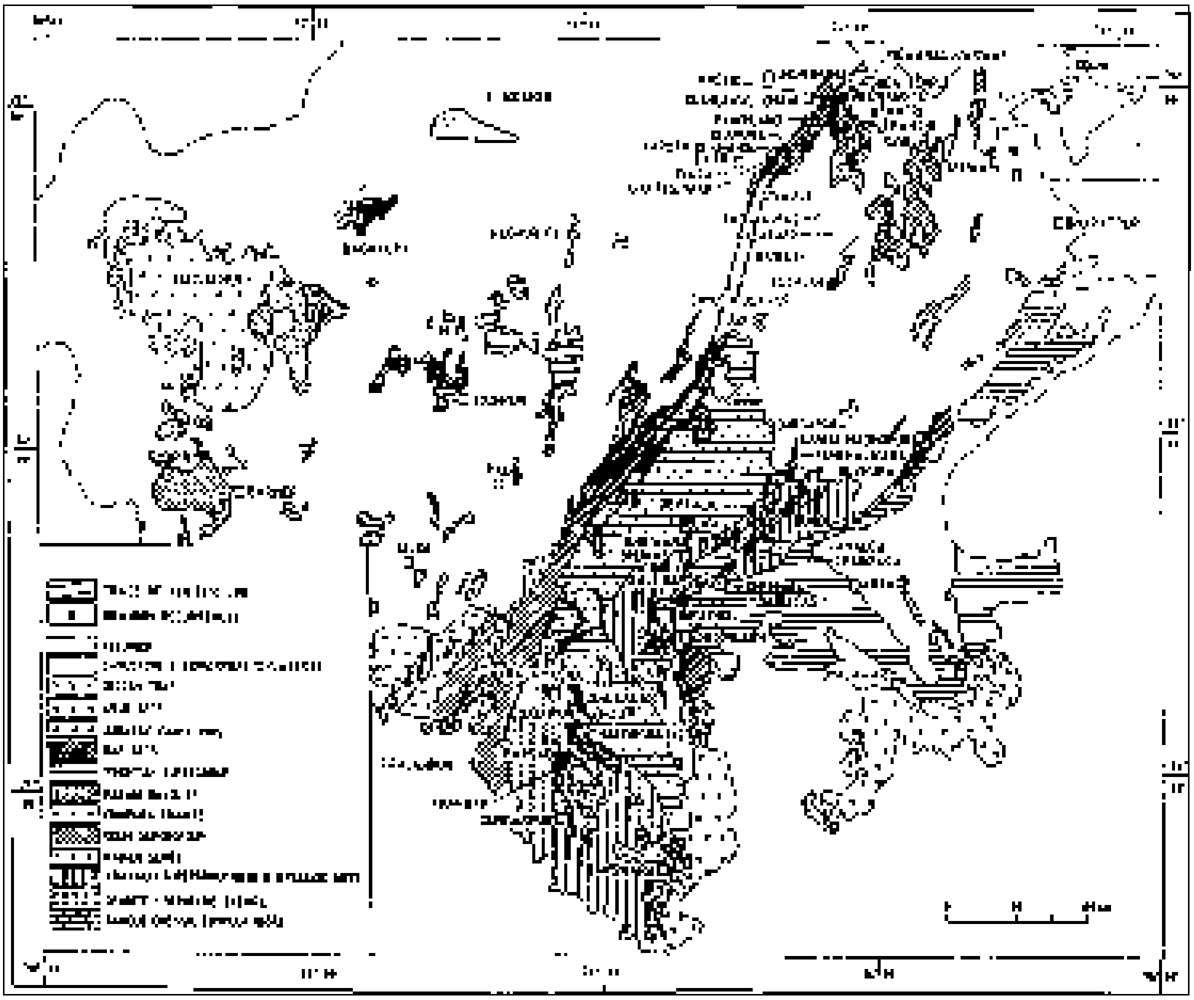

FIG. 6. Geological map of Rajasthan showing uranium occurrences.

5. Other basins

Uranium investigations have been carried out in 1980s in other middle to late Proterozoic basins in central Indian craton like Indravati and Abujhmar [39,40] in the Bastar district of Madhya Pradesh and Khairagarh basin [41] in the Bhandara district of Maharashtra. Many of these areas need to be searched again for both stratabound and unconformity types as the basement rocks are anomalously uraniferous with evidence of remobilisation of uranium into the basin.

Amongst the early Proterozoic basins like Aravalli and Delhi where hydrothermal uranium mineralization is hosted by the calcareous sediments as at Umra and Udaisagar [8,42,43,44,45] and all along the albitite zone [46,47] of northern Rajasthan, there are possibilities of finding better grades provided one can overcome the opaque areas in our knowledge of uranium mineralization and its control (Fig. 6).

Each deposit is a type by itself and is seldom repeated in the Earth's history with exact similarities and dissimilarities. Exploration inputs in India are, therefore being judiciously directed to achieve the goal of national self-sufficiency in uranium production.

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Uranium deposits of the Inkay - Mynkuduk ore field, Kazakhstan

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Abstract. As a result of the planned exploration of South Kazakhstan basin, the unique Chu-Syrdarya uranium region (ChSR) was discovered. The uranium ore of this region is located in the Cretaceous and Palaeogene sediments. Main ores are located in the Cretaceous sediments. The most interesting part of this region is the Inkay-Mynkuduk Ore Field (IMOF) containing 36% of the total ChSR resources and including 2 large deposits in the Cretaceous sediments. Uranium deposits are connected with the bed oxidation zones (BOZ). These zones extend in the aquifers up to 500 km from Tyan-Shan mountain system and create a regional redox front and uranium bodies. The BOZ role developed in the uranium mobilization from sediments when BOZ were developing in the aquifers and in the transportation and precipitation of uranium at the geochemical barrier of the redox front. Therefore it is proposed to name such deposits "BOZ deposits". In the area of the IMOF, 12.6 thousand wells amounting to 4.4 million m are drilled with a direct cost of $153 million. The IMOF contains 460 thousand tons of uranium. Ores are located in the easily permeable sediments in the form of extensive (up to 10-20 km) winding in a plane ore bands of up to 400-500 m in width. Productivity of the orebody amounts to 4-7.5 kg/m^2. Successful field in-situ leaching (ISL) tests were being carried out at both deposits. In the east part of the Mynkuduk deposit, effective uranium extraction is now being carried out. Taking into account the high concentration of uranium orebodies in the area and their favourable technological parameters, IMOF is priority area for industrial development.

1. Introduction

In 1956, the space connection between the uranium ore and boundaries of the yellow oxidated sand sediments of aquifers was revealed by geologists Mazin and Pechenkin (Uzbekistan). These oxidated sands were later named a bed oxidation zone (BOZ). Beginning in the 50s, the depression structure territories of the former USSR were subjected to extensive research to find uranium deposits similar to those discovered in Uzbekistan. Favourable conditions for the formation of a BOZ and uranium deposits connected with a BOZ were formulated soon as follows:

- Hydrodynamic situation of the artesian basin of infiltration type,
- Arid climate conditions of the ore deposition epoch,
- Favourable lithology-geochemical type of host rocks (gray-coloured, easily permeable sediments).

With these conditions in mind, the most favourable territories were the Southern regions of the former USSR, including Southern Kazakhstan. Investigations carried out here led to the discovery of the greatest uranium region in the world, Chu-Syrdarya (ChSR), which forms the foundation of the Kazakhstan's mineral base (Fig. 1).

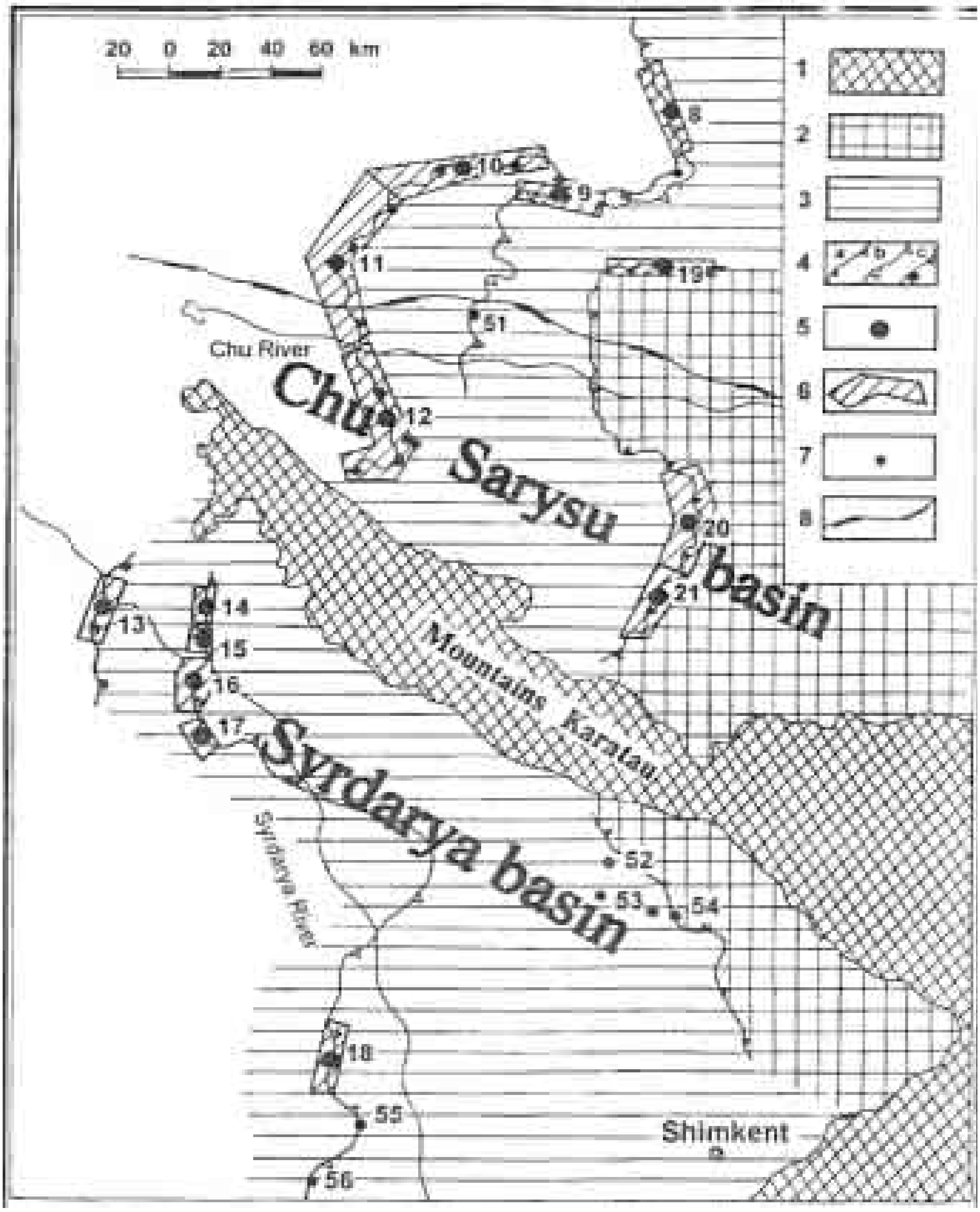
ChSR comprises the main parts of the Chu-Sarysu and Syrdarya basins separated by the Karatau Range and includes uranium ore both in Cretaceous and Palaeogene sediments. The most interesting is the ore in the Cretaceous sediments, amounting to 80% of total ChSR resources. The ore belt in the Cretaceous rocks extends for several hundreds kilometres and includes large and unique uranium deposits (Fig. 2). The portion of this belt located in the Chu-Sarysu Basin is the most productive and includes the Zhalpak, Mynkuduk, Inkay and Budyonovskoe deposits. The largest-scale, explored deposits in this part of the Cretaceous belt are the Inkay and Mynkuduk, forming the joint Inkay-Mynkuduk Ore Field (IMOF) including 460 thousand tons of uranium resources.

Deposits: 1) Kurday, 2) Botaburum, 3) Kyzylsay, 4) Djidely, 5) Manybay, 6) Balkashino, 7) Ishimskoe, 8) Zhalpak, 9) Akdala, 10) Mynkuduk, 11) Inkay, 12) Budyonovskoe, 13) Irkol, 14) North Karamurun, 15) South Karamurun, 16) North Harasan, 17) South Harasan, 18) Zarechnoe, 19) Uvanas, 20) Moyunkum, 21) Kanzhugan, 22) Sulushokinskoe, 23) Semizbay, 24) Koldjat, 25) Nizhne-Iliyskoe, 26) Kopalysay, 27) Zaozyornoe, 28) Agashskoe, 29) Shatskoe, 30) Glubinnoe, 31) Slavyanskoe, 32) Chaglinskoe, 33) Grachyovskoe, 34) Kosachinoe, 35) Fevralskoe, 36) Vostok, Zvyozdnoe, 37) Viktorovskoe, 38) Kamyshovoe, 39) Ulken-Akzhal, 40) Djusandalinskoe, 41) Melovoe, 42) Tomak, 43) Tasmurun, 44) Taybogar.

FIG. 1. Uranium deposits and ore regions in Kazakhstan.

Planned research of ChSR by drilling was begun in 1961. The first exploration was carried out in the territory of the Syrdarya Basin on the west Karatau Range incline. Exploration was undertaken with the understanding that the ore-forming BOZ expands from the Karatau Range. But the searches of the first stage did not lead to big discoveries. Only the small Kyzylkol and Chayan deposits were discovered.

The region of the Chu-Sarysu Basin was not initially a priority region due to a speckled-coloured type of Cretaceous sediments filling the Basin. The situation changed when the Uvanas deposit in the Palaeogene sediments was discovered in this region in 1963. Facies maps for every Cretaceous horizon of the Chu-Sarysu Basin were created. Using analysis of these maps the reconnaissance drilling profiles were carried out. These searches led to the discovery of the Zhalpak deposit in the upper Cretaceous sediments. In addition, the existence of the gray-coloured sediments in the Cretaceous series was demonstrated and occurrences of BOZ were revealed.



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 of Cretaceous sediments only, 4) Redox-front a) in Paleogene sediments, b) in Zhalpak horizon of the top of upper Cretaceous, c) in Mynkuduk-Inkuduk horizon of middle part of upper Cretaceous, 5) Industry uranium deposits amenable for ISL, 6) Ore fields of the industry uranium deposits, 7) Unprofitable uranium deposits, 8) North boundary of the artesian water.

Industrial depsoits: 8) Zhalpak, 9) Akdala, 10) Mynkuduk, 11) Inkay, 12) Budyonovskoe, 13) Irkol, 14) North Karamurun, 15) South Karamurun, 16) North Harasan, 17) South Harasan, 18) Zarechnoe, 19) Uvanas, 20) Moyunkum, 21) Kanzhugan
Non-Industrial deposits: 51) Sholak-Espe, 52) Kyzylkol, 53) Lunnoe, 54) Chayan, 55) Zhautkan, 56) Asarchik.

FIG. 2. Distribution of uranium deposits in the Chu-Syrdarya ore region in Kazakhstan.

Further researches led to the understanding of the regional character of BOZ development from the Tyan-Shan mountain system, located to the south, and not from the Karatau Range as was believed earlier. This fact essentially influenced the direction of exploration. It was established that BOZ has expanded over a long period since the Oligocene. In the Quaternary, in connection with the uplifting of the Karatau Range, the area of the BOZ redox front was separated in two places located in the Chu-Sarysu and Syrdarya Basins. The end of the BOZ or the BOZ redox front is located at the favourable gray-coloured channel sediments among speckled-coloured sediments of the flood plain and laguna facies, which really are extensive throughout the majority of the Chu-Sarysu Basin. The regional character of the BOZ expansion and the existence of large river systems in the Cretaceous created conditions for the formation of the almost continual ore-bearing BOZ redox front in the sediments of these systems, and thus, the formation of the greatest uranium region in the world. The most interesting part of this region, as was told above, is the IMOF.

2. Geological characterization of IMOF

2.1. Stratigraphy and formation history of the sediments and aquifers of the IMOF

The region of the IMOF is located at the edge part of the large Turan Plate in the central part of the Chu-Syrdarya Basin. The Basin is filled with friable sediments from the Cretaceous to the Quaternary. Lithified subplatform sediments of the middle-upper Palaeozoic lie in the foundation of the Basin. Friable platform sediments are continental Cretaceous of up to 320 m in thickness and shallow-marine and marine Palaeogene sediments of up to 200 m in thickness. The Cretaceous- Palaeogene series is overlaid by the red-coloured sandy-clay Oligocene- Quaternary rock complex. The formation of these sediments is connected with the young Alpine orogeny and mountain uplift in the East and, mainly, in the South-East in the region of the Tyan-Shan mountain system.

From the analysis of the regional history it is very important to emphasize the following: 1) the formation of the thick permeable Cretaceous series; 2) the universal existence of the overlaying marine Palaeogene clay series is able to play the role of regional upper confinement; 3) the intensive uplift of the Tyan-Shan mountain system in the Southeast of region, which allowed the active penetration of oxygen-bearing waters into the aquifer of the friable platform sediments; 4) the formation of the large infiltration type Chu-Sarysu artesian basin.

Cretaceous sediments, including all profitable uranium ore at the IMOF, play the main role in the sediment series of the region. Cretaceous rocks are sediments of the large alluvial plain and are, mainly, grained sediment from fine-grained sand to gravel. Clay rocks amount to not more than10-20% of series. In this case, clay beds, as a rule, have a small thickness and do not expand very much. This fact creates some difficulties in separating the series on the horizon and subhorizon. The separation of such stratigraphic units is very important for jointing ore intervals at different well profiles. This was especially important during the first stages of the search, when the inexplicit jointing could lead to mistakes in choosing the direction and in density exploration well profiles and leading to lagging exploration tempos and cost increases.

Using the data of the sediment cycle and electro-logging (Fig. 3), Cretaceous sediments were separated on the 3 horizons with an increase in thickness in an East-West direction. There are different opinions about the age of these horizons. After consideration, the European stratigraphic scheme was accepted. Nevertheless, the original horizon names will be used as was accepted in practice.

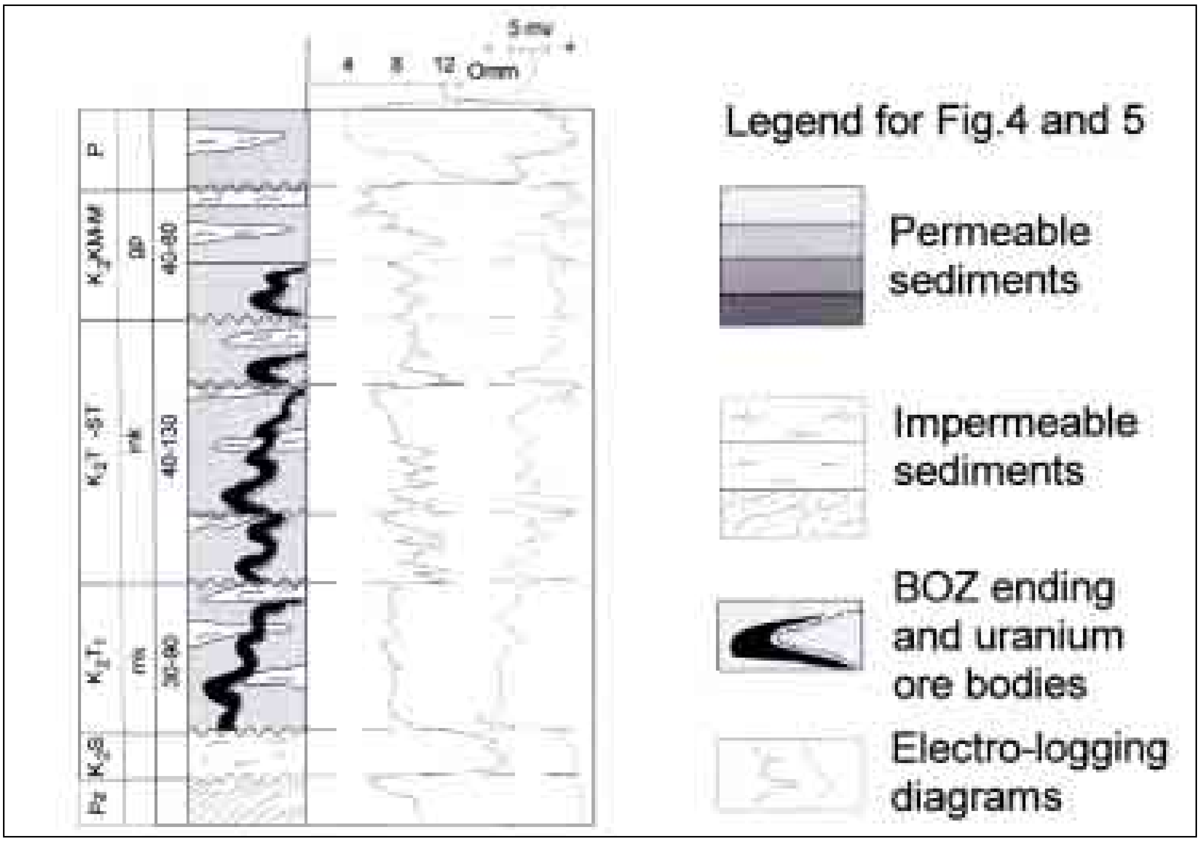


FIG. 3. Lithology – stratigraphical column of IMOF.

The lower horizon is mynkuduksky (mk), dated as Lower Turonian. The thickness of the horizon varies from 30 up to 90 m. All of the lower part is generally made up of more coarse-grained sediments. The upper part, being the end of the alluvial cycle, is made up of more fine-grained sands. Uranium ore is located, mainly, in the lower part of the horizon.

The superstratum inkuduksky horizon (ink) dates to the Upper Turonian-Santonian, is the most thick (130–150 m). The mynkuduksky horizon is separated clearly on three subhorizons (mk_1, mk_2, and mk_3). These subhorizons are not separated by clear confinements, but their alluvial cycle characteristic allows us to separate them as individual units of a series. Uranium ore is generally located in the lower and middle subhorizons.

The upper horizon, called the zhalpaksky and dated as Campanian- Maastrichtian has been researched the least because it includes uranium ore in the East part of IMOF only (Akdala section). The sediments of this horizon are characterized by less granularity and higher organic carbon content in the lower part of the horizon.

Cretaceous sediments are 80–90% grained rocks. Sands in the mynkuduksky horizon are, mainly, presented by medium-grained, and the inkuduksky contains hetero-grained sand with gravel. The mineralogical sediment content presented in Table 1 shows that 80% of consist is practically insolvable debris.

The tectonic elements and structural features of the Palaeozoic basin foundation surface feebly influence the distribution of the orebodies in the Cretaceous sediments within the IMOF area. Nevertheless, such influence at the Mynkuduk deposit is revealed in the locations of Akdala and East sections and in the orientation of the Central section (Fig. 7). At the Inkay deposit, the connection of the orebodies with the structural elements is less noticeable.

The Cretaceous and Palaeogene sediments are hydrogeologically complex, including a huge volume of the underground waters of the artesian Chu-Syrdarya Basin. The area of recharge is watershed of the Tyan-Shan mountain systems. The Tyan-Shan caused the hydrodynamic regime of Basin and the NW direction of the underground water movement. This direction was preserved despite the Karatau Range uplift in the Quaternary. The uplift of the Karatau Range had little influence on the basin hydrodynamic. Change of the mineralization and the direction of the underground waters are noticeable near the Range only, and are practically non-existent in the IMOF region. The discharge of the underground waters occurs in a direction away from IMOF. The natural velocity of the ground waters movement is not more that 2m/year. Mineralization of Cretaceous waters varies from 1 to 6 g/l. The Palaeogene water is fresh. It is a water source for use by the local population. IMOF aquifer characteristics are shown in Table 2.

2.2. BOZ development, formation and morphology of ores

The BOZ is a unique geological element of the environment of Southern Kazakhstan and greatly influenced the development and formation of the uranium ore. It is very important to examine the BOZ peculiarities because their existence is the main factor contributing to the development of such a large-scale ore formation.

The BOZ extends 500 km from the Tyan-Shan mountain range. The infiltration nature of the artesian basin and continued (beginning from Oligocene) period of BOZ development created very favourable conditions for BOZ expansion. In addition, the mostly speckled-coloured character of the basin sediments did not require essential oxygen consumption as the oxygen-bearing waters filtered through the permeable sediments. Therefore the redox front expanded such a significant distance and is located in the gray-coloured sediments of the palaeovalleys of the latitudinal extension at the Mynkuduk deposit and the meridional extension at the Inkay deposit. Karatau uplift did not influence the redox front position and formation of the orebodies. In any case, specific curvatures of orebodies in plan (Figs 6 and 7) show NW Tyan-Shan waters movement vector.

Expanding on the significant distance, the BOZ oxidated the large volume of sediments. The BOZ also mobilized and transported a large uranium quantity of uranium from the oxidated rocks. At the same time, organic material was also oxidated with the generation of hydrocarbon gases on the redox front. The accumulation of hydrocarbon gas has been determined through the analysis of drilling core samples. Grade hydrocarbon gases exceed normal level on the redox front up to 4-8 times. This fact is very important because it explains the large-scale ore formation on the redox front. The matter is that the mynkuduk and inkuduk horizon sediments are characterized by a low organic carbon content (not more than 0.04%). This quantity is, apparently, not enough for the creation of the essential reducing conditions. Therefore, the role of gases in assisting the creation of the essential reducing conditions is exceptionally important. The influence of the gas could also help explain the existence of the orebody over such a large area. In this way, BOZ directly fulfilled several functions. These include uranium mobilization from oxidated sediments and transportation in a dissolved condition over significant distances; reduce condition formation on the redox front; uranium precipitation on the redox front. In this case, the BOZ is the ore-generating and ore forming agent. Therefore, the uranium deposits formed in the friable sediments at the redox front should be named the BOZ deposit, as we name, for example, the vein deposits.

BOZ does not end simultaneously in the series as a whole. In connection with the different permeability levels of the different horizons and subhorizons, the BOZ is separated on several oxidation tongues penetrating the bed dip at different distance (Fig. 4). The inkuduk horizon has the most permeability, as will be shown below under the deposits descriptions. Therefore, the redox front in the inkuduk horizon extends the 10-18 km further than in the mynkuduk horizon (Figs 6 and 7).

In connection with the alluvial character of sediments, separated horizons and subhorizons are large sediment macrocycles. They are separated on the great number of microcycles with different permeability, in which small tongues from 1-2 to 5-10 m in thickness are developed. At the ending of such tongues, in favourable conditions the orebodies are formed as rolls with different extension wings, and bed bodies which have a form depending on the lithological composition of sediments. Different conditions caused the variety of the morphology orebodies (Fig. 5). Nevertheless, the main morphology elements are the bag part and wing parts of the rolls. The bag part attains some 10-20 m in thickness, and the wing parts attains several metres as well. Uranium ore extends sometimes along the redox front for 10–20 km, forming the highly profitable orebodies.

3. Description of the uranium deposits

The IMOF is part of the Cretaceous ore belt, and includes the Inkay and Mynkuduk deposits. Generally speaking, the boundaries establishing between deposits in the cretaceous ore belt is great conventionally. They are determined by the organization of the exploration works, the carrying out of field ISL test, the conditions of the reserves calculation and their approval in the State Reserve Commission. Nevertheless, the Inkay and Mynkuduk deposits are located in different channels system and this fact caused some differences.

3.1. Inkay deposit [2]

The Inkay deposit extends 65 km from north to south with a width of 18 km, and is the largest deposit of Kazakhstan (Fig. 6). Ore is located in the different subhorizons of the mynkuduk and inkuduk horizons, forming 9 productive beds with different productivities on the extension. The depth of orebodies is from 260 to 525 m.

Research of the deposit was carried out from 1976 to 1991. For this period, in the area of the deposit 4623 wells of 2.027 thousand m volume were drilled at a cost of $82 million (determined by the rate of rouble). The ore zone is continually traced throughout the whole area. The area of the deposit was separated into the 4 sections (Fig. 6). Details of ore determined by exploration works shown in Table 3. The most detailed works have been carried out at the sections №1 and №2 (96% of total RAR). In addition, at the section №1 the field ISL test has been carried out and this section has been prepared for industrial activity in accordance with the State Reserve Commission conditions.

The ore at the Inkay deposit has been researched in the all horizons and subhorizons. Most of the detailed works in the mynkuduk horizon were carried out at the section №1. Here the ore zone is 95% located in orebody extended over 11 km, and 706 thousand metres of wells were drilled. The distribution of uranium ores in the horizons, taking into account the researching in detail, is shown in the Table 3. The inkuduk horizon including 65% ores is the main ore-bearing horizon at the Inkay deposit.

Both horizons are filled, mainly, by permeable rocks. Presented in Table 4 is the distribution of the permeable and impermeable sediments on the horizons, showing that 80–90% Cretaceous sediments are permeable rocks. Permeable sediments in the mynkuduk and inkuduk horizons essentially differ in their granulometric composition (Table 5). In the mynkuduk horizon, the medium-grained sand is predominant (65%) and in the inkuduk horizon the role of coarse-grained sand and gravel essentially increases (35%). In addition, comparing the granulometric composition of the ore sands and non- ore sands reveals no practical differences.

The orebodies in the cross-section have a roll form with developed bag and wing parts. Bed orebodies are more uncommon. The redox front in the plan is very winding, therefore, under the 65 km deposit extension the total length of the redox front in all the subhorizons is 427 km in the mynkuduk horizon and 726 km in the inkuduk horizon. In this connection, the ore-bearing portion of the deposit essentially increases.

Table I. Mineralogical content of Cretaceous sediment sands of the IMOF on the horizon, %

	Minerals	Mynkuduk-sky, mk	Inkuduk-sky ink	Zhalpak-sky, gp
Insolvable	Quartz	65.01	71.02	74.45
	Siliceous debris	14.05	12.55	6.21
	Accessory minerals	0.03	0.06	0.10
	Total	79.09	84.53	80.76
Hardly dissolvable	Feldspar, muscovite, biotite, caolinite, montmorillonite, limonite	20.23	14.94	18.21
Dissolvable	Calcite, siderite, pyrit, marcasite	0.68	0.53	1.03
	Total	100	100	100

The ore is presented by coffinite (18%) and nasturan (82%). The technological parameters of the ore, presented in Table 6, demonstrate favourable peculiarities of the Inkay deposit ore for the ISL method. This conclusion is confirmed by the result of the field ISL test using sulphuric acid technology. The recovery coefficient of the test is 84.7% with an acid consumption of 47.7 kg/kgU.

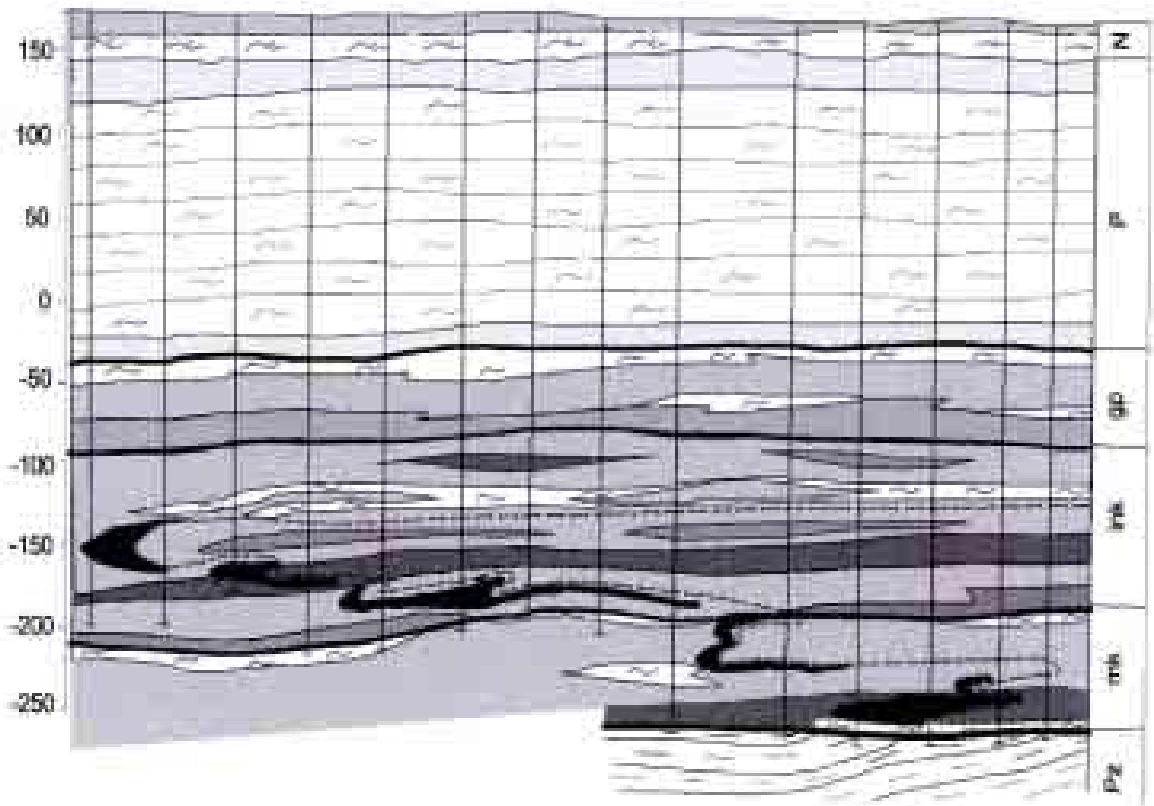


FIG. 4. Schematic cross-section of Cretaceous-Paleogene series at the IMOF.

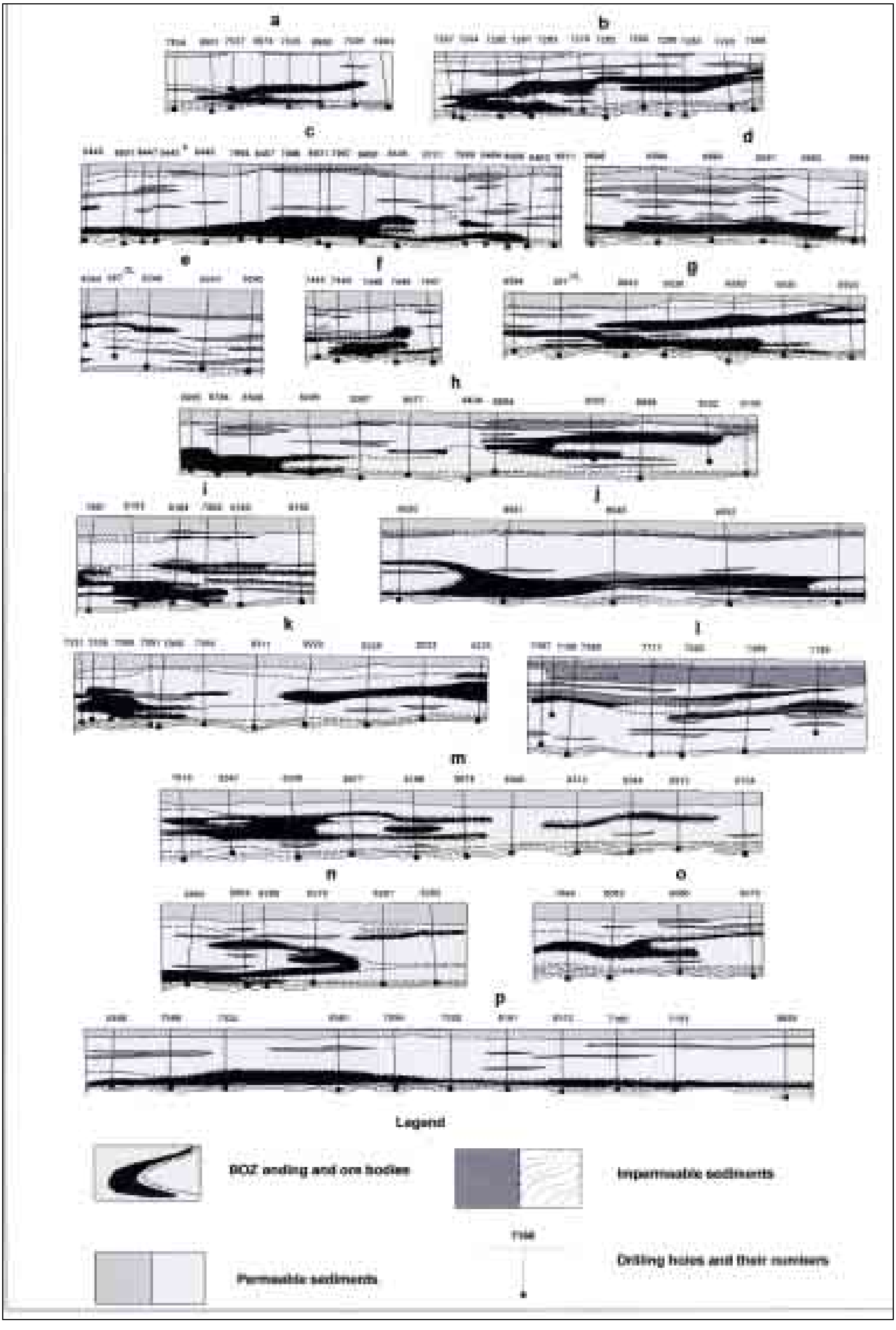


FIG.5. Orebodies morphology of Inkay-Mynkuduk ore field.

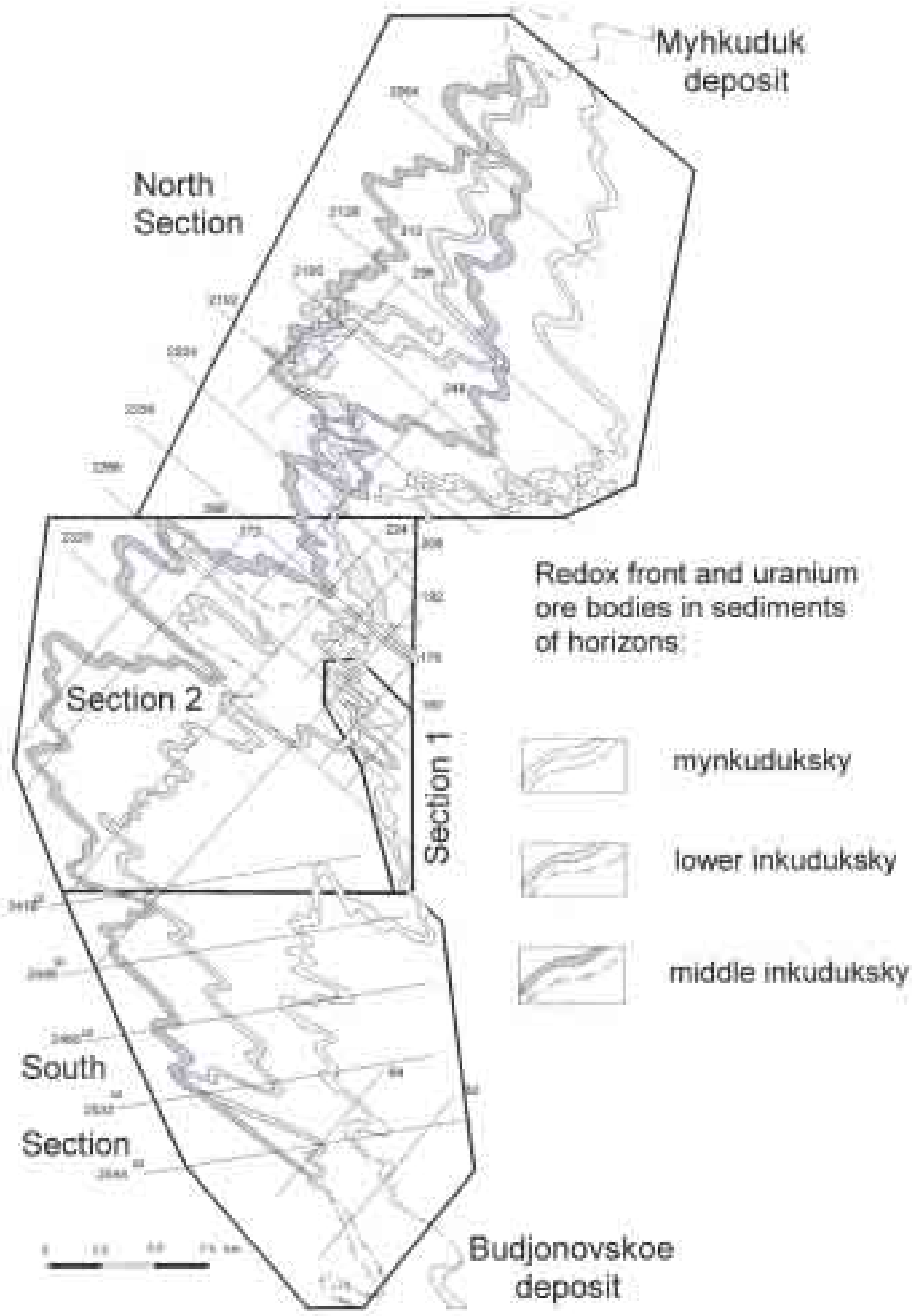
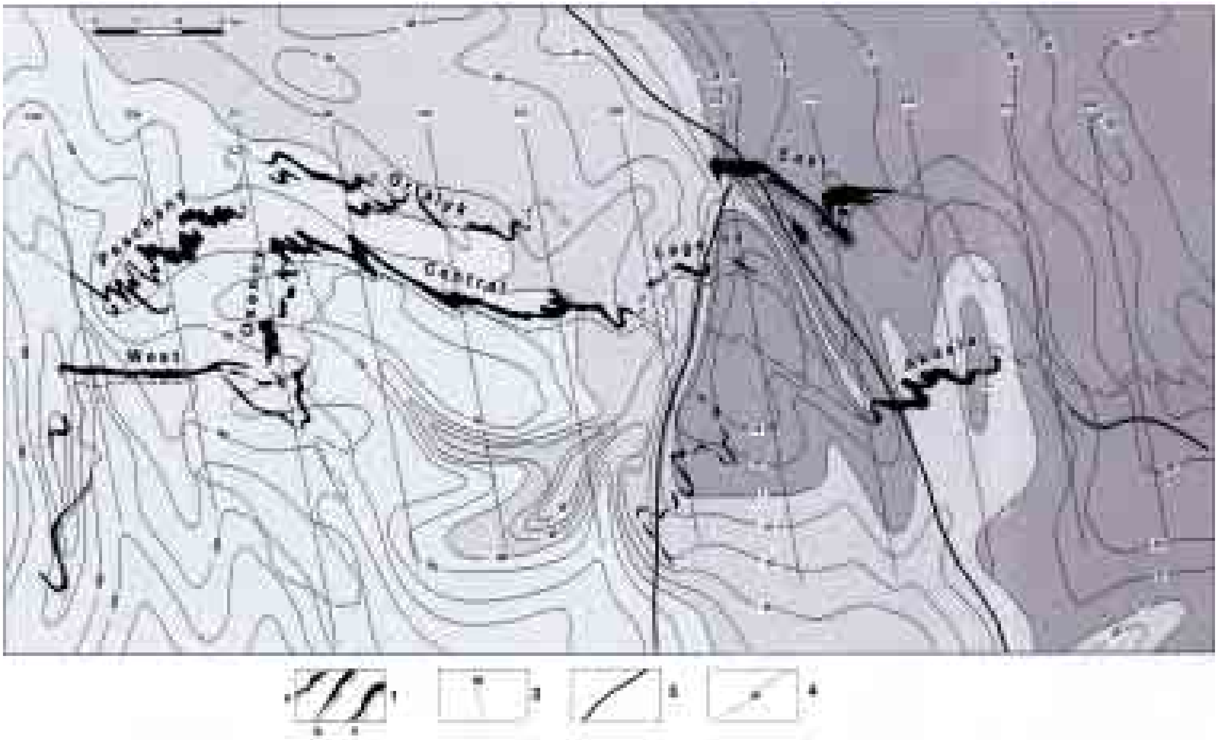


FIG. 6. Orebodies situation map of Inkay deposit.



1) Redox front and uranium orebodies in horizons: a) Zhalpaksky, b) Inkuduksky, c) Mynkuduksky, 2) Profiles of drilling holes, 3) Faults, 4) Isohypses of Paleozoic foundation surface.

FIG. 7. Orebodies and section distribution at the Mynkyduk deposit.

3.2. Mynkuduk deposit [1], [3]

The Mynkuduk deposit is the continuation to the East of the Inkay deposit, and extends 65 km from West to East. Exploration at the deposit is completed (the RAR is 95%).

Exploration was carried out from 1975 to 1989. During this period, 7955 wells were drilled with a total volume of 2373 thousand metres volume. Costs were $71 million.

As distinct from the Inkay deposit, the sections with nature boundaries are presented at the Mynkuduk deposit (Fig. 7). The most interesting sections (Table 7) are the Central (36.9% of RAR) and East (21.8% of RAR).

Orebodies, mainly, are located in the mynkuduk horizon sediments (76%). The inkuduk and zhalpak horizons include, respectively, 11% and 13% (Table 7).

All horizons are presented, mainly, by permeable sediments (Table 8). As distinct from the Inkay deposit, the sediments of the Mynkuduk deposit are characterized by relatively uniform consist. Medium-grained and fine-grained sands are predominant except in the inkuduk horizon in which the presence of coarse-grained sands and gravel noticeably increases (Table 9).

Table II. Parametres of aquifers of IMOF

Horizon	Deposit	Horizon thickness, m	Depth of piezometric level, m	Yield of well, l/s	Filtration coefficient, m/d	Mineralization, g/l	Compound
Zhalpaksky	Mynkudyk	40-75	15-75	1-8	1.5-8.8	3.3-5.8	Sulphate-hydrocarbonate, sulphate-chloride soda
	Inkay	40-60	+16-28	1.7-14.3	5.5-12	0.9-1.3	Chloride soda, chloride- sulphate soda
Inkuduksky	Mynkudyk	40-85	12-71	0.5-8	3.7-13.4	4.7-5.4	Sulphate-chloride soda
	Inkay	110-130	+5-50	1.3-18.3	2-20.6	2.1-3.1	Chloride soda
Mynkuduksky	Mynkudyk	45-80	16-92	3.5-12.5	5-20	3.2-6.0	Sulphate-chloride soda
	Inkay	30-90	+5-50	1.5-16.6	2-11.9	3.3-4.5	Chloride soda, sulphate-chloride soda

Table III. Exploration degree of the Inkai deposit on the horizons and sections, %

	RAR	EAR-1	Total
Deposit Inkay, as a whole	47.3	52.7	100
Including on the horizons:			
Mynkuduk horizon	17.8	17.2	35
Inkuduk horizon	29.5	35.5	65
Including on the sections:			
Section №1	13.0	--	--
Section №2	32.5	--	--
North section	--	26.6	26.6
South section	1.8	26.1	26.1

Table IV. Permeable and impermeable sediment distribution at the Inkay deposit on the horizons, %

Type of sediments	Horizons	
	Mynkuduksky mk	Inkuduksky ink
1. Impermeable sediments:		
clay and aleurite	20	10
2. Permeable sediments:		
medium-grained and fine-grained sand	65	30
hetero-grained and hetero-grained sand with gravel	10	30
gravel	5	30

Table V. Weighted average gradation of permeable sediments of the Inkai deposit on the horizons, %

Horizons	Gradation classes, mm						
	>2	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	<0.05
Horizons, as whole							
Mynkuduksky	3	3	4	56	13	6	15
Inkuduksky	14	9	12	38	7	6	14
Ore sand							
Mynkuduksky	4	4	6	45	19	6	16
Inkuduksky	18	9	12	35	8	4	14

Table VI. Uranium ore parameters of Inkay deposit

Parameters	Sections			
	South	№1	№2	North
Mynkuduk horizon				
Depth of orebodies, m	510	515	480	430
Square productivity, kg/m^2	4.4	7.5	5.0	3.2
Average orebodies thickness, m	6.28	6.08	5.83	3.50
Average grade, %	0.041	0.072	0.050	0.054
Average orebodies width, m	150	400	350	100
Filtration coefficient, m/d	7.1	11.6	13	11.9
Mineralization, g/l	4.5	3.3	3.5	3.3
Depth of piezometric level, m	+5-25	12-22.5	20.7-33	23-50
Average carbonate contents, %	0.3	0.3	0.3	0.2
Reserve share, %	32.9	35.3	10.2	21.6
Inkuduk horizon				
Depth of orebodies, m	350-420	430	330-380	290-370
Square productivity, kg/m^2	4.1	3.9	4.6	4.5
Average orebodies thickness, m	4.2	4.9	7.4	5.2
Average grade, %	0.057	0.047	0.037	0.051
Average orebodies width, m	200	100	250	200
Filtration coefficient, m/d	7.9-19	11.7-17.8	11.5-20.6	7.3-11.2
Mineralization, g/l	3.1	3.0	2.7	2.1
Depth of piezometric level, m	+5-25	2.5-22	10.5-30	23-48.5
Average carbonate contents, %	0.2	0.1	0.2	0.1
Reserve share, %	25.2	0.9	44.5	29.4

Table VII. Reserve distribution with ore parameters on the horizons and sections at the Mynkuduk deposit

Horizon	Sections	Average U grade, %	Productivity, kg/m^2	Reserve share, %
Mynkuduksky	East	0.030	4.20	21.8
	Central	0.047	5.73	36.9
	Osenny	0.037	3.63	7.5
	West	0.038	3.90	7.5
	Lagerny	0.025	3.03	2.3
Total		0.040	4.81	76
Inkuduksky	Ortalyk and Peschany	0.028	2.86	11
Zhalpaksky	Akdala	0.057	6.35	13

The ore occurs in all types of permeable sediments. At the deposit, 3 lithologo-filtration types of sediments are separated: 1-gravel, 2-hetero-grained sand with gravel, 3-medium-grained and fine-grained sand. Ore percentages in these types respectively are 16.5%, 26.6% and 56.9%.

The orebodies are found in roll form with developed bag and wing parts. Bed orebodies are more uncommon. Ore consists of coffinite (66%) and nasturan (34%). The technological parameters of the ore, presented in Table 10, demonstrate about favourable peculiarities of all the horizons for the ISL method, which are confirmed by the results of the field ISL test using sulphuric acid technology. The recovery coefficient of the test was 80% with an acid consumption of 89 kg/kgU. The average pregnant solutions productivity was 88 mg/l under average maximum values of 250 mg/l. Currently, successful uranium industry extraction is being carried out at the East section.

Table VIII. Distribution of permeable and impermeable sediments on the horizons, at the Mynkuduk deposit, %

Lithological types	Horizons		
	Mynkuduksky, Mk	Inkuduksky, ink	Zhalpaksky, gp
1. Permeable sediments			
Sandy gravel	9.6	21.6	--
Hetero-grained with gravel	15.7	22.5	18.9
Medium-grained sand	23.3	12.0	41.6
Fine-medium-grained sand	27.2	24.3	31.5
Fine-grained sand	11.0	12.2	6.1
2. Impermeable sediments			
Clay	9.4	7.4	1.9

Table IX. Weighted average gradation of permeable sediments of the Mynkuduk deposit on the horizons, %

Horizons	Gradation classes, mm						
	>2	2-1	1-0.5	0.5-0.25	0.25-0.1	0.1-0.05	<0.05
Mynkuduksky	9.4	4.4	5.9	34.2	23.1	7.4	14.6
incl.: lower part	10.5	5.0	6.3	33.3	23.7	7.1	14.1
upper part	5.3	2.6	4.5	37.7	26.0	8.4	15.5
Inkuduksky	24.5	10.0	9.6	26.8	9.7	6.2	13.2
Zhalpaksky	5.9	3.9	10.6	44.2	14.6	9.3	11.5

4. Inkay-mynkuduk ore field and environmental in-situ leaching impact

Planned researches of the Chu-Syrdarya Basin Cretaceous sediments began in 1971 after successful field ISL test carrying out in the Palaeogene sediments at the Uvanas deposit and after the Zhalpak deposit discovery in the upper part of the cretaceous sediment. At a later time, an ore-bearing assessment of the Cretaceous sediment was carried out through drilling searches in the 300 km belt. As a result, the Mynkuduk, Inkay, and Budyonovskoe deposits were discovered. This fact allowed the announcement of the discovery of a unique uranium belt with 750-800 thousand tons of uranium resources. Simultaneously, with drilling searches exploration was being carried out in the separate sections. Currently, the Inkay and Mynkuduk deposits forming the IMOF are the most interesting. They are the most explored and most prepared for extraction. At the deposits, the field ISL tests are being carried out and reserves are confirmed by the State Reserves Commission, which allows based on these deposits the beginning of extraction operations.

At the IMOF, 12.6 thousand wells were drilled with a volume of 4.4 million m and a cost of $153 million. Drilling exploration was carried out extremely effectively for 20 years using 6-8 drilling machines. Such exploration tempos were possible due to the geophysical methods used, which allowed the use of large volumes of drilling without cores. Reserves calculation and lithological type ore separation were carried out using geophysical interpretation data with the required volume confirmation sampling. The total resources of the IMOF are 460 thousand tons uranium, including 280.7 thousand tons of RAR.

The ore of the IMOF is characterized by favourable technological properties, which slightly differ in the area. (Tables 6 and 10). The substantial resources of the IMOF allow the distribution on its area of several industry enterprises. Therefore, the IMOF is a priority for the expansion of industrial uranium extraction in Kazakhstan.

Table X. Uranium ore parameters of the Mynkuduk deposit

Parameters	Horizons, sections		
	Mynkuduksky, Central Osenny, West	Inkuduksky, Peschany Ortalyk	Zhalpaksky, Akdala
Depth of orebodies, m	205-420	225-325	135-195
Square productivity, kg/m^2	4.8	2.9	6.4
Average orebodies thickness, m	7.1	6.0	6.6
Average grade, %	0.04	0.028	0.057
Filtration coefficient, m/d	12.3	13.4	8.8
Mineralization, g/l	3.2-6.0	4.7-5.4	4.0-5.8
Depth of piezometric level, m	58-92	62-71	69-75
Uranium mineralization, %			
coffinite	24	67	65
nasturan	76	33	35
Content, %			
sulfide iron	0.1	0.1	0.5
organic carbon	0.04	0.04	0.09
carbonate	0.3	0.2	0.1
10. Reserve share, %	76	11	13

The uranium ISL method allows Kazakhstan to keep out of large radioactive waste volumes forming by mine extraction. Sulphuric acid technology results in inessential quantity radioactive waste, which are presented by contamination equipment. At the same time, the aquifer contamination is significant.

IMOF aquifers are characterized of 1-6 g/l mineralization therefore only part of the water is suitable for use according to limitations of Kazakhstan legislation. In addition, at the redox front there is the nature contamination of underground waters by the radionuclides therefore the waters in this area are not suitable for use. Nevertheless, in accordance with the legislation of Kazakhstan, after the ISL process the water must be in the same condition as it was previously.

Experience with ISL extraction in Kazakhstan and Uzbekistan has shown that after the completion of ISL, the processes of nature demineralize its aquifers. There are data that process of the water self-reduction to its previous state could continue during 30-40 years. Therefore, taking into account that this water is suitable for use only with limitations, extracted sections should be left for the self-reducing without additional special operation. In this way, the costs for aquifer rehabilitation could be inessential.

5. Summary

1. The IMOF deposits were formed as a result of the BOZ development processes, which led to uranium mobilization from sediments by oxygen-bearing waters moving from the recharge area, and to uranium transportation and precipitation at the redox front in the favourable conditions of the gray-coloured channel facies. In addition, BOZ was the generator of the hydrocarbon gases playing the reduction role at the redox front. Because of this, IMOF deposit, as other similar deposits, should be named BOZ deposits, emphasizing the special ore- forming role of BOZ.

2. In connection with the regional character of the BOZ and the relative uniformity of the ore forming conditions, orebodies are characterized by similar morphological and technological parameters on the 130 km belt extension as a whole. Successful ISL tests were carried out at both deposits, and profitable uranium extraction at the East section of the Mynkuduk deposit allow us to foresee effective extraction at all IMOF sections.

3. Significant IMOF reserves allow to concentrate several extraction enterprises within a relatively small distance (not more than 120km). This establishes extremely favourable conditions for creating a powerful uranium production centre and makes the IMOF a priority area for the expansion of the uranium industry of Kazakhstan.

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The Imouraren deposit, Niger

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Abstract: Imouraren deposit has been discovered in the late sixties. It is located South of Arlit where two mines are mined, one open pit and one underground (Figures 1 and 2). The grades of reduced Imouraren Uranium ore are lesser than these of Arlit and Akouta. Imouraren deposit is owned by COGEMA (France): 70% and ONAREM (Niger): 30%. The concession area is about 45 square kilometers. The thickness of the deposit is between 50 and 60 meters and its depth reaches 110 to 170 meters.

1. Mineralization

The mineralization is related to fluvial sandstones of Jurassic age (oxydation/reduction system). The deposit extension is about 8 km × 5.5 km. Imouraren permit is located in Tim Mersoi Basin which is composed of sedimentary formations. It is included in Tchirezrine 2 formation (Fig. 3). The roof and the floor of the deposit are composed of formations with fine granulometry and low permeability. The soluble oxide Uranium (U6) has been precipitated and trapped at reduction conditions to give "roll front" (Fig. 4). In situ leaching is the indicated method to mine Imouraren deposit.

2. Potentials

All the Tchirezrine 2 sandstones have a mean thickness of 55 m. The orebody is divided, vertically, in three mineralized levels from the floor:

— The lower level N1, 165 m to 155 m
— The mean level N2, 155 m to 135 m
— The upper level N3, 135 m to 105 m

Three horizontal zones are identified:

— The Northern zone, the mineralized area is located in the level N1
— The Central zone, the mineralized area is located in the three levels
— The Southern zone, the mineralization area is more located in the level NI

The estimation of the resources realized by geostatistic method with a cut up grade of .06% gives the following results:

Ore = 130 900 Kt
Grade = 0.11%
Metal = 143 600 tU

3. Hydrogeology

The studies realized by CEA, COGEMA and SCET International have proved the existence of many aquifers.

Two of these aquifers are:

- — Tchirezrine 2 water table: 110 m depth
- — Teloua water table: 300 to 350 m depth.

The piezometric levels of these water tables are located between 25 to 35 m under the topographic surface. Under the Teloua water table many others are located: IZEGOUANDE, TARAT and GUEZOUMAN.

4. Physical criteria of Imouraren deposit

a) Imouraren deposit seems to present global favorable technical characteristics for ISL method:

- Sandstone hosts the uranium,
- Two water tables on the top of the deposit,
- Roll-front formation,
- Deposit is confined between two formations of low permeability,
- Average thickness of the mineralization (55 m).

b) These favorable characteristics must be completed by tests before using the ISL method. The tests are:

- Determination of hydrodynamic characteristics of the Tchirezrine 2 formation on eleven (11) sites by pumping test in order to determine the permeability (K) and the transmissibility (T).
- Hydrogeological and hydrochemical studies for the Tchirezrine 2 formation (for chemical aspects).
- Study of the leachability of the mineralized levels (on coredrill to determine densities, porosity, horizontal and vertical permeabilities, mineralogy, petrography, processing, leaching test).
- Pilot leaching.
  - — Chemical and physical characteristic,
  - — Control by piezometer,
  - — Circulation test.
- Modeling after field tests.

It concerns:

— Sdimentology	— Hydrochemistry
— Geology	— Reserves estimations
— Hydrogeology	— Economic model.

5. Conclusion

Despite this project is not finalized we think the feasibility studies will be positive because of some favorable characteristics necessary for this method.

Also, this project will be one of the most important in the world related to the volume of the deposit (143 600 tU at 0.11%).

This project is a chance for Niger.

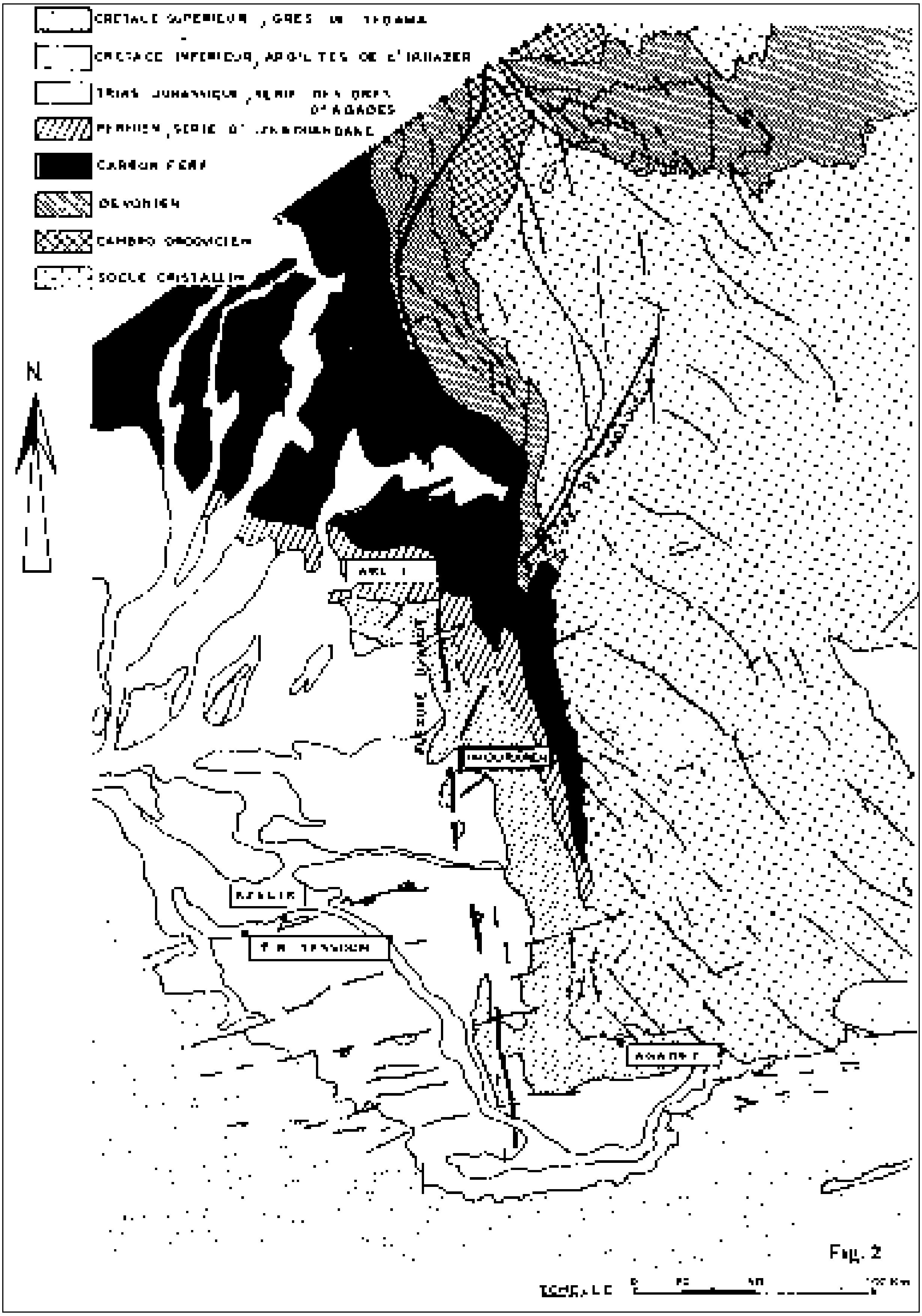

FIG. 1. General geological map of the Imouraren region.

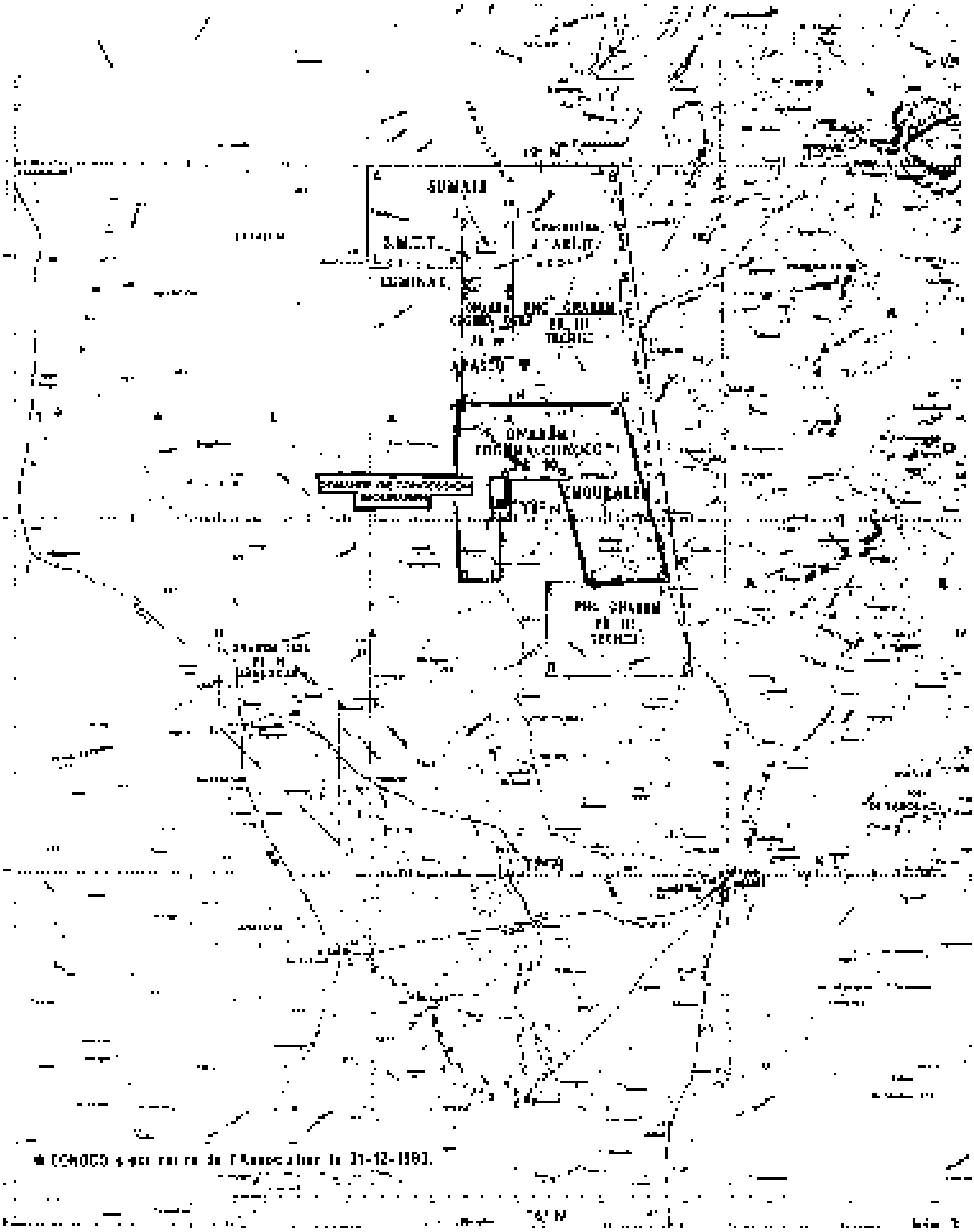

FIG. 2. AGADES.

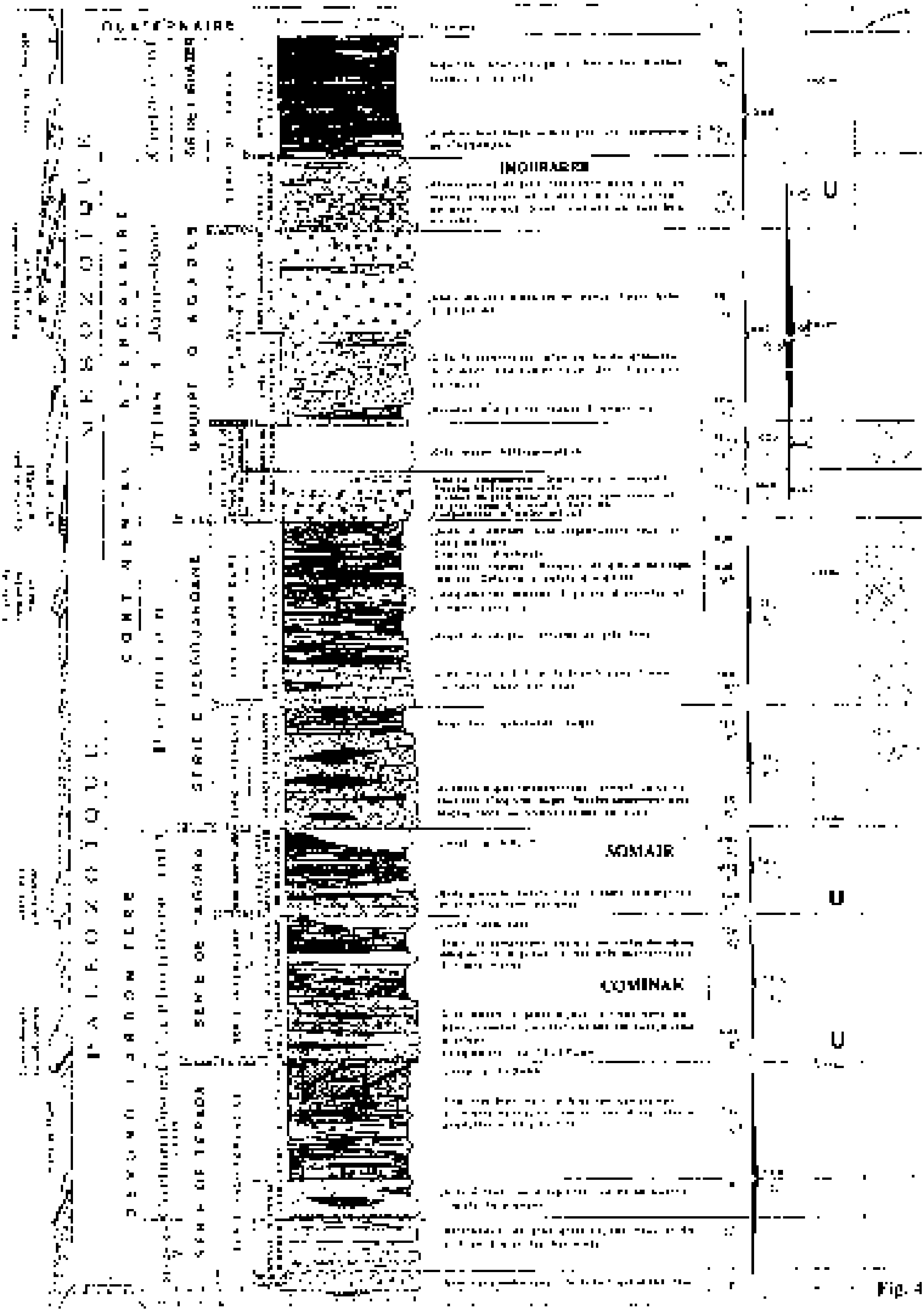

FIG. 3. Scheme of stratigraphical series.

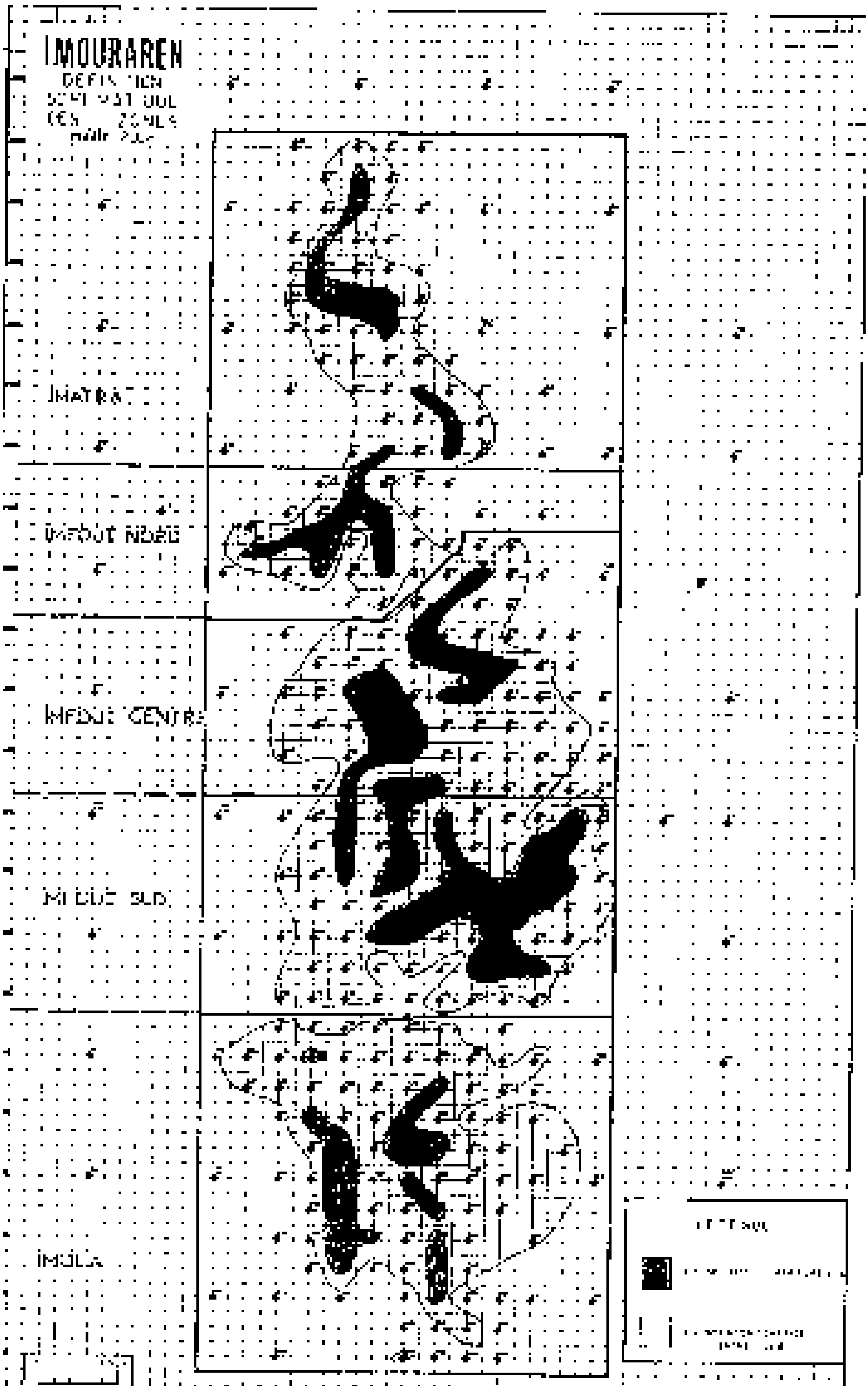

FIG. 4. IMOURAREN: Definition of schematic zones.

Uranium recovery in Romania from alternative sources and impact on environment

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Abstract. This work is the continuation of our study on uranium recovery and radium removal by processing various sources to produce goods, which might have an impact on the environment. In one study the work focused on coal ash treatment in order to extract Uranium from this source and make it available for its iron oxide use in metallurgy and minimizing the impact on the environment. In previous papers the work developed in Romania on uranium recovery from phosphates in fertilizer industry led to three uranium plants. In those papers Radium was also eliminated from phosphate fertilizers obtaining nonradioactive products. In this work various products resulted from sedimentary phosphates processing and their radioactivity was also discussed. Uranium was recovered in a simple precipitation process during the manufacture of sodium tripolyphosphate (STPP) used in detergent industry. Otherwise such a detergent may carry uranium. Similar work was carried out for phosphoric acid used in foodstuffs where uranium presence is undesirable. Special attention was given to large amounts of phosphogypsurn wastes resulted in the four fertilizer plants in Romania each producing 5-7 million tons along the years of operation being a source of concern having ^{226}Ra content 600-1000 Bq Ra/kg. Its use in agriculture or building industry is now forbidden. Various tests were carried out and proposals on its handling are given. Phosphogypsum dumping areas in all four cases are located within 1-3 km radius of large human settlements creating big problems due to its spreading by winds.

1. Introduction

Romania has a well established tradition in uranium industry starting from mining, milling, production of a concentrate, processing of the last to a nuclear compound finally converted to UO_2 and the fuel bundle to feed the CANDU 700 MW(e) nuclear reactor of Cernavoda. Heavy water is also produced in Romania.

Low grade ores are also processed by various methods but in this paper the interest is focused only on non classical sources which now create problems due to the impact on the environment.

In our previous papers [1,2,3,4] we have shown the preoccupations which have existed in the past in this country regarding uranium recovery from phosphate fertilizers industry by sulphuric and nitric acid attack. It was shown that a one cycle extraction-stripping process for uranium recovery from phosphoric acid (WPA) was developed at industrial scale and three uranium recovery plants have been built each having 35 tons/y uranium output therefore total uranium production capacity approx. 100 t/y U. This uranium resulted at 25–30 US$/kg and the costs were obtained processing WPA in a big pilot plant having 7 cu.m/h WPA capacity (almost 20% of fertilizer plant capacity).

The one cycle process developed in Romania consisted of a clarification stage for WPA, organic matter removal followed by extraction stage in a mixer-settler [5,6]. The organic extractant DEPA (di (2-ethylhexyl) phosphate) + TBP (tributylphosphate) or DEPA + TOPO (tri-n-octylphosphine oxide) have extracted both Uranium and Rare Earths (yttric group only). The following two stages involve Rare Earths and Uranium stripping. Rare Earth stripping takes place in a mixer followed by a separator the reagent being hydrofluoric acid or ammonium fluoride (prepared from hexafluosilicic acid a waste in fertilizer industry).

The next stage a similar equipment (mixer-separator) is used for uranium stripping with the same reagent above mentioned but in the presence of Fe(II) to reduce U(VI) to U(IV) inextractable species.

In the stripping process uranium instantly precipitates as $UF_4 \times H_2O$ or $(NH_4)_7U_6F_{31}$. Both compounds were converted (laboratory scale) with a previous calcination 400ºC (nitrogen atmosphere) to uranium hexafluoride (UF_6) with florine. A high purity product was obtained (Figure 1).

In this paper the study was continued based on other alternative sources or on other processes taking into account the impact on the environment. Last year we have insisted on the radioactive impact of fertilizers on environment and the ways to eliminate uranium and radium (mostly in nitric acid attack).

Starting from this idea two alternative sources are envisaged:

- Coal ashes obtained in the power plants burning inferior coals,
- Phosphate industry and its wastes.

2. Uranium elimination from inferior coal ashes

Romanian inferior coals have a high ash content of the order 20–24% therefore large amounts of ashes create big problems for a coal burning power plant the impact on environment of ash, fly ash, SO_2, NO_x (rain acids) not to mention CO_2 (green grass gas) is important.

Besides those mentioned the Romanian coal ashes have a non-negligible uranium content within the range 100–200 mg U/kg [7,8]. Experimental studies carried out in this country were related [7] to uranium recovery but iron content was also taken into account in order to an eventual use in metallurgy. Various experimental studies were carried out for uranium dissolution using mineral acids. The most suitable method involves the use of ash pellets which were prepared from ash powder and 10% sulphuric acid as binding agent. The heap leaching was carried out with 0.05–0.15 mol/L sulphuric acid at S/L ratio 1/1 by recirculation in 12–14 cycles and finally 2–4 fresh acid cycle recirculations. This process leads to 70% uranium dissolution and H_2SO_4 consumption was 180 kg/t ash. The pregnant sulphuric acid solution is transferred to an anionic resin column (Vionit ATH-1) when uranium is absorbed while most of impurities were left in solution.

The resin elution is carried out with an acidic solution consisting of 0.1 mol/L HNO_3 + 0.9 mol/L NH_4NO_3. The uranium content in eluate was 7-10 g/L. The eluate neutralization by ammonia yields a technical product of 55-60% U.

In the following table the characteristics of most representative coal ashes used in this process are given (Table 1).

Table I. Characteristics of most representative coal ashes

Source power plant	Specific gravity kg/cu.dm	Specific area sq.cm/g	SiO_2 / $A1_2O_3$	Size < 0.07	U %
CET Craiova	2.278	4425	1.9	40	0.02
CET Paroseni	2.264	1077	1.8	67	0.012
CET Doicesti	2.010	3155	2.5	59	0.018

The depleted pellets are washed with water S/L 1/2 and this water is used to prepare the leaching solutions. The desintegrated mass is mixed with water S/L 1/4 and the separation is carried out using hydrocyclones.

As already mentioned acid consumption is high, in the case of hydrochloric attack 2500 kg/t ash. In the case of sulphuric acid this consumption is 180–220 kg/t ash. Even in this case the values are prohibitive.

The presence of 2% MnO_2 as oxidant added in the process leads to slightly higher yield but acid consumption is similar even if reaction time is shorter.

The only incentive might be the association with recovery of other elements like Ti and Fe (TiO_2 and Fe_2O_3). The last component is 60%. The radioactivity elimination should also be taken into account.

Radium elimination in this process is based on its precipitation on $BaSO_4$ as $Ba(Ra)SO_4$ before solution being sent to uranium separation on anionic resin.

However this study was left at pilot plant stage being considered a prohibitive process from economical point of view.

3. Phosphate industry and its wastes

Wet Phosphoric Acid (WPA) 30% P_2O_5 resulted by sulphuric acid attack (dihydrate process) of phosphate rock has also been used in this country for production of phosphate soluble salts (mono, di, tri sodium phosphates, hexametaphosphates and sodium tripolyphosphate (STPP).

3.1. Sodium tripolyphosphate (STPP)

It is an important product obtained at industrial scale for use in detergents starting from WPA. Uranium content of WPA was given in our previous work [9] and is of the order 100 -140 mg U/L. STPP is produced in Romania according to the flowsheet shown in Figure 2.

Therefore the WPA undergoes a purification stage consisting of: organic matter removal, SO_4^{2-} excess removal, filtration, florine and silica elimination as Na_2SiF_6 clarification etc. The following steps of the industrial process require the WPA treatment with sodium carbonate. During this process the heavy metals are precipitated and removed while a ratio NaH_2PO_4/Na_2HPO_4 of 1/2 is obtained. However at this stage uranium is not precipitated the same time with heavy metals so it is not eliminated from orthophosphate solution mixture since it is present in hexavalent state that is as $Na_4[UO_2(CO_3)_3]$ soluble form.

Therefore in the final stages of orthophosphates concentration, drying and calcination to result STPP, uranium existent in WPA is found in the end product and later in the detergent. Uranium in STPP is usually 250 mg/kg.

In order to eliminate uranium, after heavy metals filtration, the solution is treated at 60–70°C with an efficient reductor like in Blockson process [10] when U(VI) is reduced to U(IV) which is precipitated, filtered, washed resulting a cake. Uranium concentration in the cake is dependent on its initial content in WPA, but it is usually 10–17% U. Therefore the cake undergoes a further treatment in order to obtain a higher grade product.

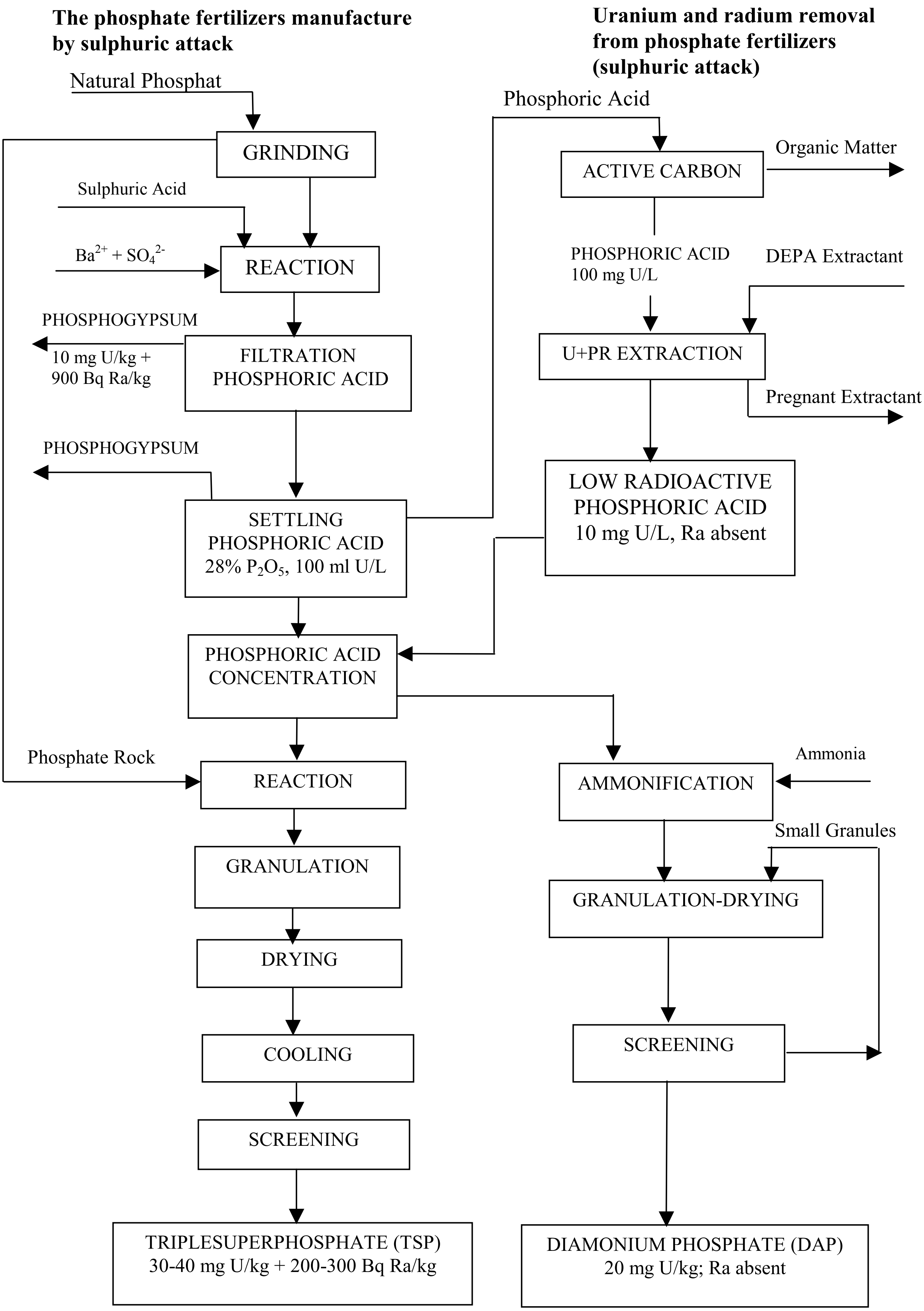

FIG. 1. Process developed at industrial scale in Romania, a version to take into account the radioactivity elimination [6].

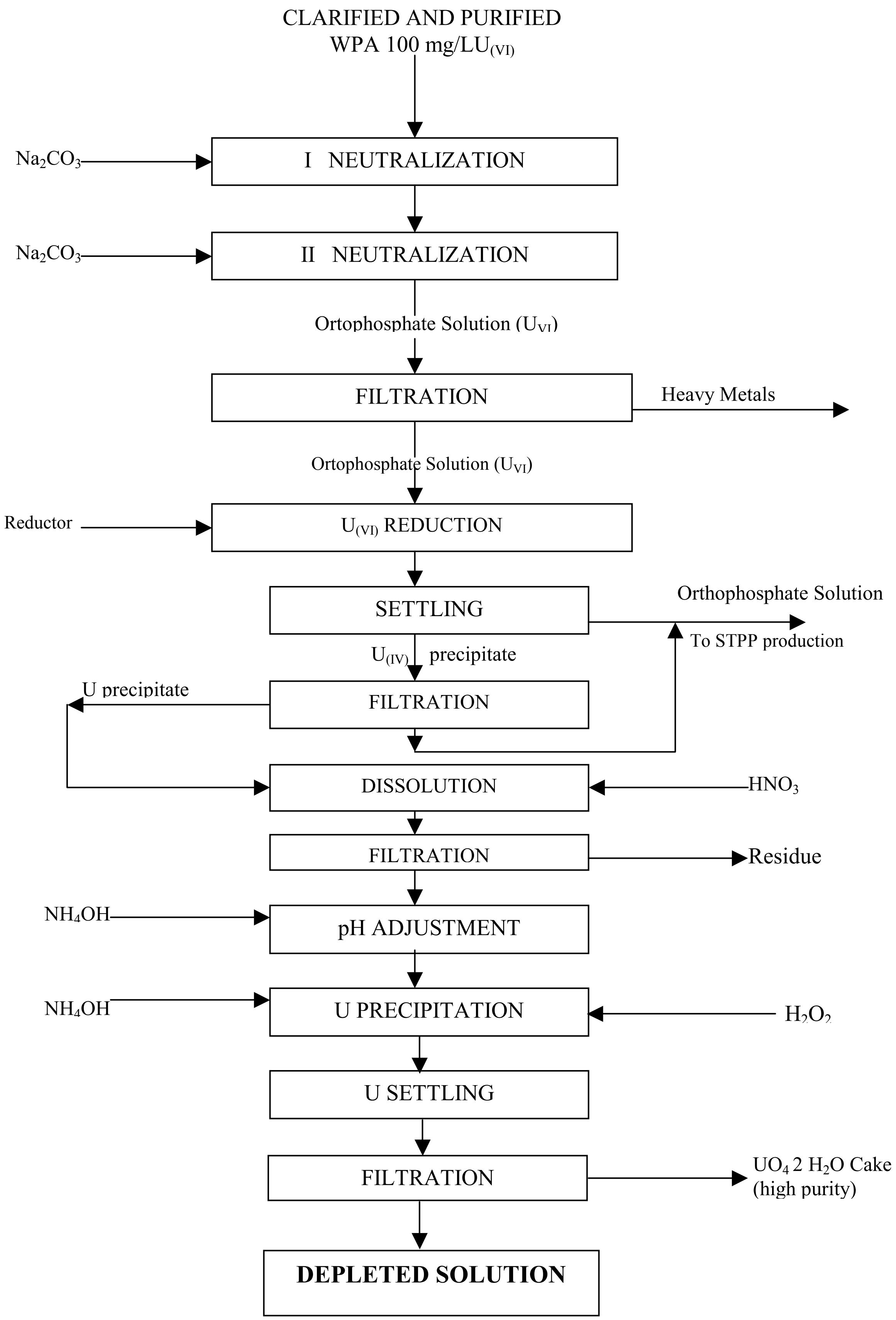

FIG. 2. STPP production in Romania.

The cake is dissolved in nitric acid solution, a filtration is required, then the aqueous nitric solution is corrected to pH = 2.5 and uranium is precipitated as a high grade product with hydrogen peroxide. A continuous adjustment of pH is required to be carried out with ammonia otherwise pH fluctuates (decreases).

More than 95% of existent uranium in orthophosphates has been eliminated and recovered. A less costly alternative to this process is based on U(VI) reduction to U(IV) in WPA by iron scrap. In this case uranium is precipitated with heavy metals as phosphates and is separated at filtration stage. However, its content is now only 0.2-0.4% U but not at all negligible. This method seems also attractive.

In these two processes uranium is eliminated from STPP. ^{226}Ra is also absent since it was removed at sulphuric acid attack of phosphate rock and was carried on $CaSO_42H_2O$.

3.2. Phosphoric acid production by solvent extraction (WPA purification)

A plant was built in Romania to produce phosphoric acid destined as ingredient in foodstuffs as such or as salts. The process uses as raw material WPA produced by sulphuric acid attack of phosphate rock. A solvent extraction method was considered to extract only the phosphoric acid leaving the rest of impurities in the aqueous phase. The initial WPA was clarified and purified of various undesirable impurities (F^-, SiO_2, organic matter etc).

A final purification and separation is carried out with an organic solvent, which extracts only H_3PO_4. In Romanian process butanol was the choice as solvent. The phosphoric acid is the only extracted component. After separation of the two phases the solvent is distilled, condensed and recirculated while phosphoric acid of high purity is left unchanged.

The aqueous phase (the raffinate) left at extraction stage having a smaller volume held all inorganic impurities at higher concentration than in original WPA. However our measurements have shown that only half of uranium is found in the aqueous phase the rest of 50 mg U/L was extracted by butanol the same time with H_3PO_4 and at distillation stage uranium was left in H_3PO_4. Therefore our determinations have shown that Uranium presence in H_3PO_4 intended for use in foodstuffs cannot be tolerated and the plant was shut down.

3.3. Phosphogypsum obtained in phosphate fertilizer industry

In our previous papers [1,2,3,11] on phosphate fertilizer radioactivity it was shown that almost all ^{226}Ra was carried by $CaSO_42H_2O$ in the process of sulphuric acid attack of phosphate rock. Phosphogypsum is obtained in large amounts since per each ton of phosphate reacted with sulphuric acid, 1.5 tons phosphogypsum wastes have resulted.

There are 4 fertilizer plants in Romania processing each 330 000 t/y phosphates by sulphuric attack therefore 500 000 t/y phosphogypsum is obtained in each case. These plants were in operation 20–30 years and phosphogypsum accumulated is of the order of 5–7 millions tons deposited around the plant creating big problems, due to the fact that dump site is in the vicinity of big settlements on a radius of 1–3 km. One plant is near an important Black Sea Resort. Strong winds are spreading phosphogypsum powder on large areas the same time with ^{222}Rn.

Our measurements have established that ^{226}Ra content of phosphogypsum of sedimentary origin has average values 600-1000 Bq/kg exceeding the permitted limits mentioned last year at IAEA of 1 Bq/kg. Uranium content of 10–20 mg/kg is also exceeded compared with maximum 1 mg/kg allowed.

Phosphogypsum of volcanic origin has Ra activity (more exact from Thorium descendents) of 150 Bq/kg. Phosphogypsum was largely used as soil amendment and as raw material in building industry. The current regulations in many countries (USA) have prohibited its use therefore its accumulations and the problems are always present.

Many years ago a plant was built in Romania to process phosphogypsum in order to make it acceptable as wallboards. Some flats were built using wallboards for interior rooms. Our measurements have shown that ^{226}Ra radioactivity of these walls was 300-400 Bq/kg and ^{222}Rn concentration higher than in normal rooms. Therefore the plant was shut down and the use of this material forbidden.

Our studies regarding an eventual radium abatement in phosphogypsum starting from hydrocyclone processing separation led to a fine fraction of 700 Bq/kg and a coarse fraction of 200–300 Bq/kg each representing approx. 50%.

Chemical treatment of phosphogypsum to obtain either $(NH_4)_2SO_4$ which is a fertilizer or Na_2SO_4 by conversion with corresponding carbonates cannot solve the problems due to large amounts of phosphogypsum.

The only alternative to phosphogypsum use is in our opinion restoration works of dumping sites to eliminate the radioactive contamination of the environment. In other countries [11, 12] due steps were taken to avoid its impact on environment but in Romania no such works were involved.

At present it is considered that Radon evolution is only possible from superior layers of phosphogypsum perhaps 3–4 m depth. The inferior layers contribution of Radon evolution is minimized. Therefore a dump site levelling off and coverage with various protection layers is envisaged. A drain system is to be taken into account.

The great problem is the quantity of 150 million tons phosphogypsum accumulated worldwide each year. At present a practical use is not allowed neither in agriculture nor in building industry it is no longer dumped in rivers or sea due to radioactivity accumulation of radioactive decay products in marine life.

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Perspective to discover profitable uranium ore in Ukraine

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Discovered commercial uranium deposits of Ukraine are presented in two genetic types: (a) endogenic metasomatic deposits in albitites of the Ukrainian shield and (b) exogenic epigenetic deposits in Paleogene sand-coal cover sediments of the Ukrainian shield. At present, deposits in albitites of the Kirovogradsky ore region are main source of uranium in Ukraine. They are being mined by underground method. Deposits in sand-coal sediments are not mined now due to ecological reasons. However, two of them (Devladovskoe and Bratskoe deposits) have been mined out in previous years using *in situ leaching* method.

In a whole, uranium mineral base of Ukraine according to uranium reserves can supply mining industry during several decades. At present, thirteen units of 5 nuclear power plants existing in Ukraine consume 2310 Mt of uranium annually. Uranium consumption will increase during following years in connection with installation of new reactors. In 2005 it will make 2890 Mt per year approximately. It is necessary to begin exploitation of new uranium deposits within Kirovogradsky ore region to provide such consumption. However, deposits discovered here are presented usually by low-grade ore with uranium content of 0.10–0.15% what specifies its cost.

These facts predestine significance of geological research in Ukraine to improve the quality of existing uranium mineral base. The examination of obtaining data about uranium mineralization in Ukraine including world experience in uranium geology shows that this problem can be solved in two main directions:

— To involve in exploitation sandstone uranium deposits, particularly deposits in coal-bearing sediments of the Ukrainian shield cover, suitable for *in situ leaching,*
— To discover commercial uranium deposits of new genetic types with high-grade (in comparison with deposits in albitites mining now) or complex uranium ore.

Advanced *in situ leaching* method using now in the world allows mining small low-grade deposits attaining high uranium recovery from ore (from 60% to 95% depending upon lithological ore type and ISL flowchart) and low mining cost (less than US$ 10–20 per kilogram of uranium).

Uranium deposits of sandstone type in Ukraine are located in Paleogene coal-bearing cover sediments of the Ukrainian shield fulfilling erosion tectonic paleodepressions in basement within the Dniprovsky brown coal basin (Dniprobas). Kirovgeology units have discovered and explored here seven small uranium deposits of this type (Devladovskoe, Bratskoe, Safonovskoe, Surskoe, Sadovoe, Novogurievskoe, and Chervonoyarskoe). As it was mentioned above, two of them (Devladovskoe and Bratskoe) have been mined out. These deposits are located in three uranium ore regions: (1) Saksagansko-Sursky, (2) Ingulo-Inguletsky, and (3) Yuzhno-Bugsky. Besides indicated deposits, a lot of uranium occurrences of the same type (more than 90) are discovered within these regions, but their assessment is not completed.

It should be noted that acid leaching was used only during exploitation of Devladovskoe and Bratskoe uranium deposits, as well as during experimental mining of some orebodies of

Safonovskoe, Sadovoe and Novogurievskoe deposits. The efficiency of other ISL technologies, particularly ecologically safe technology of carbonate-oxygen leaching was not studied at any mentioned deposit or occurrence. Attention should be paid also to the fact that complex character of mineralization on some deposits and occurrences of this type is established: except uranium ores contain such elements as molybdenum, selenium, thallium etc. However, their industrial importance practically is not certain.

To involve sandstone uranium deposits in operation the performance of the following works is planned:

(1) Complete development of Safonovskoe (43m), Sadovoe (25m) and Surskoe (7m) deposits for mining,
(2) Complete exploration of Novogurievskoe (39m) and Chervonoyarskoe (12m) deposits, carry out prospecting of Krinichanskoe (48m), Khristoforovskoe (15m), and Elenovskoe (47m) occurrences and evaluation of Khutorskoe (42m) and Petromihaylovskoe (8m) occurrences.
(3) Conduct complex of laboratory and field geo-technological tests on ISL sites within typical deposits using different ISL technologies with the objective to choose the main effective one according to uranium recovery and ecological requirements.
(4) Revise data about uranium mineralization at three ore regions of Dniprobas with the objective to outline areas within their limits for detail exploration at a scale 1:25 000 and most perspective occurrences that are subjects to a prime evaluation.

At present, according to the second point, systematization and generalization of a huge actual material about geological structure and uranium mineralization of Ukraine, which has collected for last 50 years is completed now. The analysis of this material has shown that there are serious geological preconditions to discover new uranium deposits in Ukraine which have high-grade ores in comparison with metasomatic deposits in albitites of Kirovogradsky ore region mining now. It is confirmed by detection of numerous uranium objects (occurrences and mineralization) of hydrothermal vein and vein-impregnated types in basement of the Ukrainian shield. The same objects characterized by increased uranium content (up to 1–3%) are revealed on a northwest slope of the shield, in a zone of upper Proterozoic structural-stratigraphic unconformity (unconformity-related type). However, the degree of radiometric investigation of the shield and its slopes is such that majority of uranium occurrences revealed here has not estimated for today.

It is caused by very difficult character of uranium mineralization of both types. In this connection executed researches are, as a rule, insufficient for the reasonable conclusion. The data on special deep research of investigating territory testify the same: within the limits of the Ukrainian shield only its insignificant part (about 35 000 km^2 or 17.8% of its area) is covered by rather detailed deep exploration (1:50 000 scale and larger). Areas near slopes of a shield are investigated even worse.

In these conditions one of the important tasks of geological research is to clarify features of genesis and distribution of uranium formation of considered ore types: hydrothermal vein type on the shield and unconformity-related type on its northwest slope. Forecast criterion and research attributes of endogenic uranium formation with reference to geological conditions of the Ukrainian shield are established on the basis of analysis of actual data about uranium mineralization on the shield and its slopes. The most significant of them are thermal granite-gneiss domes generating uranium-bearing fluids, deep faults as channels of their moving to the upper horizons of the earth crust, and imposition of hydrothermal metasomatic process and uranium formation during different periods of tectono-magmatic activization in fault zones.

The map of high-grade Uranium mineralization of the Ukrainian shield of a scale 1:500 000 is made using indicated and other research criteria and attributes. As a result, 24 ore and potentially ore areas which are perspective to discover uranium deposits of hydro-thermal vein type and have general area of 18 570 km^2 (or 9.3% of all territory of the shield) are allocated within its limits. Besides this, 2 potentially ore areas which are perspective to discover uranium deposits in a zone of upper Proterozoic structural-stratigraphic unconformity within Riphean Volyno-Orshansky paleodepression and have general area of 1970 km^2 are also allocated on a northwest slope of the shield. Among them, 5 areas on the shield (Skvirsko-Tetievsky, Gayvoronsky, Kazankovsko-Zheltorechensky, Vasinovsky, and Volchansky) and one area on its northwest slope (northern part of Dubrovsky area) are allocated as the most favorable for detailed exploration. It was done according to the maximal combination of exploration attributes and the degrees of their development.

The majority of uranium occurrences, including Chervonoshahtarskoe occurrence (uranium contents 3.3% U on 1.85 m of its thickness), Severo-Bereznianskoe occurrence (uranium contents 0.47% on 15.85 m of its thickness including 5.65% on 0.85 m), and Vostochno-Annovskoe occurrence (uranium contents 1.20% on 6.67 m of its thickness including 2.34% on 1.5 m) etc. is concentrated in the limits of indicated areas as well as within other perspective areas.

The further research within the limits of the allocated perspective areas and, first of all, within 6 prime areas consists in more profound study of available data about them as well as in the beginning of detailed exploration of a scale 1:25 000 – 1:10 000 on the defined separate local sites, and evaluation of the most perspective but not enough investigated occurrences. According to all available data, the following occurrences are referred.

— Vostochno-Annovskoe (236p), Geikovskoe (131p) and Lagodovskoe (146p) within Kirovogradsky block,
— Sergeevskoe (245p) and Shirokobalkinskoe (235p) within Dniprovsky block,
— Dibrovskoe (221p), Guliaypolskoe (167p) and Barbasovskoe (47p) within Priazovsky block.

The practical realization of activities listed above during coming years in both directions will allow to decrease the cost of uranium mining in Ukraine and to improve the economy of uranium industry in the country.

Uranium deposits of Ukraine for ISL mining: Developments in uranium resources of Ukraine for in situ leach (ISL) uranium mining — Historical analysis, operational, geological, environmental and economic aspects

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Abstract: From 1961-1968 uranium production center of Ukraine, East Concentrating Mill and Zheltiye Vody Hydrometallurgical Plant has carried out first Ukrainian In Situ Leaching (ISL) uranium project in Devladovo of Sofiivka district (Dnipropetrovska province) and in 1964-1969 the second in Bratske of Mikolaivska province. The experiences were executed with the acid leach system. Despite its limited applicability for this time to specific types of uranium deposits called as Sandstone Uranium Deposits, the in situ leaching (ISL) method of uranium production has grown in importance for its competitive cost and has proven to be an environmentally sound technology with very little disturbance to the environment. It was also recognized that there are two distinct approaches of ISL uranium production being practiced in Eastern Europe, in particular, in Ukraine, and in the USA, later in Kazakhstan and Uzbekistan. Commercial in situ leach (ISL) uranium mining in the United States began in the mid-1970s. In 1968, for the first time in the former USSR, the East Concentration Mill and Zheltiye Vody Hydrometallurgical Plant has implemented In Situ Leach (ISL) uranium mining technology in the Devladovske uranium deposit (Figs. 1 and 2).

1. Devladovske uranium deposit development

Head - Mr. Nikolay Petrovich Kokoshnikov. He was in Devladovo for 10 years. He is now the head of labor protection of the east concentration mill and Zheltiye Vody hydrometallurgical plant ("ShidGZK"). He takes a legitimate pride in the Devladovo project participation and tells the history about this technology elaboration.

The Ukrainian ISL uranium technology was elaborated by the department of minerals dressing in the Krivoy Rog Mining Ore Institute. The pilot project of this technology was implemented in Devladovo.

The Ministry of Middle Engineering Industry of former USSR (MINSREDMACH) adopted Ukrainian innovations to implement the ISL technology in the Middle Asia Republics.

The leadership of ShidGZK were awarded by Kiev and Moscow authorities. For the technology implementation were used:

- Polyethylene casing pipes of 100 mm. diameter and 70–80 m long,
- Wire-net filters,
- Cement and clay for casing,
- Injection and recovery wells: 4 per 1 = 50 × 20 × 30 m,
- Resin AMR (class A), 20 tons per 5 recovery wells,
- Sorption column SNK,
- One cycle of nitrate regeneration = 1.5 days.

The commercial product – $Na_2U_2O_7$ was transported to the hydrometallurgical plant. The technological scheme is:

- Regeneration,
- Sorption,
- Precipitation,
- Filtration.

The production cost was a lot cheaper than from conventional mines.

Periods of System	Sub-periods	Layer	Depth in metre	The rock characteristics is looking typical for this geological province
QUATERNARY			10	1. Forest loam
			10	2. Clay
NEOGENT	MIOCENE	SARMATIAN	10	3. Grey Clay and sand
PALAEOGENE	EOCENE	KIEVSKIY	9	4. Fire-clay of white colour
			5	5. Fire-clay of white colour
		BUCHAN	15	6. Coal clay and sand, brown coal
MESOZOIC AND KAINOZOIC				7. Burrow of weathering
PRECAMBRIAN				8. Migmatite of grey granite with dykes

FIG. 1. Schematic litostratigrafic section of the place where the Devladovske uranium deposit was mined by in situ leach (ISL).

Description of construction wells is shown in Figure 3.

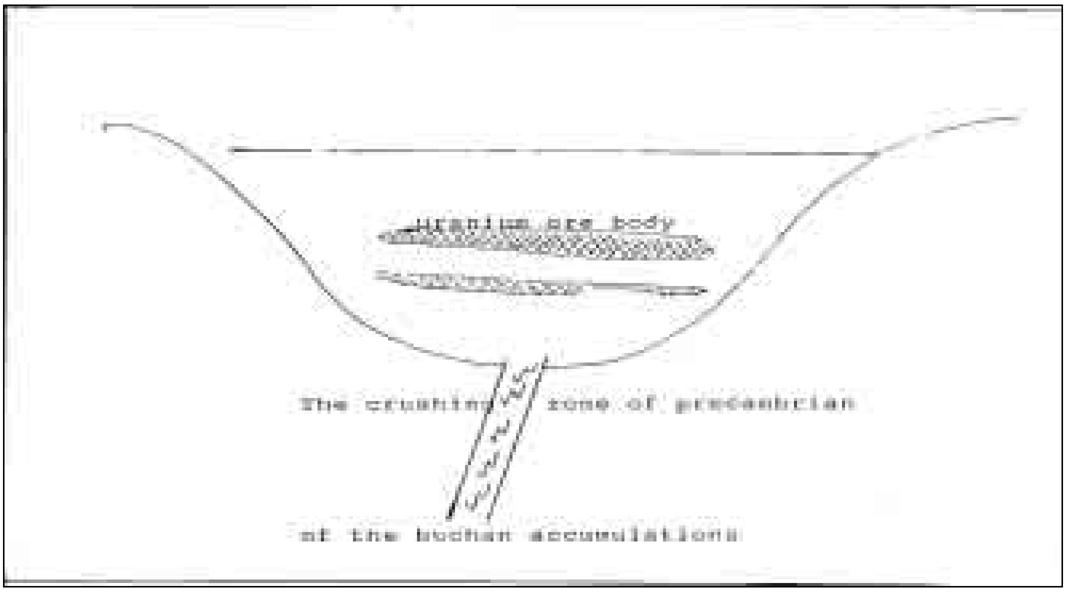
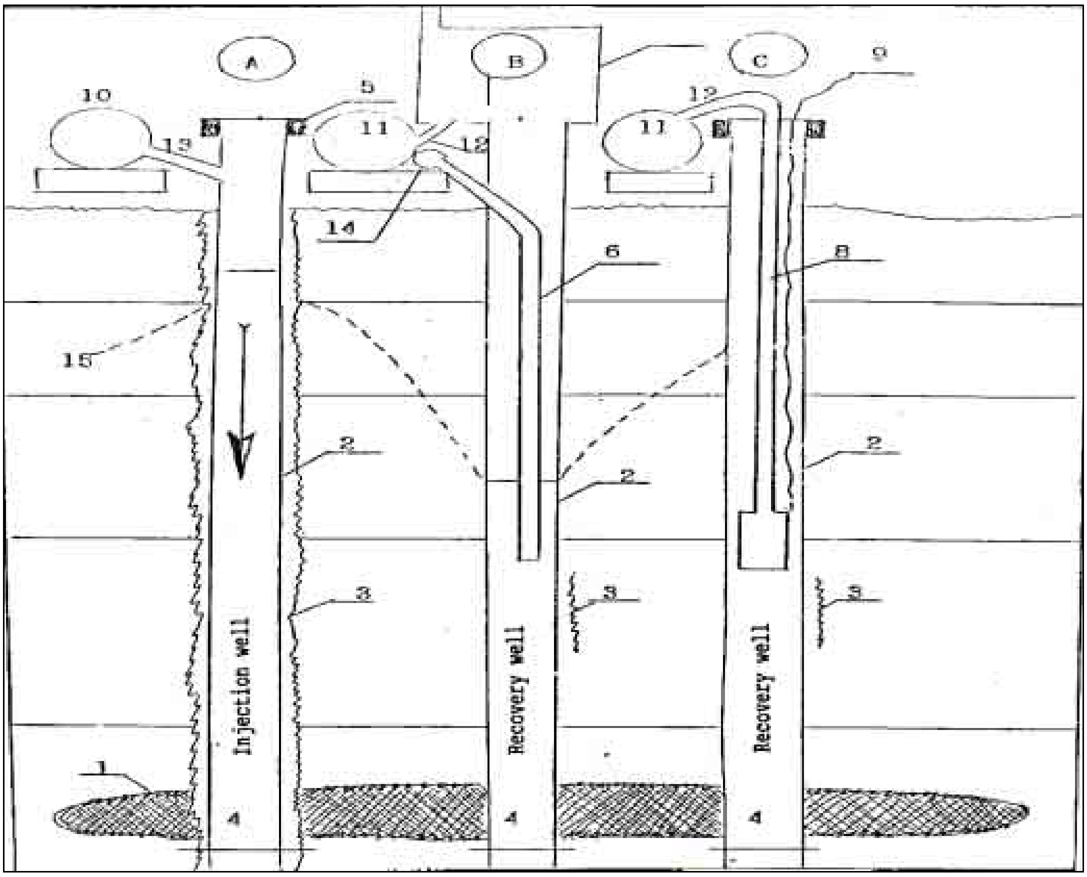


FIG. 2. The scheme of hydrodynamics isolation of Buchan accumulations- Devladovo-Ternovska Palaeovalley (buchan called in Ukraine – Buchack).



A) Pumping into; B) Pumping out with airlift; C) Pumping out with electropump.
1) Uranium orebody; 2) Casing pipe, 3) Cementation, 4) Filters, 5) Concrete head, 6) Airlift, 7) Airregulator, 8) Solution hose with pump, 9) Electrocable, 10) Pomping pipe system, 11) Pomping pipe system for uranium solution collection, 12,13) Hoses, 14) Airpipe; 15) Parameter level.

FIG. 3. The technological wells construction operated at the Devladovo and Bratske uranium deposits.

2. The Ukrainian ISL technology was modernized and developed at the Bratske uranium deposit

The former head of the Bratske industrial site Mr. Valeriy Vladimirovich Davidov is still working at ShidGZK, proud of the ISL technology and sure that it is necessary to restart uranium in situ leaching in Ukraine.

To develop the Bratske uranium deposit there was used the same technological scheme but with different parameters:

— More intensive of recovery and injection wells disposition,
— New sorption column was in 10-15 times productive than in Devladovo,
— Airlift was replaced by electric pumps.

30 technicians were involved in the Bratske uranium project and 200 local people for the service.

1990: Moscow-Zheltiye Vody

In 1990, the Ministry on nuclear energy and industry of the former USSR passed to the ShidGZK the Ecological Passports of Devladovo and Bratske ISL sites liquidation. For the Devladovo project the Ecological Passport was approved with the signatures of the Chairman of Sofiyvska district council and the Chairman of Dniepropetrovska province on ecology and mineral resources utilization.

The same procedure was made for the Bratske ISL project. Principles of the Passports are that any deposit of mineral resources have issued on environment for:

— Air,
— Surface,
— Water resources

3. Analysis of sandstone uranium deposits of Ukraine: Geology, mineral base, exploration and mining experience, environmental protection, and perspectives of development

Dnieper brown coal basin (Dniprobas) is located within the limits of the Ukrainian shield. It is traced from northwest to a southeast for 740 km by a wide bar (up to 180 km) along middle part of the Dnieper river. Its total surface is 102 000 km^2. Two structural layers participate in basin structure: a) Precambrian basement with Mesozoic and Early Paleogene, and b) Cainozoic sediments. Intensively peneplaned basement is plunged from northwest to southeast from marks +300 up to –20.

The widely ramified river network was generated on raised in connection with Laramide orogeny (mainly in Middle Eocene) area of the Ukrainian shield. It was formed in erosion tectonic depressions in the basement succeeding mainly disjunctive disturbances of meridian and in a smaller measure of diagonal system.

According to the features of genesis, depending on a relief and hypsometric location of the basement, 3 lithologic facies can be marked out in coal formation. Their primary development is characteristic for various parts of the basin.

The lake-marsh facies can be divided into two types based on character of geological section: a) complex of watershed plateau (northwest and central part of the basin), and b) complex of coastal plain (northern slope of the western part of the Ukrainian shield).

The river facies can be also divided into two types based on character of a geological section: a) complex of small peleorivers as well as waterheads and tributaries of larger rivers in watershed area of a central part of the basin with rather increased slopes that causes predominant development watercourse sand facies, and b) rather large paleovalleys in east part of the basin with weak development watercourse facies in their middle parts.

The lagoon–estuary complex is characteristic for middle and bottom parts of rather large paleodepressions in the east part of the basin and cut into the basement up to 80 meters. Mainly it is combined by clay and coal sediments with high coal saturation and sharply subordinate distribution of sand facies usually adjacent to the tops of a section.

The sedimentary cover of the Ukrainian shield in connection with the limited development of waterproofs is characterized by primary distribution of ground water and water supply by atmospheric precipitation on watersheds. In regional plan the Ukrainian shield can be considered as uniform hydraulic water–bearing complex. The streams of oxygen waters are as a whole directed from watersheds to regional and local drains. These streams caused formation of a surface oxidation depth zone in which there was an initial enrichment of waters by uranium owing to uranium leaching from sediments. They formed kaolin layer of clay weathering crust within watersheds using primary montmorillonite–hydromica crust with certain radiogeochemical background of the basement. At the same time water accumulated main weight of uranium as well as a number of other components, which are particularly necessary for formation of uranyl–carbonate complexes, sliding in the poorly alkaline environment (G.G. Churzin et al., 1980). The widespread uranium formation of ground–infiltration type was generated on the contact between depth zone of surface oxidation and underlying coal-bearing sediments owing to disintegration of uranyl–carbonate complexes in low acid environment as well as under influence of reduction properties of organic substance and sorption of metal on a coal–clay material.

The greatest industrial value is represented by deposits adjacent to sediments of a river complex with significant development of coal sand and, in a smaller measure, sandy coal where large orebodies with thickness up to 18–20 and more occur.

3.1. Features of geological and hydrogeological structure of area and uranium deposits

The uranium deposits investigated in Ukraine are mainly located in east part of the Central Dniprobas. There is the town of Zhovti Vody in the middle of describing territory where the mining enterprise bases. The main river here is Dnieper.

3.1.1. Stratigraphy and lithology

Archean and Proterozoic is represented by crystalline rocks. Granitoid rocks are dismembered according to their structural and textural features, petrography and radiogeochemical background. Granite and migmatite are predominant.

Cainozoic sediments compose platform cover overlying eroded basement surface. These rocks include Paleogene, Neogene and Quaternary sediments of continental and marine facies.

Paleogene system is represented by not dismembered sediments of Lower and Middle Eocene, Buchak and Kiev suites as well as Kharkov layer.

The Lower and Middle Eocene not dismembered sediments (1–2) overlay the basement occupying the deepest parts of paleovalleys. The thickness of sediments is 10–30 m sometimes up to 60 m. In waterheads and on slopes of paleovalleys it makes 1–5 m. Sediments are represented by continental facies of river valleys.

Sediments of Kiev suite ($_2kv$) overlay rocks of Lower and Middle Eocene, Buchak suite or the basement. The Kiev sediments are distributed more widely than Buchak sediments in middle and bottom parts of paleovalleys.

Sediments of Kharkov layer ($_3hr$) overlay rocks of Kiev suite, partially basement and sometimes Buchak sediments. They are represented by clay–sandy sediments of coastal–marine and seldom continental facies. Their mineral composition is mainly quartz–glauconite.

Neogene system (N_1-N_2) is represented by Miocene and Pliocene sediments overlaying Paleocene rocks and basement. They are marine without any paleontologic species.

Quaternary sediments (Q) are not dismembered and overlap Neogene clay–lime sediments. They are eroded in river valleys and represented by loam, soil and modern sediments.

3.1.2. Structural and geological conditions

Folded structures are characteristic only for a lower structural level (crystalline basement). There are dome–like infrastructures in region combined mainly by granitoid. Synclinorium structures fulfilled by rocks of sedimentary–volcanic formation frame these domes.

Disjunctive dislocations are widely developed in the basement. Structures of submeridional direction prevail among faults.

Paleowatersheds of three orders are marked out in the Ukrainian shield. Paleowatershed of the I order divides basement surface into southern and northern slopes. Paleowatersheds of the II order have submeridional direction and divide paleodepressions. Paleowatersheds of the III order have different directions and divide offshoots of paleovalleys' heads.

The modern hydronetwork on the greater extent of the valleys washes out sedimentary rocks significantly cutting tertiary sand and coal–clay–sand sediments on different depth. The modern hydronetwork depends upon paleodepressions, directly. The geomorphologic conditions of area are defined by its location within eroded plateau on the left bank of Dnieper river.

3.2. Brief characteristics of oxidized and un-oxidized rocks of sedimentary cover of the Ukrainian shield

Churzin in summary section of sedimentary cover of the Ukrainian shield selects four types of characteristic of oxidized and unoxidized rocks of close lithologic structure (Fig. 1.) namely:

1–2: Upper Neogene and Quaternary oxidized and unoxidized rocks of upper clay layer. Unoxidized rocks include of clay of green and gray color sometimes with lime seams. Their composition is montmorillonite–hydromica with ferrous oxides.

Oxidized rocks were generated in a zone of infiltration of surface (atmospheric) oxygen waters.

3–4: Tertiary oxidized and unoxidized permeable sediments.

Unoxidized rocks are developed extremely within paleodepressions. These coal-clay-sand sediments overlay the basement. Oxidized rocks in section of sedimentary cover are located, as a rule, above unoxidized rocks. Unoxidized rocks show the conditions of their genesis and oxidized rocks – character of epigenetic changes.

3.3. Weathering crust as a main source of uranium

Three types of weathering crust of crystalline rocks are selected depending upon time of formation: old, young and transformed.

Old weathering crust of crystalline rocks has arisen in continental conditions as a result of transformation of basement under influence of weathering factors. The significant basement areas are located above erosion basis (both regional, level of the Black sea, and local, levels of the rivers). Obviously, these basement areas till now, since a moment of the Ukrainian shield creation as platform structure, are exposed constant weathering owing to infiltration of atmospheric precipitation containing oxygen and carbonic gas. The main enrichment of underground waters by uranium occurs during their transit from supply area to unloading basin (local drain) in process of oxygen–bearing underground water flow on a basement surface (on and through granitoid weathering crust which has high uranium clarke).

Thus, main source of uranium to create such deposits in coal–bearing sediments of the Ukrainian shield, in our opinion, is the mobile uranium of weathering crust of crystalline rocks.

3.4. Brief characteristics of uranium deposits

Uranium deposits in accordance to their reserves concern to middle and small–sized. Orebodies of all deposit morphologically have similar structure and are extended in the plan along paleochannel or shield of paleodepression. In the first case width of orebodies is controlled by width of paleochannel and changed from 50–80 m up to a several hundreds meters. In the second case orebodies of the same width are controlled by extension of wedge–out subzone of zone of country rock level–by–level oxidation. Length of deposits is 2–4 km.

The areas of main uranium deposits make hundreds thousands – millions square meters. Small–sized orebodies have surface of ten thousand meters (Fig. 2). In section balance deposits orebodies consist of numerous horizontal, wing–like and against each other orebodies which have complicated contacts between themselves. Mineralization forms ore–bearing zones. “Microrolls” formed within wedge–out of level–by–level oxidation zone of productive horizon sediments are telescoped in section. The thickness of orebodies at these areas reaches 10 and more.

The depth of ore is changed from 10–20 m to 70–80 m. According to the grade ore is low–grade and poor.

- The majority of uranium deposits of Ukraine have the comparable sizes,
- The scales of deposits depend upon area sizes of deposits.

3.5. Granulometric structure of country rocks

Tertiary sediments contain gravel, sand, dust and clay particles. Characteristics of uranium deposits of Dniprobas are the presence of a lot of dust particles among rockforming particles. Country rock and ore of the same deposit are very close according to their composition. At the same time each deposit has certain composition of country rock and ore.

The general feature of all sandstone uranium deposits of Ukraine as well as of other regions in the world is the low permeability of ore in comparison with permeability of country rock. As a whole all sandstone uranium deposits of Ukraine are characterized by a pressure head mode of underground water of productive horizon. However value of water pressure and water level depth essentially differ for different deposits.

One of characteristics of natural conditions of uranium deposits of Ukraine is that the productive horizon of all explored uranium deposits can be marked by simple engineering and geological conditions. Quick ground and karst zones are absent in productive horizon. There are quick ground and cavernous limestone above ore horizon at separate deposits (Devladovskoe and Safonovskoe uranium deposits, respectively).

Uranium deposits of the same genesis, geological structure and hydrogeological conditions in sedimentary cover of the Ukrainian shield according to the majority of indications with reference to their mining by underground leaching are practically similar. Distinctive features of deposits and separate orebodies are (N.N. Makarenko, 1986):

— Geological condition of deposits of balance ore,
— Scales of uranium deposits defining by their area sizes,
— Granulometric structure, coal material content and ratio of permeability of ore and country rock,
— Rate and composition of water of productive horizon,
— Engineering and geological structure of deposit defining by features of layers above ore.

3.6. Mineral and petrographic characteristics of ore

1. The uranium ore of sandstone deposits and orebodies have identical mineral structure, uranium mineralization and lithologic varieties of country rocks. Uranium ore is represented by brown coal, sand and clay. Pure varieties of these rocks are not marked among ores. All of them have mixed structure.

The uranium minerals in coal sand and clay are represented by smallest grains of coffinite and uranium oxides in aggregates with pyrite as well as by uranium sorption on iron hydroxides, kaolinite forming auras around inclusions of pyrite, coal and uranium minerals.

2. Chemical characteristic of uranium ore of different sandstone deposits of Ukraine is identical. This ore is coal–aluminosilicate.

The uranium almost evenly is contained in all classes of granulometric composition with small enrichment in fine class.

In ore sand sorbate and gumate uranium makes about 80%, in coal and clay it is changed from 5 up to 15%. Metal–organic and isomorphic uranium is not extracted from accessories by these solvents that makes from 1% up to 4.5%.

Several water–bearing horizons are productive for uranium (from one to three in different parts the Ukrainian shield) joined in one water–bearing complex presented by Tertiary sediments of channel facies. The distribution of a productive complex is controlled by paleovalleys. The supply of productive horizon occurs by atmospheric precipitation at outcrops of permeable Tertiary sediments.

The upper waterproof of deposits is represented by clay and rocks of mixed composition. It is distributed practically at all deposits. The waterproof thickness is changed from 1 m to 10–12 m and as a rule makes 3–5 meters.

The role of lower waterproof in all cases executes weathering crust of crystalline rocks underlying productive horizon practically everywhere. The structure of sediments of productive horizon is rather motley. In spite of the fact that predominant lithologic difference of ore and country rocks at all sandstone deposits of Ukraine is the sand with different sizes of grains there are sediments of different grain–size structure, from clay to sand and sand–grus sediments, in productive horizon.

The high degree of variability of sediment structure results in significant filtration heterogeneity of productive horizon.

The depth of underground water level from a day surface is changed from the first meters up to several tens meters and depends upon a relief of a day surface.

As a whole, the chemical composition of water of productive horizon is changed over a wide range of anion and cation contents. Mineralization of water varies in enough wide limits also.

The research of filtration properties of sediments of productive horizon of sandstone uranium deposits of Ukraine has shown that the value of filtration ratio of the majority of experimental drillholes installed in different parts of uranium deposits is changed from 1 to 10 meter per day.

Characteristics of all deposits of Ukraine are also that underground water of productive horizon is not used almost for economic needs of the enterprises and population. In the long term their use also is improbable as this water has frequently unsatisfactory quality and limited distribution.

3.7. Ore epigenetic zones and process of uranium formation

There are five main top–down epigenetic subzones associated with development of ground oxidation zone in sedimentary cover of the Ukrainian shield:

1. Subzone of surface oxidation adjacent to surface (infiltration).
2. Depth subzone of surface (ground) oxidation.
3. Subzone of level–by–level oxidation.
4. Subzone of uranium mineralization.
5. Subzone of epigenetic not altered rocks.

The subzone of level–by–level oxidation is ore–forming. This subzone is divided from a depth subzone of ground oxidation within paleochannels fulfilled by Tertiary permeable coal–clay–sand sediments. It is developed into layers of permeable sediments by means of “flow” of ground water in them. The form of a subzone of level–by–level oxidation in plan and especially in section is complex that is explained by frequent overlapping and accordingly by filtration heterogeneity of alluvial sediments fulfilled paleodepressions. In section this subzone represents multilayer flows of oxygen ground water into Tertiary coal sediments in the form of “tongues”.

Sedimentary rocks in subzone of level–by–level oxidation are painted mainly in yellow that is stipulated by presence of iron here in oxidized form. The area of wedge out of level–by–level oxidation subzone in coal sediments controls modern geochemical barrier and it is a place of uranium accumulation.

The subzone of uranium mineralization represents “polyroll” consisting of numerous “microrolls” formed on “tongues” of level–by–level oxidation that corresponds to multilayer structure of productive Tertiary coal sediments. The subzone of epigenetic not altered rocks is represented by green and gray clay of upper essentially clay sediments and Tertiary coal–clay–sand sediments of gray, black and dark-brown color with minerals that are indicators of reduction environment: glauconite, carbonate, pyrite and coal substance.

The process of uranium formation according to N. Makarenko and G. Churzin proceeds as follows: surface water (atmospheric precipitation) percolates through a loam–clay sediments on watersheds of platform basement. During infiltration ground water is partially enriched by uranium. Then, under gravitation, in depth subzone of surface oxidation underground water flows down on basement weathering crust in paleodepressions. The part of water will penetrates into this basement weathering crust and goes through it. Other part of underground water “rolls down” on a surface of weathering crust in paleodepressions. Then located stream of water goes to the local drain through underground drains. During such movement the leaching of uranium from basement weathering crust occurs. This uranium in the form $Na_4[U_2$ $(\ _3)_3]$ is transported by oxygen ground water from area of underground water supply to area of its unloading.

On the contact of oxidized and not oxidized rocks in brown coal sediments mentioned complex is broken up and, being released from uranyl ion which is being sorbed by coal and partially clay substance in a zone of uranium formation, forms uranium deposits.

On the basis of stated above it is possible to make the following conclusions:

1. A geological structure and the hydrogeological conditions of uranium deposits are monotonous enough and are defined mainly by the following:

— Two–layered structure of the Ukrainian shield (sedimentary cover and basement),
— Adjustment of uranium mineralization to Tertiary coal sediments of different granulometric structure which distribution is controlled by paleovalleys and paleochannels in the basement,
— Supply of productive horizon by atmospheric oxygen–bearing water forming uranium formation,
— Location of low–grade uranium ore on the boundary of wedging out of ground level-by-level oxidation zone of permeable sediments of productive horizon limited by waterproofs,
— One–layered distribution of ores in section in the form of ribbon–like zones (up to 100 m) of significant square;
— Monotonous for different deposits lithologic type and texture of ore, structure of cement as well as content of impurities (coal material, sulfides, carbonates); the ore can be easily treated by sulphate solutions.

2. Middle– and small–sized sandstone uranium deposits of Ukraine are as a whole characterized by significant similarity of a geological structure and hydrogeological conditions.

3. Alongside with general similarity uranium deposits and separate orebodies have features of geological and hydrogeological structure that define different conditions of mining by ISL method.

3.8. Character of filtration heterogeneity of productive horizon and its influence on the process of underground uranium leaching (Fig. 4.)

Vertical filtration heterogeneity of the Ukrainian uranium deposits is stipulated by frequent alternation of sand, clay and coal–clay–sand layers as well as presence of clay and gravel lenses in section.

According to the character of "vertical" filtration heterogeneity of productive horizon Makarenko determines its three varieties:

1) There is a high permeable layer in section of productive horizon with filtration ratio from 10 to 30–40 meters per day, represented by coarse sand, sand–gravel sediments. It is located at the bottom of a section at certain gypsometric level and has significant extent in the plan.
2) There are high permeable layers of limited sizes in the plan in section of productive horizon located in different parts of horizon and on different gypsometric levels.
3) Layers of high permeable sediments in section of productive horizon, despite of a general high degree of visibility vertical filtration heterogeneity, are absent.

The character vertical filtration heterogeneity influences significantly oxidation of the block of leaching and creation of productive solutions as well as extract of useful component. This parameter essentially influences all parameters of the ISL process (Figures 5 and 6).

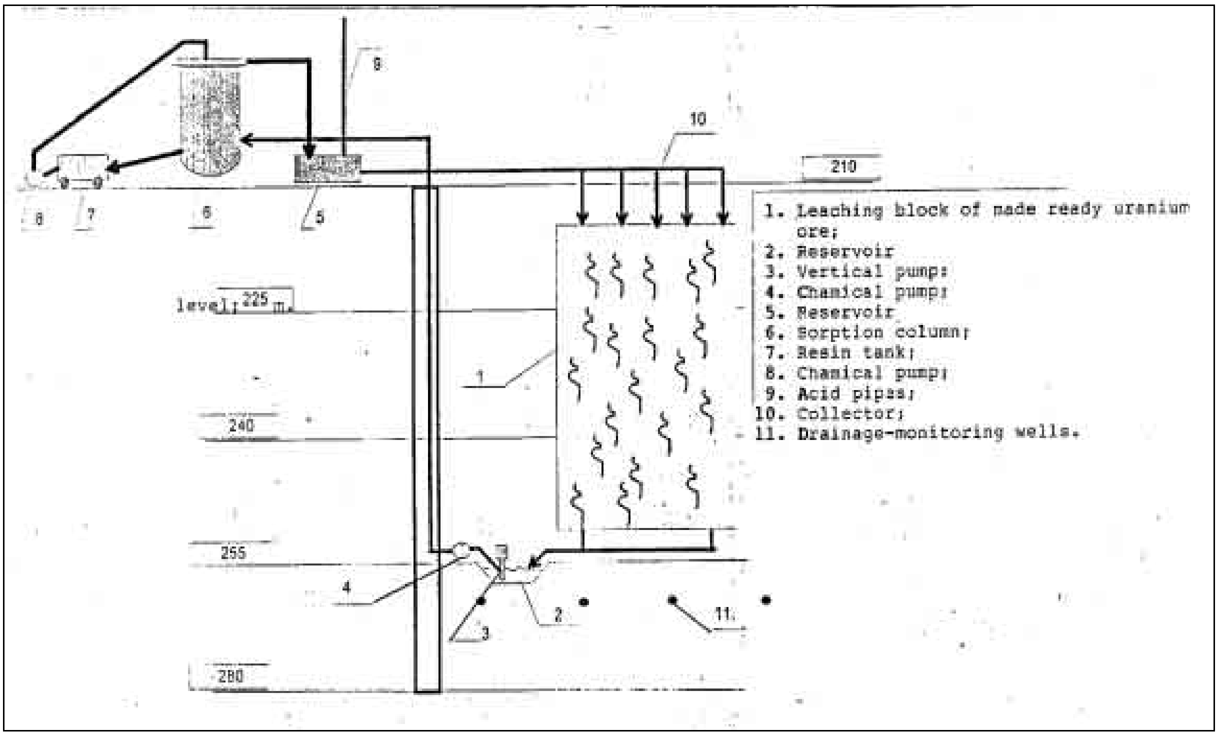


FIG. 4. The East integrated mining and concentration works, the principle scheme of leaching block.

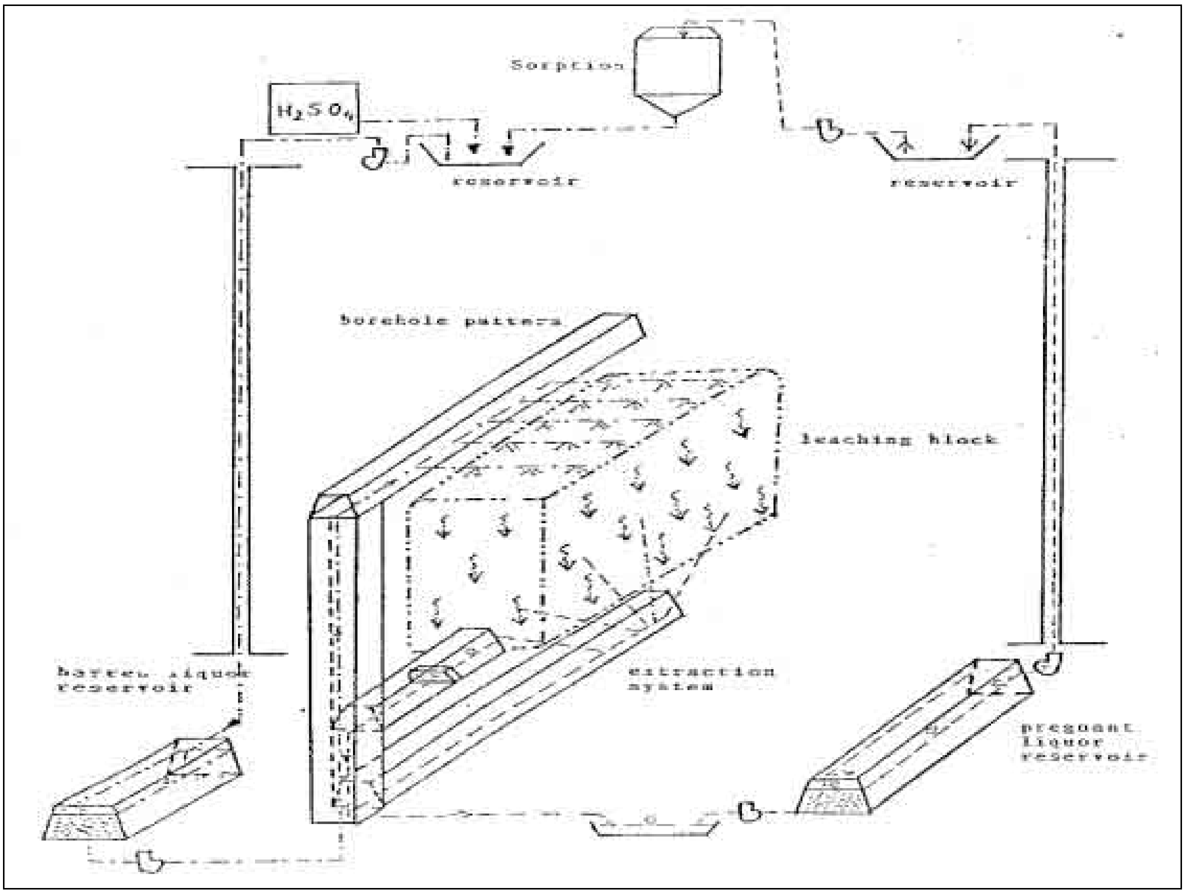


FIG. 5. ShidGZK: the East integrated mining and concentration works, the scheme of leaching block by sulphuric acid.

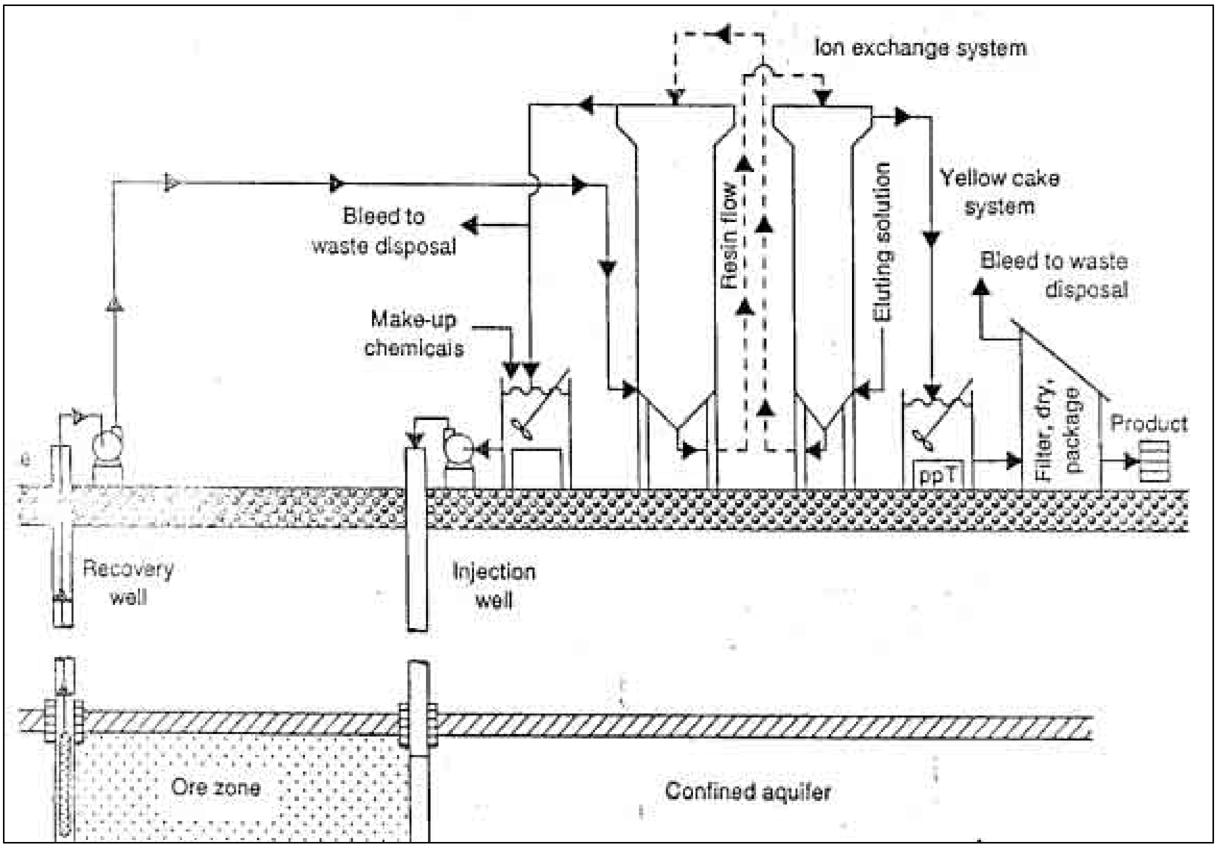


FIG. 6. The internationally approved ISL technological scheme which the State Geological Enterprise "Kirovgeology" are planning to implement.

3.9. The result of field test at the Safonovskoe uranium deposit Geotechnological parameters of the ISL process

All problems of field tests were solved. The experiment has led up to an achievement of uranium extraction of 78% in the Central block of drilling area (checking drilling data) under of given 70%. The basic data for account and clarification of geotechnological parameters of the ISL process are obtained and the methods to use results of experience at all deposits are determined. The data about optimum technological modes ISL are obtained also.

The suitability of all uranium ores, in independence from their quality is established. The highest speed of uranium extraction from the ordinary ore is determined by field and lab tests.

The average concentration of uranium in technological solutions (without contents and tails) during the period of active uranium leaching in zone of maximum extraction in central drillholes of the Central block has made 33 mg/l. The relation for period of active metal leaching in a zone of maximum extraction has made 2.6. Acid capacity of rocks of productive horizon is 0.7 (7 kg/t). Specific expense of acid is 83 kg / kg.

3.10. Result of field test based on inspection drilling data

As a result of the analysis of data obtained from technological, observant and inspection drilling, the oxidation zones of country rocks of productive horizon and zone of uranium leaching and redeposition, ore grade according to uranium extraction are determined. Correction factor to account expected uranium extraction under degree of ore oxidation is determined. The dependence of uranium extraction degree upon ore grade (uranium cut–off grade) is determined also.

The zones of uranium leaching and redeposition are marked based on ratio between radium and uranium in ore intervals. At the same time radioactive balance in ores before ISL test and legitimacy in change of distribution radium in ISL process taken into account are determined preliminarily.

Ore were divided into 2 groups based on actually achieved metal extraction: a) with a high degree of extraction – coal sand in which about 80% of metal is concentrated; b) with the lowered extraction – coal–clay–sand ore, ore in lenses of brown coal and coal clay within essentially sand rocks of productive horizon.

During solving problem of deposit exploration methods of ore parameters determination, boundaries of productive horizon, control of the equipment of technological and hydrogeological drillholes, control of ISL field test procedure, definition of results and calculation of technological parameters, geotechnological dividing of deposit into districts based on laboratory and field research are specified and developed (for Dniprobas).

For the first time reference of small– and middle–sized hydrogen uranium deposits of Dniprobas with uranium content about 0.02–0.04% and high filtration heterogeneity in section of productive horizon to industry is practically proved. In connection with that the exploitation of the Safonovskoe deposit is begun even before completion of exploration. This is promoted by the natural factors typical for such deposits, namely:

— Forms of uranium in ore easily extracted by weak sulphate solutions; mainly sand structure of country rock with good water permeability that provides high (not less than 70%) uranium extraction,

— Low acid capacity of country rocks in connection with absence of carbonates and other acid capacious substances,
— Ore depth which is rather favorable for ISL method as well as practically universal localization of productive horizon among waterproofs,
— High aria factor of ore formation which is equal 1 as a rule.

In this connection it is expedient to emphasize presence of a group of deposits in Dniprobas with explored and previously evaluated reserves, which are similar to the Safonovskoe deposit. The low costs and speed of metal mining organization at reviewed type of deposits taking into account existing mineral base and possibility of its extension (including all regional geological and economic factors) allow to evaluate perspectives of development of ISL mining in Dniprobas highly enough.

3.11. Evaluation of ore complex of sandstone uranium deposits of Ukraine

It is established that the following chemical components besides main ore component (uranium) are accumulated in structure of epigenic zone: selenium, molybdenum, rhenium, vanadium, yttrium and elements of lanthanum group (K. Brovin and V. Natalchenko).

In connection with that the proofs of complex ore of sandstone deposits as have appeared rather recently and major part of such deposits were discovered and explored in Ukraine per prior years the question of evaluation of complex uranium ore remains poorly investigated.

At the same time during exploration of the latter (in terms of discovering) Safonovskoe deposit we have carried out evaluation of selenium and molybdenum in outlines of high-grade uranium ore which make accordingly 500 t and 300 t.

3.12. Result of preliminary research of selenium and molybdenum leaching

The research is conducted in five versions with different leaching reagents:

— 1.5% solution of sulphuric acid,
— The same with addition of hydrogen peroxide,
— 3% a solution ammonium carbonate with addition of hydrogen peroxide,
— The same with addition of potassium permanganate,
— 3% solution of sulfurous sodium.

When sulphuric acid is used to leach uranium both with addition of oxidizer and without it the uranium is extracted only in solution. Selenium and molybdenum remain in cake. In case of using of ammonium carbonate the high extraction of uranium and molybdenum in solution is observed. When potassium permanganate is added selenium is extracted in solution.

The following technological sequence of complex ore mining is the most rational:

(a) Uranium extraction with application of 1.5% solutions of a sulphuric acid,
(b) Underground liquidation of residual sulphuric acid using alkali solutions,
(c) Selenium and molybdenum extraction by solutions of sulfurous sodium. Additional extraction of residual uranium is also possible at this time.

3.13. Environmental protection during mining of sandstone uranium deposits in Ukraine

As it is known that the ISL technology to mine uranium deposits is more rational and sparing in relation to environment than traditional mining method. Especially it concerns to such characteristics as:

- Specific water consumption is 1.9–2.7 m^2 per standard unit of production, in case of underground mining – 10.6–21.9 m^2,
- Pollution of ground surface,
- Area of surface complexes.

The environmental protection within uranium deposits of Ukraine acquires the special significance since they are located in areas of fertile black soil agricultural areas where provision with underground fresh water for drinking water–supply is low. The thickness of a fertile layer within deposits makes 0.4–0.9 meters.

In process of uranium underground leaching the weak solutions of a sulphuric acid can occur partial pollution of a ground surface and underground waters become soiled.

The sites of possible congestion of earth and surface drains polluted with technological solutions are being revealed and their further clearing is carried out. The level of possible pollution of waters in artificial reservoirs located in beams near deposits is constantly inspected.

Rehabilitation and returning of grounds in an agricultural turn–over is carried out stage by stage according to the schedule of mining and sequence of deposit development. To limit underground spreading of technological solutions the following requests are executed:

- The balance of volumes injection and pumping is controlled in leaching process,
- Operational drillholes are carefully cemented outside to prevent flow of solutions from one water–bearing horizon to another,
- On a closing stage of leaching the washing of rocks by sheet or returnable solutions arriving from installed operational blocks is carried out,
- All kinds of drillholes are tamped during their liquidations. The observation drilling grid both on productive and in adjacent horizons will be organized.

Main problem in conditions of Ukraine regarding environmental protection during exploration and mining of sandstone uranium deposits by ISL method is the temporary ground allotting. All other questions including underground pollution by sulphate solutions are solved without a heavy damage to environment. In case of competent realization of operations these negative effects can be minimized and practically eliminated on a day surface.

The forecasting of sandstone uranium deposits is carried out on the basis of the collection and analysis of drilling geological materials of various purposes. The main request is the availability of description of lithologic structure and coal sediments, and that is very important of natural color of drilled rocks.

All territory of research is divided into three areas according to the degree of perspectives:

1. The perspective areas where so called “critical regions” are determined - contact between zone of modern ground oxidation and coal sediments.
2. The unpromising squares where “critical regions” are absent.
3. Areas where additional exploration with reconnaissance drilling and core sampling of all sedimentary section up to depth below modern regional erosion basis is required.

3.14. Main directions of further activity

As it is known, the ISL method was developed and applied for the first time in the world on the Devladovskoe deposit. In October, 1961 the productive working solutions were obtained and since 1964 the industrial exploitation was begun. The successful operation was completed in November, 1983.

Till now Kirovgeology has discovered ten sandstone deposits in Dniprobas which are suitable for ISL mining. There is a significant potential to discover new deposits both within known areas and in other less explored parts of Dniprobas.

As it is known, the problem of complex ore both at known and discovered deposits should be studied. By–product extraction of selenium, molybdenum, rheniurn and rare earth elements from ore increases economic efficiency of operations essentially.

4. Conclusion

The heap and in situ leaching are developing the energy resource saving technology of poor uranium ore mining and processing with minimum influence on environment.

The heap and block ISL technology provide:

- 30–40% of the cost reduction of uranium ore mining and processing,
- 15–20% waste reduction (reduction of rock and dirt dumps, as well of outbalance ore),
- Reduction in 2–3 times of solid waste after the hydro-metallurgical plant,
- Reduction in 2–3 times of technical water for yellow cake fabrication,
- Reduction in 2–2.5 times of sulphuric acid, and, sulphuric anhydride and aerosols emission,
- Reduction in 2–3 times of nitric oxide emission from the hydrometallurgical plant,
- Reduction in 2–3 times of ore dust emission by reason of uranium ore transportation decreasing,
- Waste utilization by putting into mine as laying in place of sand.

5. Perspectives

After the participation in the IAEA–SME Training Programme on “In Situ Leach Uranium Mining – Planning, Operational and Environmental Aspects” that was being held in Casper, Wyoming, from 13 September through 10 October 1998, Ukraine is recommencing the ISL uranium mining but with alkaline leach system.

4 ISL modules are planning for operation with annual productivity of 1000 metric tons for next 10–15 years. The investment case is in US $ 250 million.

Uranium mineral base of the Republic of Uzbekistan

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“Kyzyltepageologiya” State Geological Enterprise of State Committee
on Geology and Mineral Resources of the Republic of Uzbekistan

The main uranium estimated and inferred resources making up the mineral base of Republic of Uzbekistan are located in the Central Kyzylkum uranium–ore province.

Geologically the province is a block of young epi–Hercynian platform re–formed by Alpine tectogenesis. Numerous NW and approximately N–S fractures have broken up the province into a mosaic of uplifted and lowered blocks. Fold pre–Mesozoic foundation is outcropped in core parts of the uplifted blocks. Sub–horizontal Cretaceous–Paleogene–Neogene deposits of 600 m to 1000 m thickness cover the lowered blocks. Section of the deposits is presented by multiple alternation of permeable grit–sand and non–permeable silt–clay packages.

Uranium deposits of the province belong to two types: “sandstone” and “black–shale” ones.

The “sandstone” type forms stratiform uranium deposits in permeable Cretaceous and Paleogene sand horizons on redox barriers of bed oxidation zones. Mineralized zones of this type have simple or complex roll forms in section, and long, very tortuous tapes in plan. The width of these tapes can be of many hundred meters, and the length of several tens kilometers. The age of the mineralization varies from 10 Ma to recent. The “sandstone” type of ore is oxide one (pitchblende, pitchblende–uranium black, sometimes with coffinite admixture). Average grade of uranium is 0.026% to 0.180%. Along with uranium, the ore has selenium, vanadium, molybdenum, rhenium, scandium and lanthanoides in commercial levels. Depth of the deposits is 50 m to 600 m. The deposits of this type occur in eight Cretaceous and in three Paleogene water permeable horizons.

Twenty-two deposits of the “sandstone” type have been identified in the Central Kyzylkum province.

The second type deposits are connected with Pre–Cambrian – Early Paleozoic chert and carbonaceous slate. The deposits have either stratiform or complex stockwork morphology and belong to poligenic type. They were essentially re–formed in a Neogene–Quaternary oxidation zone, and this re–formation to the great extent defined current morphology of the deposits. The age of the mineralization varies from 400 Ma to recent. Oxides (pitchblende-uranium black) and uranyl–vanadate–phosphates present the “black-shale” ore. Depth of the deposits is 20 m to 450 m. Average grade of uranium is 0.06% to 0.132%. Economic and sub-economic grades of molybdenum, vanadium, yttrium and gold have been identified in the ore as well.

5 deposits of the “black–shale” type have been discovered in the province.

As for 1 January 1999, explored traditional uranium resources (RAR+EAR by IAEA’s classification or C_1+C_2 by State Committee on Geology of Republic of Uzbekistan’s classification) are: 185.8 Kt of uranium, including 138.8 Kt of the “sandstone” uranium and 47.0 Kt of the “black–shale” uranium. These figures show that traditional uranium resources of Uzbekistan did not change in practice. Mined out uranium of the “sandstone” deposits was compensated by exploration, the “black–shale” deposits are not under operation last years in Uzbekistan.

114.7 Kt of uranium of the “sandstone” type from 138.8 Kt can be extracted by underground leaching with operation costs not more than $40/kg of uranium, 24.2 Kt will cost up to $130/kg due to complex geo–technical conditions. 36.0 Kt of uranium from 47.0 Kt of the “black–shale” type are open pittable with subsequent heap leaching with operation cost not more than $40/kg of uranium. 11.0 Kt located deeper can be mined out with operation costs up to $130/kg.

As for 1 January 1999, inferred traditional resources (EAR–II+SP or P_1+P_2) are 242.7 Kt of uranium, including 188.8 Kt of the “sandstone” type and 53.9 Kt of “black–shale” type. Small, 3%, reduction of the inferred resources compared with 1 January 1997 occurred because part of these resources was provided up to EAR–I category after further exploration.

Navoi Hydro–Metallurgical Plant (NHMP) deals with uranium operation on the territory of Uzbekistan since 1956. The NHMP comprises following mining operations: Severnoe operation in Uchkuduk, #5 operation in Zafarabad and Yuzhnoe operation in Nurabad. Five modern towns with total population about 500 000 have been constructed on the base of the uranium mining industry.

The NHMP is an industrial complex having whole cycle of uranium production: it finances uranium reconnaissance and exploration, which are fulfilled in the main by “Kyzyltepageologiya” State Geological Enterprise (SGE) of the State Committee on Geology and Mineral Resources of Uzbekistan, mines and processes uranium ore to uranium concentrate in form of uranium mixed lower and higher oxide.

In terms of mining technique, underground leaching is the main method of operation. Earlier (before 1995) the NHMP had open pit and underground mines. All mining techniques are of general use but some mining technological regimes, which are now–how of the NHMP.

Currently, the NHMP exploits eight deposits, which comprise about 28% of all estimated resources of the “sandstone” type.

It is notable, that exploration activity in the Republic is focused on deposits of the “sandstone” type or promising areas where discovery of such type deposits is possible. Non–explored traditional resources have a good enough chance to be provided up to explored resources after worked out reconnaissance–exploration works. All this witnesses to a stable state of the uranium mineral base of Republic of Uzbekistan.

Certain studies are carried out to extend potential of the mineral base and to study possibility to identify non–traditional for the Republic uranium deposit types competitive on the world market. Prerequisites to discover the “discordance” type deposits with contrast ore in foundation are under study. The search for low cost ore analogue of sub–surface recent deposits connected with Quaternary riverbeds in the North America is fulfilled.

Complex Geological–Ecological Expedition of “Kyzyltepageologiya” SGE studies radiation situation in the Republic. The studies are carried out in various scales from 1:500000–1: 1000000 to 1: 10000 – 1: 2000.

Background radioactivity of territory of Uzbekistan is defined by radionuclides (mainly uranium and thorium) dispersed in rocks and soils. Natural background level of gamma-radiation on major part of the territory is 10–30 μr/h. Annual irradiation dose for the population is 90–250 millirem/year while normal level is 500 millirem/year.

Territory of Uzbekistan can be conventionally divided into three main zones by the value and character of natural background level of radioactivity: NW with 15–20 μr/h gamma–field, central with very contrast gamma–field from 5 μr/h to 60 μr/h depending on outcropped rocks and SE with 20–40 μr/h gamma–field.

Technogenic radionuclide pollution of territory of Uzbekistan occurs due to mining operation activity in general.

Environmental conditions in underground waters on areas of mineral deposits are unfavorable even before mining. The underground waters are highly mineralized (3–8 g/1), with increased contents of sulfates, chlorine, strontium, selenium, iron and manganese. Radionuclide level in underground water of ore zones 5 to 10 times increases the maximum permissible concentration.

During mining and processing of uranium ore radioactive dust and radon pollute atmosphere, radionuclides pollute waste and underground waters. All this causes necessity of measures for protection of the nature. The NHMP isolates the uranium production wastes, fulfills dust suppression, purification of wastewater, construction of burials.

Following succession of nature protection measures used to be implemented in case of uranium operation and processing plant liquidation: a study for following projecting of the liquidation; projecting of the liquidation and land reclamation; co–ordination of the project with State Committee of Environment of Republic of Uzbekistan; liquidation and reclamation; turning over the reclaimed lands to the local authorities.

Republic of Uzbekistan in its policy follows and fulfills all items of the Agreement between Uzbekistan and IAEA about guarantees in connection with the Pact about non–spreading of nuclear weapon and Additional Protocol to the Pact.

Uzbekistan has no needs in uranium currently. All the metal is exported from the Republic and sold to other countries. In nearest years all uranium will be mined from eight deposits. One–two additional properties could be involved in operation. There is no uranium storage in the Republic as for 1 January 1999.

Malargüe complex closure — Estimated cost, Argentina

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Abstract. Since the early fifties in the Argentine Republic, uranium ore deposits have been mined and yellowcake produced by different metallurgical processes in several sites. At the end of the production stage, the operator started the facilities decommissioning, according to the procedures approved by the Regulatory Authority, and the process tailings were confined and monitored to avoid their dispersion into the environment, but without final disposal. The present regulations and standards, internationally accepted, propose the suitable management of the tailings with the objective to return the disturbed ecosystem to the community either in the same or similar conditions than the original one. For that reason, the Comisión Nacional de Energía Atómica – CNEA (National Atomic Energy Commission) encouraged the "Environmental Remediation of Uranium Tailings Sites Project", which consists in the design and implementation of an integrated management plan (Fig. 1).

1. Uranium mine and mill tailings

In Argentina, there are several sites with uranium mine and mill tailings. They are still under the control of the operator waiting for remedial actions. They are: Malargüe (700 000 t of tails), Huemul and San Rafael (1 895 000 t of tails) in Mendoza province, Córdoba (57 000 t of tails) and Los Gigantes (2 400 000 t of tails) in Córdoba province, Tonco (500 000 t of tails) in Salta province, Pichiñán (145 000 t of tails) in Chubut province, La Estela (70 000 t of tails) in San Luis province and Los Colorados (135 000 t of tails) in La Rioja province.

2. Environmental remediation of uranium tailings sites project

Project objective

The project objective is the uranium mine and mill tailings management and the remediation of the sites, in order to mitigate and control the environmental impacts generated, taking into account the provincial, national and international regulations in this matter.

Project scope

The scope of the project covers remediation works and studies, consisting in the implementation of remediation works as well as environmental audits, environmental impact assessments, risk analyses, public consultation processes and preparation of engineering plans and designs at the different sites.

Design objectives

- The dose limit specified by the Regulatory Authority should be observed,
- The annual releases of radioactive and non-radioactive contaminants to the environment should be kept under the limits specified by the Provincial and Federal Authorities,
- Any exposure arising from the site must respect the ALARA (**A**s **L**ow **A**s **R**easonably **A**chievable) principle,
- The options that minimize the institutional control and the maintenance should be preferred,
- The use of passive barriers to confine the contaminants should be maximized.

FIG. 1. Uranium activities in Argentina.

3. Legislative and regulatory framework

The laws in this area, that we need to take into account are:

Ley Nuclear (Nuclear Law)

The Nuclear Law establishes the responsibilities in the nuclear field. Two organisms are included: the “Comisión Nacional de Energía Atómica” – CNEA (National Atomic Energy Commission) and the “Autoridad Regulatoria Nuclear” – ARN (Nuclear Regulatory Authority).

Norma Básica de Seguridad Radiológica AR 10.1.1 (Basic Standard of Radiological Safety) 1995

The purpose of this standard is to achieve an appropriate level of protection for people against the risks associated with the exposure to ionizing radiation and the radiological safety of the facilities or the practices.

The scope of the standard is limited only to the protection of human beings only. It is considered that standards of protection that are adequate for this purpose will also ensure that no other species are threatened as a population, even if individuals of the species may be harmed.

Código de Minería (Mining Code)

The Mining Code (MC) establishes that the mining must be done in accordance with policy, safety and preservation rules of the environment. It gives the environmental protection legislation frame.

The environmental and mining agencies in each province are the enforcement authorities of the code.

Ley de Gestion de Residuos Radiactivos (Radioactive Waste Management Law)

It creates the National Radioactive Waste Management Programme, belonging to the National Atomic Energy Commission. This programme deals with the treatment, conditioning, storage, transport and disposal of low, medium and high level radioactive wastes, as well as developing and implementing all the mechanisms required to attain their objectives.

4. Malargüe

At present the project is starting with the decommissioning of the Malargüe complex. The Malargüe Complex is located about 500 m NE of the northern outskirts of the town of Malargüe. The town is 420 km south of the city of Mendoza, the capital of the province.

This facility started up in 1954 producing yellow-cake with surrounding minerals. The process was conventional acid leaching and had crushing, wet milling, agitated acid leaching, thickening, solvent extraction and ion exchange, precipitation, filtration, drying and packing. The original process and capacity changed until reaching 250 t/d of mineral. This plant operated until 1986 when it was closed up (Fig. 2). Along its life this complex produced 752 000 kg U.

About 700 000 metric tons of uranium tailings were disposed off during the 32 years of operation of the Malargüe facility. The average grade of uranium ore processed by the mill was 0.14% of uranium.

5. Decommissioning alternatives

The more suitable alternatives analyzed for tails remediation was:

- Remediation in situ,
- Remediation in the same place but with displacement,
- Remediation in other place in the south of Malargüe,
- Remediation in San Rafael.

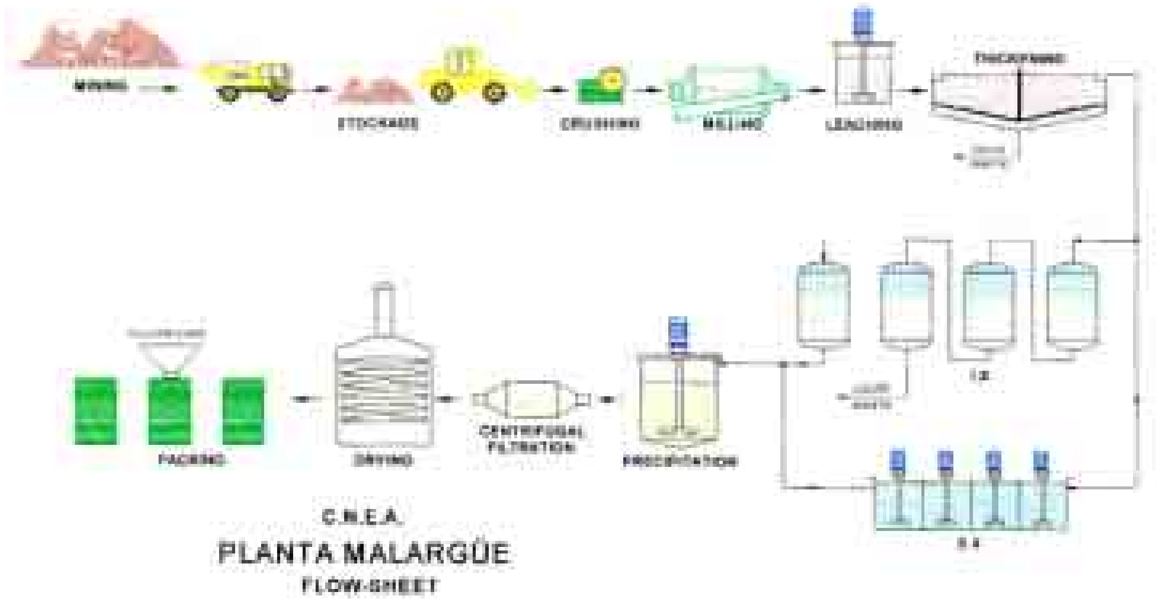

FIG. 2. Malargüe plant

6. Alternative selection

Having studied all the possibilities, we made a chart with the 10 items we consider most important and used pondered weight (Table 1).

Table I. Alternative assessment matrix

		Options			
Items	**%**	**1**	**2**	**3**	**4**
Sociological-institutional factor	18	2	4	3	1
Start up time	2	3	4	4	1
Execution time	5	4	3	1	4
Conceptual engineering	5	1	3	4	3
Monitoring	15	1	4	4	4
Long time works	10	1	4	4	4
Environmental impact during decommissioning	5	4	3	2	1
Environmental impact on long term	22	1	3	4	2
Costs	8	4	3	1	2
Deferred costs	10	1	3	4	2
Total	100	44	**86**	83	60

In this framework we assign some importance percentage to the different items, and we relate the relative incidence of the item in each option. We assign a number from 1 to 4 and consider the highest as the most favorable and the lowest as less favorable. These numbers are equivalent at: 1=25%, 2=50%, 3=75%, and 4=100% of the first column. Then we sum all these results and the highest sum is the best option.

Once it is selected, the engineering for the disposition of the mineral is carried out.

7. **Engineering design** (Fig. 3)

The following design was developed:

▪ Foundation

In order to prepare the new site for the wastes, it should be necessary to perform different tasks such as decontamination of the soil and preparation of the foundation in order to homogenize the soil base response to avoid the differential settlement.

According to the soil characteristics and the total amount of materials to be disposed off, the first actions to be taken on the foundation soil are:

- To dig the first 30 cm,
- To scarify, and then
- To compact the soil.

▪ Engineering barrier

The proposed confinement system is composed by a natural barrier of materials, arranged in different layers, according to a design.

Once the soil has been compacted, the laying placement of the lower barrier of the system follows. This barrier consists of:

- Porous material,
- Sand-slimy, and
- Clay.

▪ Tailings transport and disposal

The physical, chemical and mechanical characteristics of the tailings were studied. The assessment of these data allowed the selection of the most filled methodology to remove the material from the existing pile.

Furthermore, the tailings vertical extraction was decided, according to the granulometric studies and pilot assays on terraces of work scale bank. The tailings will be moved to the new site by trucks, controlling dampness, in order to prevent powder pollution.

Wastes will be arranged in compacted layers, and will be neutralized with lime in order to stabilize them. Due to the fact that the materials are heterogeneous, they will be located according to their mechanical behaviour, i.e., those of greater resistance will be located in the lower part of the system and those of smaller in the upper part.

▪ Cover

The tailings will be covered with a natural multilayer barrier. The objectives of the multilayer barrier are: to reduce the radon release and gamma radiation, to minimize the rainfall infiltration, to prevent the dehydration of the clay layer and to provide a barrier against the erosion in the long term.

The multilayer barrier is composed by a clay compacted layer, a sand-slimy soil compacted layer and the last, is a rocks layer.

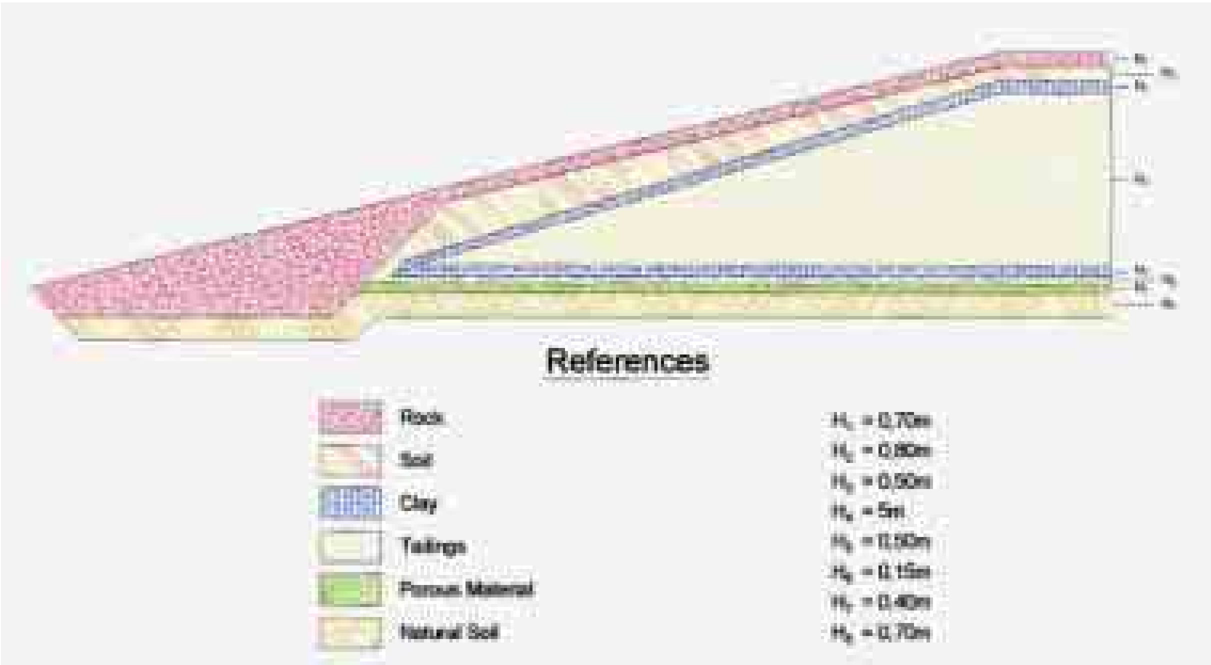

FIG. 3. Confinement system - Cross section.

8. Project execution and costs

After concluding the productive stage in 1986, the natural drying of the liquid wastes began and we started filing the relevant institutions to obtain the necessary approvals.

Approvals

Previous to initiating work approvals were obtained of: ARN and Government of Mendoza. These works did not generate any cost because they were made by CNEA.

Beginning of the work

After agreements were achieved the dismantlement of the complex began.

Demolition of facilities

The whole equipment in the industrial complex was dismounted and decontaminated with acid laundry. Some parts were sold and others moved to different sectors of CNEA.

All fixed facilities such as buildings and masonry structures were demolished and they were decommissioned in the mineral tails.

All the metallic structures and the pipes were reduced to small pieces and placed together with the mineral tails.

The floor of the industrial complex was removed until reaching the non-polluted underground. This material extracted was also settled with the existent tails.

Preliminary works

A drainage was built to maintain depressed the underground water level due to an eventual extraordinary ascent, impeding its contact with the tails sector. The superficial drainage of the sector was also stabilized. Now the surface of the first sector is being cleaned and prepared for the beginning of the final work.

Demolition of facilities	$ 1 000 000
Preliminary works	$ 1 000 000
Provision and settling of barriers	$ 5 600 000
Cleaning of contaminated soils	$ 400 000
Setting and compacting clean soils	$ 400 000
Tails deposition	$ 2 300 000
Final parking	$ 100 000
Deferred costs	$ 400 000
Assumed final cost	$11 200 000

14.89 US $/Kg U produced

These works are expected to be finished by mid 2003.

Decommissioning and reclamation of ANHUA uranium mine

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Abstract. Since the late 1980s a number of uranium production facilities in China were closed and are in various stages of decommissioning. To date 5 mines have been decommissioned. ANHUA mine is situated in west part of Hunan province in South China. The production of uranium ore began in 1974 and stopped in 1986. Decommissioning and reclamation programme started in July 1992 and completed in May 1997. This paper describes the experience in sealing of drift entrances, covering of waste rock piles and rehabilitation of cadmium contaminated farmland with replantation.

1. Introduction

ANHUA Uranium Mine is situated in west part of Hunan province in South China. It is the medium size underground mine with the capacity of 60000 tons of ore per year. The uranium ore was shipped to Hengyang uranium plant by rail for the recovery of uranium. The construction of the mine started in 1971, the production of uranium ore began in 1974 and stopped in 1986. The decommissioning and reclamation project started in July 1992 and completed in May 1997.

2. Site characterization

The mine is located in hilly area with many small streams and brooks. The elevation of this area ranges from 200 m to 600 m. The lowlands are populated and agricultural area. The climate of the area is characterized by subtropical monsoon zone with high precipitation, mild temperature and humid weather. Annual average precipitation is 1673 mm and mean annual evaporation 1121 mm. Annual mean temperature is 16.2ºC. The site covers an area of 6.6 km^2 and the distance to the railway is about 1.5 km.

3. Radiation and contamination situation before reclamation

The uranium orebody occur in small pockets and ore depth from surface is less than 200 m. Some uranium ores were characterized by an association with small amount of cadmium sulphide (0.038%). The orebody was exploited by underground mining and by approaching it through drift and inclines (Fig. 1). The main source of pollution are summarized as follows.

3.1. Release of radioactive contaminants from drift entrance

There are 31 drift (or inclined shaft) entrances in total. Although all the entrances have been blocked off with cement–grouted rock when the mining operation was completed, radon release and mine water seepage from the entrance still occurs. The annual radon exhalation is 1.46×10^{12} Bq and the annual release from radionuclides of liquid effluents is 3.26×10^{10} Bq.

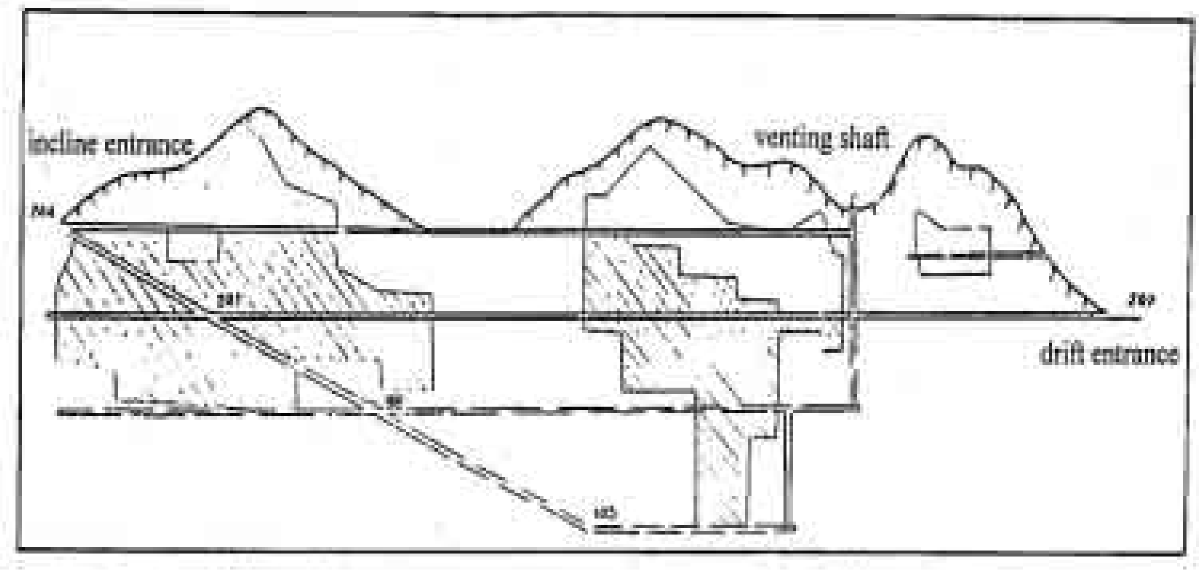

FIG. 1. Schematic diagram of drift development method.

3.2. Waste rock piles

Waste rock piles are situated near the drift entrances and totaled about 0.77 million tons and occupied an area of around 10 hectares (Fig. 2). The main radioactive exposure around site area is originated from waste rock piles and annual radon exhalation is 4.04×10^{12} Bq.

3.3. Industrial site

5 industrial sites including ore bin, winch house etc covered an area of 37 680 m^2. The annual radon exhalation is 1.77×10^{12} Bq.

3.4. Equipment and scrap materials

All the tanks, ion exchange columns, pumps, pipelines used in mining operation became contaminated, surface α contamination is over 0.08 Bq/cm^2.

3.5. Cadmium contamination of farmland

The mine is located in an area with high cadmium background. Cd content in the base soil reached 1.89 mg/kg in maximum and 1.33 mg/kg in average. During the mining operation, the treated mine water and waste water were discharged into river and streams. The rice field of 70 acres around the mine became contaminated by cadmium to some extent. Rice and maize which is traditionally main crops in the area contain Cd higher than state food limits.

4. Regulatory and design objectives

The regulation and standards that govern the decommissioning activities in China have been established by State Environmental Protection Administration, taking into account the recommendations of international organizations (ICRP & IAEA), the standards promulgated by the U.S. Environmental Protection Agency for the remediation of uranium mill tailings and the Chinese regulations. The decommissioning activities are managed in accordance with the following standards:

- Effective equivalent dose to the individual in the critical group below 0.25mSv/year,
- Radon control: Reduce radon flux over the surface of the final pile to an average release rate of less than 0.74 $Bq/m^2 \bullet s$
- Clean up of land
  Maximum concentration of radium-226: Average over any 100 m^2 area
  Top 15 cm (average) 0.18 Bq/g
  Below 15 cm (average over 15 cm layers) 0.56 Bq/g
- Decontamination of habitable structures
  Maximum radon daughter concentration, including background 0.02 working levels ($4.16\times10^{-7}J/m^3$) to the extent reasonably achievable, but not to exceed 0.03 working levels ($6.24\times10^{-7}J/m^3$)
  Maximum gamma, above background: 20 μR/h(17.5×10^{-8}Gy/h)
- Decontamination of equipment and scrap material
  Suface contamination: less than 0.04 Bq/cm^2 for unrestricted use
  less than 0.08 Bq/cm^2 for restricted use
- Cadmium concentration for drinking water 0.01mg/L.

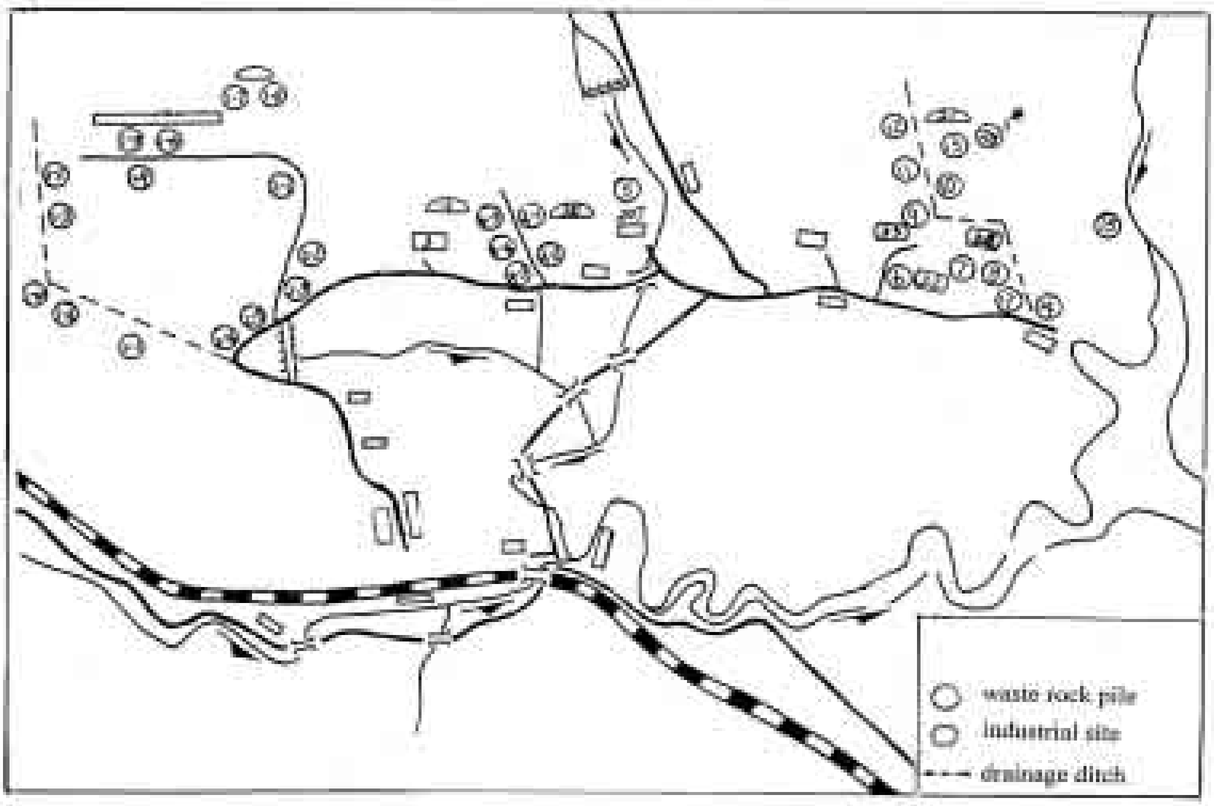

FIG. 2. Lay out of decommissining engineering.

5. Decommissioning process

5.1. Sealing of drift entrance

Seepage or overflow of mine water from drift entrance is the main source of liquid pollution. Two methods are used for the sealing of drift entrance. One is the construction of blocking wall which is employed for the drift having low inflow rate and competent rock mass. The thickness of the wall ranges from 3 m to 5 m. The wall and host rock were cemented by slurry pressure injection. The structure of the blocking wall is shown in Figure 3. The construction of blocking section is employed in the case the drift has loose rock with high inflow rate and less depth from surface. The length of the section is about 80 m. The section is filled with rock and sand and cemented by slurry pressure injection through drilling holes. The structure of the blocking section is shown in Figure 4. After completion of sealing engineering the overflow or seepage of mine water and radon release from entrance are avoided, and environment has been improved.

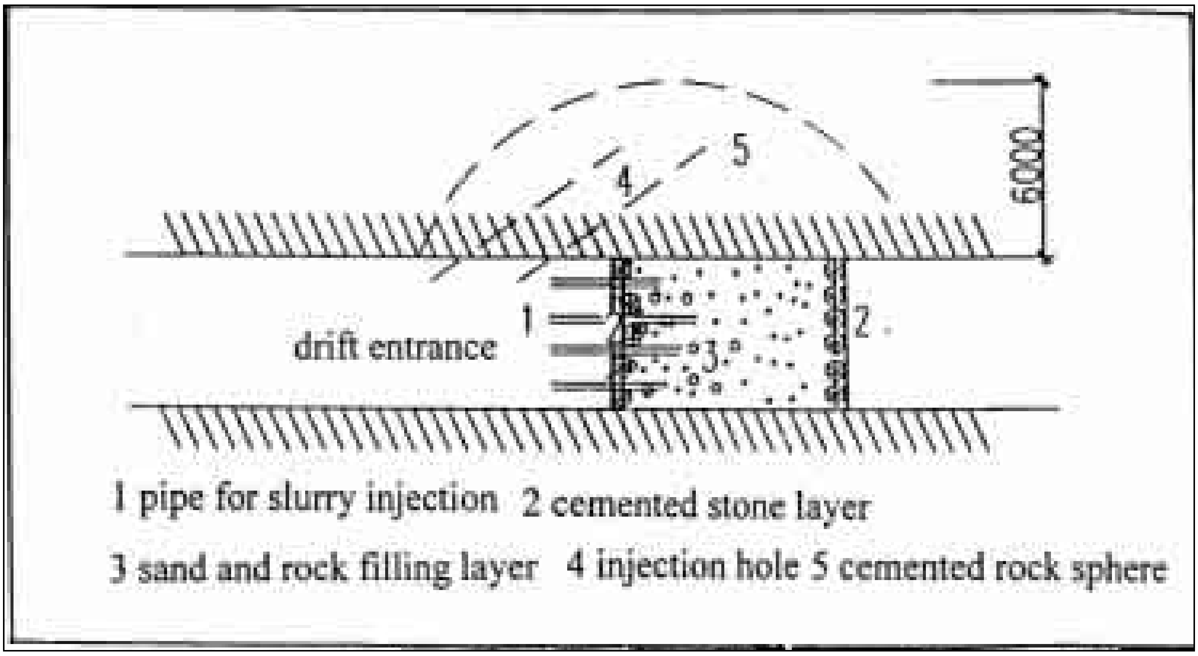

FIG. 3. Schematic diagram of blocking wall.

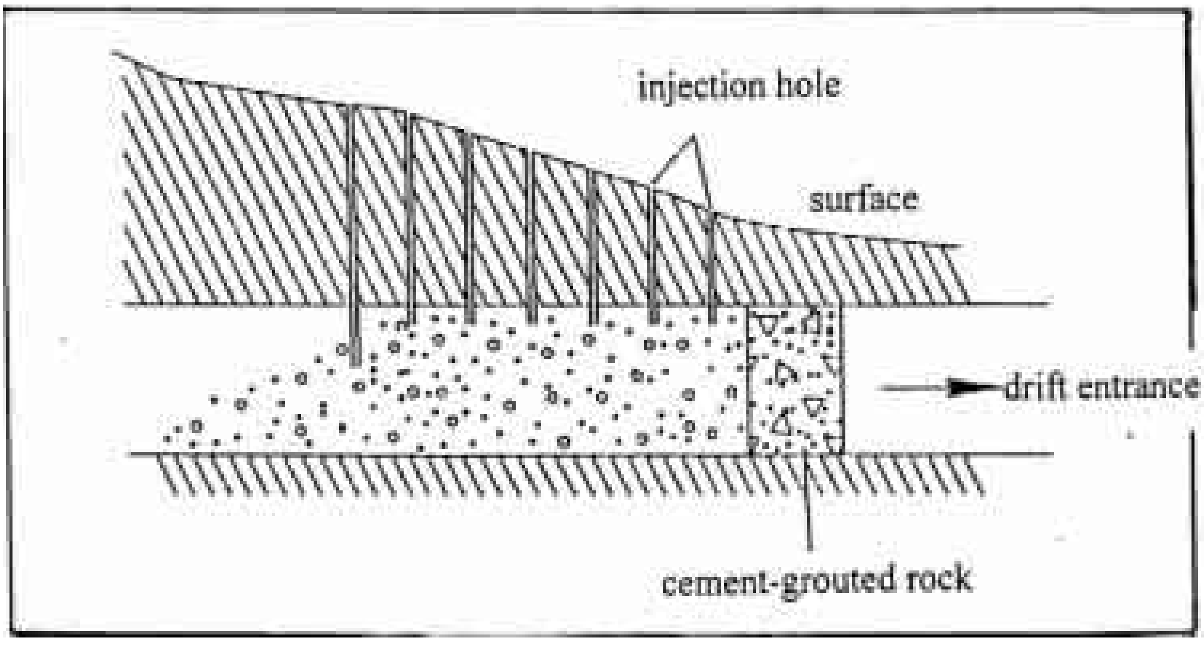

FIG. 4. Schematic diagram of blocking section.

5.2. Waste rock piles and industrial sites

Most of waste rock piles are situated on hill slopes with steep gradient. The slopes of the piles should be flattened to minimize erosion. In cases where rock piles are difficult to be reshaped, rock armouring with 8 m × 8 m grid are constructed on the slopes. The embankments are also constructed on the foot of slope to assure the stability of side slopes. Drainage ditch are usually required to discharge flood water. The entire pile is covered with native soil (0.5–1 m thick) and vegetation with trees and bushes was established to stabilize the surface against long term erosion. Average radon exhalation after reclamation is 0.52 Bq/m^2•s, less than the level before reclamation (1.28 Bq/m^2•s).

5.3. Decontamination of equipment and buildings

Equipment and buildings were decontaminated with water spraying followed by cleaning with 1% $NaCO_3$ solution or 5% citric acid solution. Areas and walls which have been contaminated by ore piles can be decontaminated by removal of surface layers of soil and wall by scrapers. These wastes were disposed in drifts of mine or buried under waste rock. After decontamination α surface contamination for most of equipment and materials is less than 0.04–0.08 Bq/cm^2.

5.4. Rehabilitation of Cd contaminated rice field

Rehabilitation of Cd contaminated rice field should be conducted in accordance with the principle of contamination ecology and agricultural economic ecology. Restructuring of agricultural production and selection of Cd resistant crop were carried out. It is found from series of investigation and experiments that mulberry is adapted to the Cd contaminated circumstances. In addition, Cd absorbed by mulberry from soil is concentrated in roots and trunks. The Cadmium can hardly go into the leaves of mulberry and Cd content of less than 2.5 mg/kg in leaves have no harmful effect on silkworm breeding. The rain water is enough for the growing of mulberry tree without any irrigation and further contamination of soil is avoided. On the other hand during the most of time of the year, Cd is present in the form of oxidized state which is water soluble and can transport into deeper layer of soil with rain water infiltration. As a result, the soil of cultivation layer will be purified. The local farmers made a profit from growing of mulberry and breeding of silkworm.

6. Summary

31 drift entrances have been sealed. Radon release from the entrances and seepage of mine water were avoided. Radon flux from waste rock piles and industrial sites were reduced from 1.28 Bq/m^2•s to 0.52 Bq/m^2•s and less than the limit 0.74 Bq/m^2•s. Gamma radiation were reduced from 78.7×10^{-8}Gy/h to 26.8×10^{-8}Gy/h. Total radon release is reduced from 7.27×10^{12} Bq/a to 1.96×10^{12}/a.

The concentration of Cd in streams and river was reduced to less than 0.01 mg/L. Cd contaminated rice field has been rehabilitated in the way of replantation and the sericulture is a more profitable industry. This rehabilitation method will be of great environmental, economic and social benefit.

Environmental impact of uranium mining and milling in the Russian Federation

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Abstract. Two Uranium Production Centres were in operation in Russia. Priargun Mining–Chemical Production Association (PPGHO) is active and Lermontov State Enterprise "Almaz" is closed. PPGHO is the operator of Streltsovsk Uranium–ore district, which include 19 deposits of volcanic type. Mining was operated since 1968 by two open pits (both are depleted) and five underground mines and ore processing since 1974 at the local milling plant. Since 90th low-grade ores are being processed by heap leaching. The contaminated area cover 842 ha. Main sources of the environmental pollution are the tail ponds of processing and sulphuric acid plants. The principal environmental problem is increasing accumulation of liquid and solid radioactive wastes. "Almaz" was the operator of two small vein-type uranium deposits by two underground mines since 1950 till 1990. Ore bulk was processed from 1954 at the domestic milling plant and from 1965 to 1989 also by in place leaching and heap leaching. The area of radioactive contamination covers 134 ha: 79.7 ha of milling tail pond and 54.4 ha of mining waste rock dumps. Main source of environmental contamination is radon-222 exhalation from the tail pond.

1. Introduction

Uranium production in the former Soviet Union was a strategic task. Economic and environmental aspects were of minor importance. As a result low-grade and small-size deposits were developed too and high production capacities were kept for a long time. Financial reserves for decommissioning and rehabilitation activities had not been put in place.

Two Uranium Production Centres has been in operation in Russia:

- Priargun Mining-Chemical Production Association (PPGHO) is active and
- Lermontov State Enterprise "Almaz" is closed.

Their total output since 1954 is about 110 000 mt U [1]. A large amount of radioactive wastes has been accumulated on both facilities.

2. JSK "Priargun mining-chemical production association" (PPGHO)

2.1. Site characterization

State JSK "Priargun Mining-Chemical Production Association" (PPGHO) is the only active uranium production centre in Russia in last decade. It is located in Chita region of Russia, 10-20 km from the town of Krasnokamensk with about 60 000 population. Mining has been operated since 1968 by two open pits (both are depleted) and five underground mines: 3 are active (mine 1,2,4) and 2 stand by (mine 7,8) (Fig. 1). 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. Since, 90th some amount of low-grade ores is being processed by heap and in-place (in-stope) leaching. Total U production amounted more than 110 000t [1].

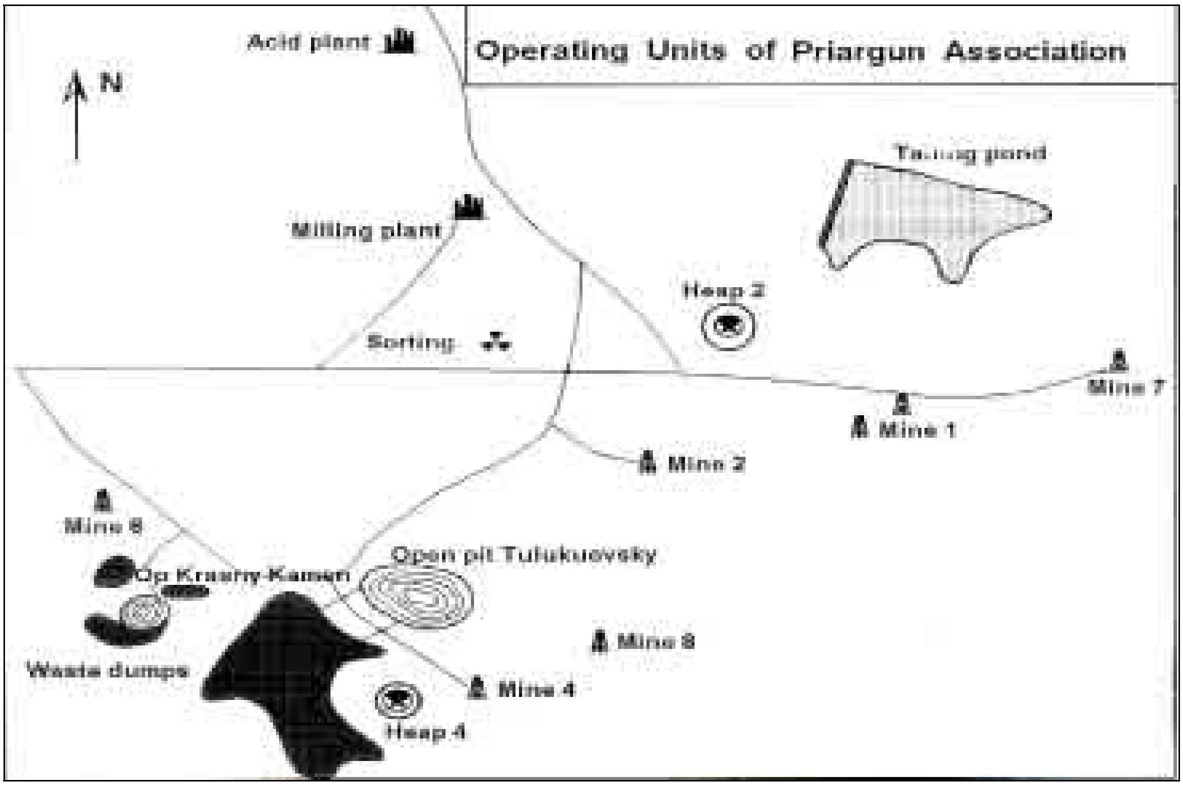

FIG. 1. Operating units of Priargun Association.

The production is based on 19 volcanic–type deposits of Streltsovsk U–ore region with the average U grade about 0.2%, situated at the area 150 km^2 (Table 1): 17 deposits are situated in volcanic rocks and sediments (13 of them are in effusives of sheet facies and 4 in effusives of neck facies) and 2 large deposits occur in basement rocks (Antei in granite and Argunskoye in granite and marble). Geological setting of deposits is described in many publications [2, 3, 4]. Since the beginning of uranium mining in 1970 ten deposits have been brought into production and two of them (Tulukui and Krasny Kamen) have been depleted by open pit operation. Most deposits have been explored underground and stand by for future development.

2.2. Production capability

The annual production at Priargunsky in 1996–1998 amounted 2500 to 2600 t U. Dominant production comes from underground mining and conventional milling. Currently relatively high-grade ore (over 0.3%U) of deposit Antei in granite (mine 1) is the main mining object. Insufficient amount is produced from the low-grade ores by heap leaching and in place (or block) leaching methods.

The main criteria for determination of processing method is the ore grade. Radiometric sorting is used to separate mined ore. Ore with grades over 0.3% U is crushed and processed at the plant. Mined ore with grades 0.15 to 0.30 is placed in the surface heaps containing 1 to 2 mln/t each. The project heap leaching recovery is 70 to 80% of in–place metal. Underground block leaching is designed for low–grade ore (0.1 to 0.15% U) [3].

The RAR resources of about 140 000 [1] can satisfy the planned requirements for the next 50 years. However low world uranium prices force to mine relatively high–grade ores with

0.28% U. This makes rest resources with low–grade ores unfavorable for current conventional mining. Nevertheless Priargunsky Association, even with its declining ore grades and high costs, will continue to be the cornerstone of Russia's uranium industry. The annual production is planned to reach 3500 t U, equally divided between conventional milling and leaching methods (heap leaching and underground block leaching).

Table I. Uranium deposits of Streltsovsk district

Deposit	Resources	Operational status	Host rocks	Shape of orebodies
1. Streltsovskoye	Large	Active – UG mine 1	Dacite, basalt, felsite,	Stockwork, vein
2. Tulukuevskoye	Large	Depleted – open pit	conglomerate	
3. Shirondukuevskoye	Middle	Stand by – UG mine 7		Stockwork, tabular vein
4. Yubileinoye	Middle		Felsite, basalt, conglomerate, sandsone	
5. Vesenneye	Middle	Active – UG mine 4		
6. Novogodneye	Middle			
7. Martovskoye	Middle			
8. Lutchistoye	Middle	Active – UG mine 2		
9. Oktyabrskoye	Large		Dacite, basalt	
10. Malo-Tulukuevskoye	Middle	Stand by – UG mine 8		
11. Antei	Large	Active – UG mine 1	Granite (basement)	Vein, Stockwork
12. Argunskoye	Large	Explored – UG mine 6	Marble, granite	
13. Zherlovoye	Small			
14. Krasnyi Kamen	Small	Depleted – Open pit	Effusives of neck facies	
15. Pyatiletneye	Small			
16. Yugo-Zapadnoye	Small			
17. Dalneye	Small	Explored	Conglomerate, sandstone	Tabular
18. Bezrechnoye	Small			
19. Urulynguevskoye	Small			

* Resources of deposits: Large >15.000t., middle 5.000-15.000t., small <5.000t.

2.3. Environmental situation

The main source of the ground water pollution is the seepage from the tail ponds of hydrometallurgical and sulphuric acid plants. Their total volume is 300 mln.cub.m. and 9000 Ci radioactivity. The characteristics of wastes is presented in Table 2.

Table II. Characteristics of wastes

Type of waste	Area, ha	Ml. ton	U, %	Radioactivity $\times 10^{-9}$ Ci/kg	Radon emanation $\times 10^{-3}$ Ci/m^2 year
Milling tail pond	600	40.0	0.009	30-750	0.93-23.2
Acid plant wastes	320	5.6	Traces	30-250	---
Radiometric sorting wastes	48	8.0	0.012	27-350	0.84-11.0
Piles of low grade ores	270	28.0	0.009	27-350	0.84-11.0
Mining waste rock dumps	80	7.0	0.002	27-80	0.84-2.50
Open pit waste dumps	275	190.0	0.001	27-80	0.84-2.50

The aggregated area of radioactive contamination is 842 ha: 723 ha at industrial site with the level 60 to 240mR/hr and the rest 119 ha in the sanitary protection and observation zones with the level to 60mR/hr [5].

More than 20-year environmental assessment emphasis two main environmental problems:

— Increasing accumulation of liquid and solid radioactive wastes;
— Progressive radioactive contamination of natural hydrogeological systems, which creates potential threat to portable water supply.

2.4. Waste management

Tailing pond is considered as most dangerous unit, regarding large amounts of radioactive wastes and sections overfilling. The potential threat of dam accident with wastes seepage to Urulungui and Argun rivers exists at the milling tail pond. The project of milling and acid tail ponds reconstruction is in progress. It includes:

— Strengthening of dam bodies and building of protective dam around the portable water bore holes;
— Construction of intercepting wells below the tailing pond dam;
— Designing the system of hydrogeological monitoring in the special wells.

However, the construction of special plant for liquid wastes treatment is considered as the most effective way.

Mining waters has been discharged into Bambakai valley over 20 years. The effluent has been stopped in 1996, when mine water restoration plant based on zeolite sorption technology has been built.

Tulukui and Krasny Kamen open pits are the first two depleted deposits of Streltsovsk region. The project of their closure is adopted.

Environmental activities, including rehabilitation of the territories and wastes utilization will be realized in the whole volume as far as the utilities closure will take place.

3. Lermontov State Enterprise “Almaz”

3.1. Site characterization

The first organization responsible for uranium production was the Lermontov Complex, presently - *Lermontov State Enterprise “Almaz”*. “Almaz” is located 1.5 km from the town Lermontov, Stavropolsky region of Russia. The region included Beshtau and Byk vein–type uranium deposits with total uranium resources 5 300 tones and 0.1% U grade. They have been operated by two underground mines since 1950. Mine 1 (Beshtau) was closed in 1975 and mine 2 (Byk) in 1990. Ore bulk was processed since 1954 at the processing plant by sulphuric acid leaching, and from 1965 to 1989 also by in-place (in-stope) leaching and by heap leaching. From the 80th till 1991 U ore bulk from Ukraine and Kazakhstan has been also processed at “Almaz”. After 1991 U production has been stopped, apatite flotation concentrate is being processed at the plant for fertilizer production. The uranium production totalled 5 685 tonnes, with 3930 tonnes extracted by underground mining and 1755 tonnes using ISL technology.

3.2. Environmental situation

The area of radioactive contamination covers 134 ha, including 79.7ha of milling tail pond 54.4ha of mining waste rock dumps (Table 3) [5, 7].

Table III. Measurement of radioactive contamination

Wastes	Area, ha	Amount, ths. t	Alfa activity, Ci	Beta activity, Ci
Tailing pond	79.7	14 047*	26 998	18 624
Waste mine 1 (Beshtau)	36.0	4 425	1 353	2 343
Waste mine 2 (Byk)	18.4	3 961	830	586
Total	134.1	22 433	---	---

* Plus 5900t of toxic substances and 5300 t of fluor gypsum.

The main source of environmental contamination is radon-222 exhalation from the tail pond. The contamination of ground water took place due to milling waters drainage from the tailing pond, especially at the first years of milling plant operation. Currently the quality of groundwater satisfies the standard.

3.3. Waste management and rehabilitation

Mine 1 (deposit Beshtau). The partial rehabilitation of waste dumps has been carried out at 1993-1994. The equipment for mining mater restoration was installed in 1993, but currently it is not in operation (mining waters contain to 2.2mg/l U).

Mine 2 (deposit Byk). The works on waste rocks rehabilitation are executed for about 30%. The rehabilitation of heaps after heap leaching is completed.

Milling plant. The partial decontamination and dismantling of buildings and territories, which are used now for apatite processing, has been carried out.

Tailing pond. The project on rehabilitation and decommissioning of milling tails pond is at the state examination. The main tasks of this project are:

- Organization of the special environmental service;
- Arranging 1.5m thick layer of phosphogypsum and the following soil drainage layer;
- Reconstruction and extension of monitoring system;
- Designing the system of storm water diversion.

4. Future production centres

Three new ISL production centre are planned to come into operation in the next 10 years [1]. The environmental assessment of deposits amenable for ISL is based on two main principles:

- Deposit location within the closed hydrogeological structures;
- Isolation of leaching area from the water supply utilities.

5. Conclusion

The general environmental characteristic of Russian uranium producing facilities can be regarded as typical for the countries of the former Soviet Union. The world experience shows that environmental costs of decommissioning and rehabilitation activities after closure are much higher than during operation (UMTRA in USA and Wismut in Germany) [6]. The environmental costs should be included in the initial cost calculation and adjusted continuously during production. This is as a subject for international co-operation, especially regarding the plans for future uranium production and new centres development.

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Natural attenuation processes in Cenomanian sediments following acid in situ leach mining of uranium, Stráž pod Ralskem, Northern Bohemia, Czech Republic

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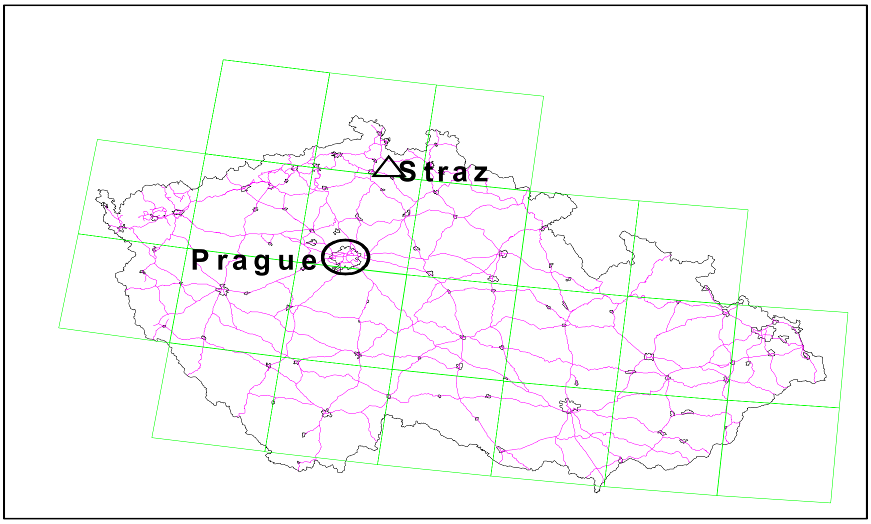
Abstract. Decommissioning of the Stráž uranium district in Northern Bohemia is underway following 30 years of continuous production. To date, both underground mining (1968-present) and in situ leach (ISL) mining (1980-present) have been performed at the Hamr I underground mine and the 1.5 km distant Hamr ISL mine. The ore-bearing zone occurs in the Cretaceous Northern Bohemian basin in Cenomanian sediments. The mines are operated by the state uranium company, DIAMO, located in Stráž pod Ralskem. At present, a hydrobarrier between the Hamr I and the ISL mine allows the co-existence of the two mine types. Water injected into the hydrobarrier maintains the hydrostatic conditions for the ISL mine while decommissioning of the underground mine is proceeding. Following decommissioning of the Hamr I mine, DIAMO proposes that 2-5 million m^3 of free water from the nearby Stage I and Stage II tailings impoundments be used to restore the hydrostatic equilibrium at the Hamr I mine. Following flooding of the mine, injection of water at the hydrobarrier would cease, followed by active restoration of the aquifer. The objective of this restoration is to prevent contaminated Cenomanian waters from reaching the water supply wells for the town of Mimon, about 6 km to the southwest. This paper describes natural attenuation processes of Cenomanian sediments and fluids reacting with the acid ISL lixiviant solutions based on mathematical modeling with a mineral solution equilibrium code. PHREEQC is used to model these reactions. Based on the mineralogy, the Cenomanian sediments provide extensive buffering for low pH solutions of the lixiviant and rapid precipitation of Al^{+3}, $SO4^{-2}$, and U^{+4} species.

1. Location of Stráž

Stráž pod Ralskem is located in Northern Bohemia 100 km north of Prague about 30 km from the German border (Fig. 1). The Stráž uranium district, discovered in the late 1950s is located in the Cretaceous Bohemian Basin, ranging in age from Lower Cenomanian, Turonian, to Coniacian sediments. The uranium ore is syn-depositional concentrated in humate-rich sediments near the base of the Cenomanian sediments.



Source: Michal Stibitz, Institut für Geowissenschaften, Leoben

FIG. 1. Stráž pod Ralskem, Czech Republic

2. Cenomanian sediments

Cenomanian sediments are composed of greywacke, sandstone, siltstone, and lacustrine sediments deposited as a transgressive sequence. The middle and upper Cenomanian sediments are composed of fine grained, unsorted, poorly consolidated sediments, with fucoid (worm) burrows. Colour ranges from yellow to light gray.

3. Lower Cenomanian ore zone

The Lower Cenomanian sandstones are a greywacke sequence of fluvial, coarse- to fine-grained, angular “sedimentary breccias” or angular rock fragments at the base, dark-gray to black, and are rich in organics such as coaly material. The greywacke overlies lacustrine and paludal sediments containing abundant organic material. The uranium contained in these sediments is syn-sedimentary [1-5].

4. Turonian Aquitard

Overlying the Cenomanian is a lower Turonian aquitard composed of limey siltstones and clays, marls, clayey siltstones, and locally marly sandstones. This represents a marine transgression marked by carbonate deposition at the base of the lower Turonian, which grades upward to limey siltstones, marls, siltstones [1].

5. Tectonic & structural setting

The Hamr I and ISL mines (Fig. 2) are structurally isolated from the surrounding basin by the Stráž Fault which trends NE-SW. This forms the boundary between two tectonic blocks, the southern block containing the U deposits, and the northern block having the processing plant and tailings ponds.

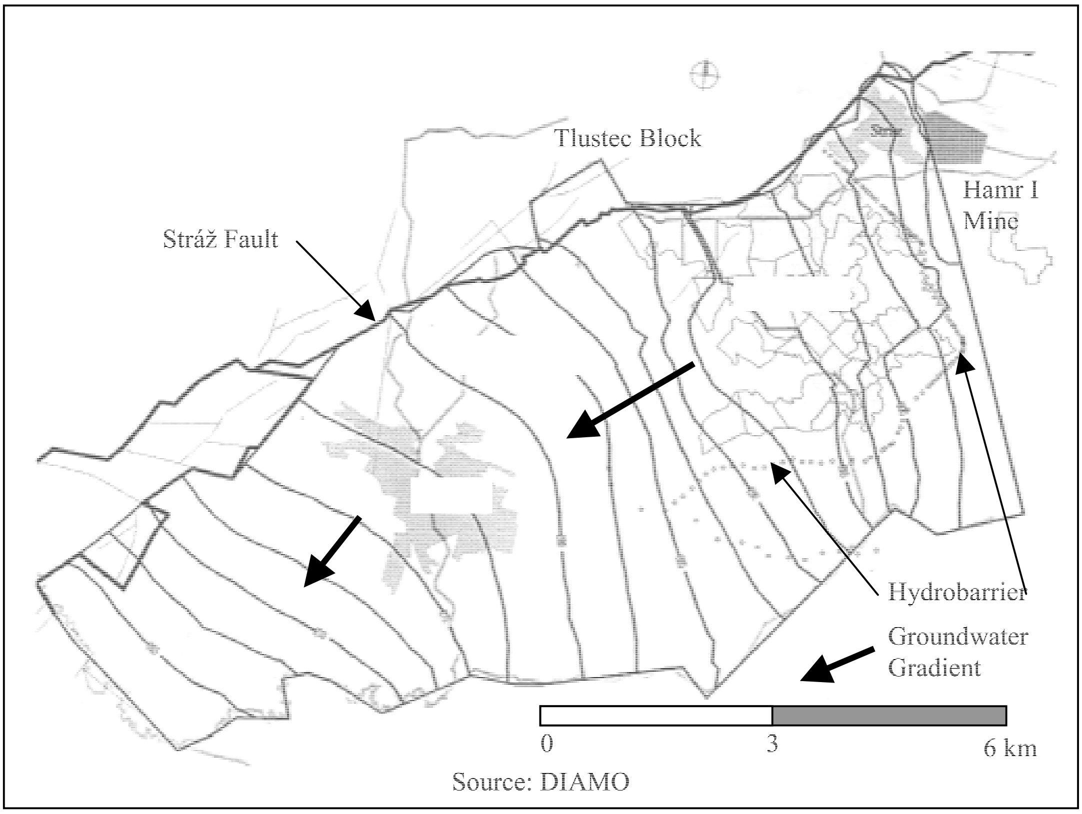


FIG. 2. Stráž structural setting.

6. Volcanic rocks

In the basin, two types of volcanic rock are present characterized by volcanic breccias (diatremes) and intrusive stocks and dykes. The location and distribution is structurally controlled by the asymmetric development of the deep faults in the basement. The dykes tend to follow tectonic lineaments, mainly in SW-NE direction, and the occurrence of diatremes or intrusive stocks is associated with the intersection of the lineaments in Cretaceous sedimentary rocks [1].

The diatremes and stocks are important to the Stráž ISL mines because of the co-existence of diatremes and dykes in the ore zones, causing some interference with induced flow in the production wells.

7. Mineralogy of Cenomanian sediments

The mineralogical composition of the Cenomanian sediments includes quartz, mica (1–14%), sulfides (1%), kaolinite (15-40%), siderite (up to 2%), and all other minerals less then 1% [2]. Uraninite (0.2%) is the primary uranium mineral. The source of the sediments and uranium is the weathering of nearby Hercynian granites and metamorphic rocks of the Bohemian massif. The granites are frequently autometasomatic forming extensive vein-type uranium deposits and characteristic two-mica granites (biotite and muscovite). As a province, the Bohemian massif is significantly enriched in uranium. For geochemical modeling, a “typical” rock composition is proposed in Table 1.

Table I. Cenomanian rock composition in ore zone

Mineral	Composition	Percent	g	gmw	Moles
Quartz	SiO_2	61.3%	6,130	184.2351	33.27262
Kaolinite	$Al_4[Si_4O_{10}](OH)_8$	30.0%	3,000	516.2638	5.810983
Muscovite	$KAl_2[AlSi_3O_{10}](OH,F)_2$	5.0%	500	398.2938	1.255355
Pyrite	FeS_2	2.0%	200	119.979	1.666958
Siderite	$FeCO_3$	1.5%	150	115.8562	1.294708
Uraninite	UO_2	0.2%	20	270.0277	0.074066
			10 000 g		

8. Diagenetic processes

Kaolinite is of authigenic origin and forms by weathering of orthoclase ($KAlSi_3O_8$), albite ($NaAlSi_3O_8$), and anorthite ($CaAl_2Si_2O_8$) feldspars and the rock composition is strikingly similar to the weathering model of Goldich (1938) discussed by Langmuir (1997) [6]. The original sediment composition is an arkose (>25% feldspar) or greywacke (15–50% clastic feldspar) reflecting the short distance of transport from a granitic / metamorphic highland. The reduced nature of the rock reflects the presence of two Fe^{+2} phases, siderite ($FeCO_3$) and pyrite (FeS_2), formed syngenetically in association with organic materials in paludal and lacustrine environments during deposition. Authigenic aqueous organic material, biologically degraded from the paludal zones, was transported short distances into overlying arkose and greywacke and precipitated as interstitial humate similar to humate-type uranium deposits described by Adams and Saucier (1981) [7] in the Grants Uranium Region, New Mexico.

9. Modeling parameters

The estimate of porosity is 0.25 and bulk density is about 2.5. Based on these parameters, 1 liter of formation fluid is contained in 4 liters (4 000 cm^3) of rock weighing 10 000 g. One additional modeling component is added to account for trace composition of the lixiviant solution. The proposed lixiviant fluid composition includes trace fluorine to account for F^- probably brought into solution from the dissolution of fluorine-bearing muscovite. Fluorite might also occur in Tertiary volcanic breccias and dykes swarms in the ore zone.

10. ISL process

DIAMO uses the acid ISL process to recover uranium at Stráž. A well field is drilled into the ore-bearing horizon. The pattern of extractor and injector wells is typically a "5-spot" pattern composed of 1 injector well at the centre and 4 extractor wells. The distance from the injector to the extractor wells is about 15 m. Large well fields are designed using "staggered line drives" composed of scores of wells to match the flow capacity of the ion-exchange plant and the geometry of the ore zone. To date, the Hamr ISL mine includes a total of over 9000 production wells and about 10 000 exploration boreholes.

11. Lixiviant preparation

Ground water from extractor wells is mixed with 1 part HNO_3 to 8 parts H_2SO_4 to form a lixiviant, which is injected into the ore-bearing horizon. Pregnant lixiviant from the extraction wells passes through a pressurized ion exchange column to recover uranium. Acid is added and the solution is again injected. The quantity of acid used in the injection wells is sufficient to maintain a pH of 0.5 in the extraction wells [4]. Approximately 40 pore volumes of lixiviant are injected in this manner to achieve a uranium recovery of about 90%, depending of the type of ore. Measured composition of the pregnant lixiviant is presented in Table 2.

Table II. Measured lixiviant composition

Component	Units	ISL Lixiviant
PH	Units	0.5
SO_4^{-2}	mg/l	33 000 – 80 000
NO_3^{+}	mg/l	600 -1400
$^{226}Ra^{+2}$	Bq/m^3	50 000-90 000
Al^{+3}	mg/l	10 000 – 20 000
U	mg/l	100-500 [1]
F^-	mg/l	5
TDS	mg/l	50 000-100 000

Source: DIAMO [4]

12. Geochemical model

The PHREEQC [8] code is used with the WATEQ4 database to model the lixiviant and subsequent reactions with the host rock. PHREEQC allows for modeling only equilibria and does not incorporate kinetics. Hematite (Fe_2O_3), Jurbanite ($AlOHSO_4$), and Alunite ($KAl_3 (SO_4)_2 (OH)_6$) precipitates as well as the initial mineral phases. During modeling, two mineral phases, pyrophyllite ($Al_2Si_4O_{10} (OH)_2$) and diaspore (AlOOH), reach saturation, but are not precipitated because the kinetics of reaction are probably too slow. Notably, the ISL solution is barren of Na^+, Ca^{+2} and Mg^{+2} reflecting the virtual absence of Na^+, Ca^{+2} and Mg^{+2} – bearing mineral phases in the weathered host rock. This eliminates the possibility of precipitation of montmorillonite (smectites) or illite. Time of residence of the solution is several decades.

13. Design of model

The modeling process includes three components: 1) Modeling the natural geochemistry of water in the Cenomanian sediments; 2) Modeling the lixiviant solution in contact with the ore-bearing rock; and 3) Modeling the reaction of the lixiviant solution with water in equilibrium with the sediments through successive dilution of the original lixiviant. An assumption is made that the natural background water chemistry reflects the equilibrium concentration of the mineral components.

13.1. Equilibrium with rock of Cenomanian composition

No data are available describing the water chemistry of the Cenomanian sediments. In order to approximate the composition, equilibrium of the mineral phases contained in the Cenomanian sediments with demineralized water is calculated and presented in Table 3. Reflecting the high solubility of Fe+2 in reducing groundwater, a fraction of the siderite ($FeCO_3$) dissolves in the modeled groundwater resulting in Fe+2 values of about 40 mg/l. The pH of the resulting solution is 5.6 with a pe of -2.4. No attempt is made to model the reaction of the organic material. Diagenesis of the organic materials has produced bituminous coals, probably locally baked by intrusive dykes and volcanic breccias to natural cokes.

Table III. Modeled natural groundwater conditions

Element	Moles/l	mg/l
pH		5.573 units
pe		-2.424 units
Density of water		0.9999 kg/l
Al^{+3}	1.78E-08	0.00048
CH_4	1.32E-03	21.07
Total Carbonate†	9.94E-03	596.31
Fe^{+2}	7.22E-04	40.30
K^+	9.99E-05	3.91
Na^+	1.71E-04	3.93
SO_4^{-2}	4.35E-10	0.00
Si	1.05E-04	2.93
U	5.26E-14	0.00

† Total carbonate includes all aqueous carbonate species such as CO_2, HCO_3^-, $FeHCO_3^+$, $CaHCO_3$, $FeCO_3$(aq), CO_3^{-2}, $CaCO_3$(aq).

13.2. Modeled Lixiviant composition

The lixiviant solution is modeled by adding 0.1 M HNO_3 to demineralized water and allowing the solution to equilibrate with the mineral phases in the rock and adjusting the pH with H_2SO_4 to 0.5. This solution represents an approximation of the pregnant lixiviant in the extraction wells and is presented in Table 4. The modeled solution contains over 4 times the total dissolved solids of the measured lixiviant. Table 4 compares the modeled concentration of the lixiviant with the measured lixiviant and expresses the difference as a factor. Clearly far more H_2SO_4 is required to adjust the pH (8 – 20 times) in the model than is required in practice. AMM and DIAMO [9,10] are performing estimates of the kinetics of reaction of kaolinite and uraninite in the context of developing a coupled groundwater – geochemical code called AMMPRQ for modeling the Stráž ISL mine [11,12].

Table IV. Modeled lixiviant composition (extraction well)

Component	Moles/l	g/l (Modeled)	g/l (Measured)	Factor
PH		0.5 units		
Pe		5.3 units		
Density of Water		1.442 kg/l		
Al^{+3}	1.56E+00	42.1	10 – 20	2 - 4 X
Total Carbonate	1.30E+00	77.7		
Ca^{+2}	6.40E-05	2.56		
Cl^-	1.72E-04	6.10		
F^-	1.37E-04	2.60	5	
Fe	2.11E+00	117.8		
K^+	1.26E+00	49.1		
Na^+	0.00E+00	0.00		
SO_4^{-2}	7.01E+00	673	33 – 80	8 - 20 X
Si	5.57E-05	1.56 mg/l		
U	7.41E-02	17.6	0.1 - 0.5	35 – 176 X
TDS (Estimated)		989	50 - 100	10 – 20 X

Uranium phases

Both U+4 and U+6 sulfate phases (Table 5) are mobilized by the lixiviant in the model. The ratio of U+4 to U+6 is 235 to 1 indicating that an oxidant (HNO3) is probably not required.

Table V. Uranium phases in lixiviant

Species	Moles / l	mg/l U
Total U^{+4}	7.402E-02	17,618.39
$U(SO_4)_2$	7.387E-02	17,584.07
USO_4^{+2}	1.433E-04	34.11
Total U^{+6}	3.146E-04	74.89
UO_2SO_4	2.511E-04	59.76
$UO_2(SO4)_2^{-2}$	6.084E-05	14.48

13.3. Successive dilution and reaction with ground water

Equal parts of the lixiviant solution and the modeled natural groundwater are reacted and brought into equilibrium with mineral phases in the rock. At each stage, the products of the reaction are introduced into the next stage.

Three phases are allowed to precipitate in addition to those already present. In addition to the mineral phases present in the rock, the aluminum bearing phases Jurbanite ($AlOHSO_4$), and Alunite ($KAl_3 (SO_4)_2 (OH)_6$) are allowed to precipitate as well as Hematite (Fe_2O_3).

Gibbsite ($Al(OH)_3$) and Boehmite (AlOOH) did not reach saturation. Pyrophyllite ($Al_2Si_4O_{10}(OH)_2$) and diaspore (AlOOH), reached saturation, but are not allowed to precipitate because the kinetics of the reaction are probably too slow. Figures 3 and 4 present the results of these reactions. Appendix I lists the possible reactions and the saturation index of several mineral phases.

14. Dilution, reaction, precipitation, and equilibrium

Following injection of the lixiviant, the solution chemistry is modified by either dilution, reaction with ground water and by equilibrium with mineral phases in the rock resulting in precipitation. Fe^{+2}, Al^{+3}, and U achieve equilibrium with the natural groundwater after less than 10 dilutions. F^- and N^{-3} do not react and are reduced by dilution alone. $U^{(+4\ \&\ +6)}$ and SO_4^{-2} are rapidly precipitated (<3 dilutions), while Al^{+3} precipitates in the first 10 dilutions. N2 (g) is reduced to N^{-3} in the first 2 dilutions.

15. Kinetics of ISL mining

During the mining process, the actual rates of reactions between the rock components do not allow equilibrium conditions to be established. However, as indicated by measured lixiviant composition, 50–100g/l of dissolved solids are present in the pregnant lixiviant, compared to 989 g/l in the modeled lixiviant.

The AMMPHRQ code under development by DIAMO and AMM (Applicace Mathematickych Modelu, s.r.o) and the development of an experimental kinetic database for uranium and aluminum are currently underway [9, 10, 11, 12] based on core-leach studies and calibration with ISL mining data.

The major chemical reactions are tabulated in Appendix II. A significant fraction of the rock is dissolved by the lixiviant and largely re-precipitated after dilution with ground water. N_2(g) and CO_2(g) did achieve significant pressures in the simulation for the lixiviant. Because these gases are allowed to equilibrate with air at the surface during mining, they were modeled as such in PHREEQC. Gas equilibrium is not permitted during the mixing of the lixiviant with natural ground water. Degassing reduced the subsequent amounts of NH_4 and CH_4 present following dilution of the lixiviant.

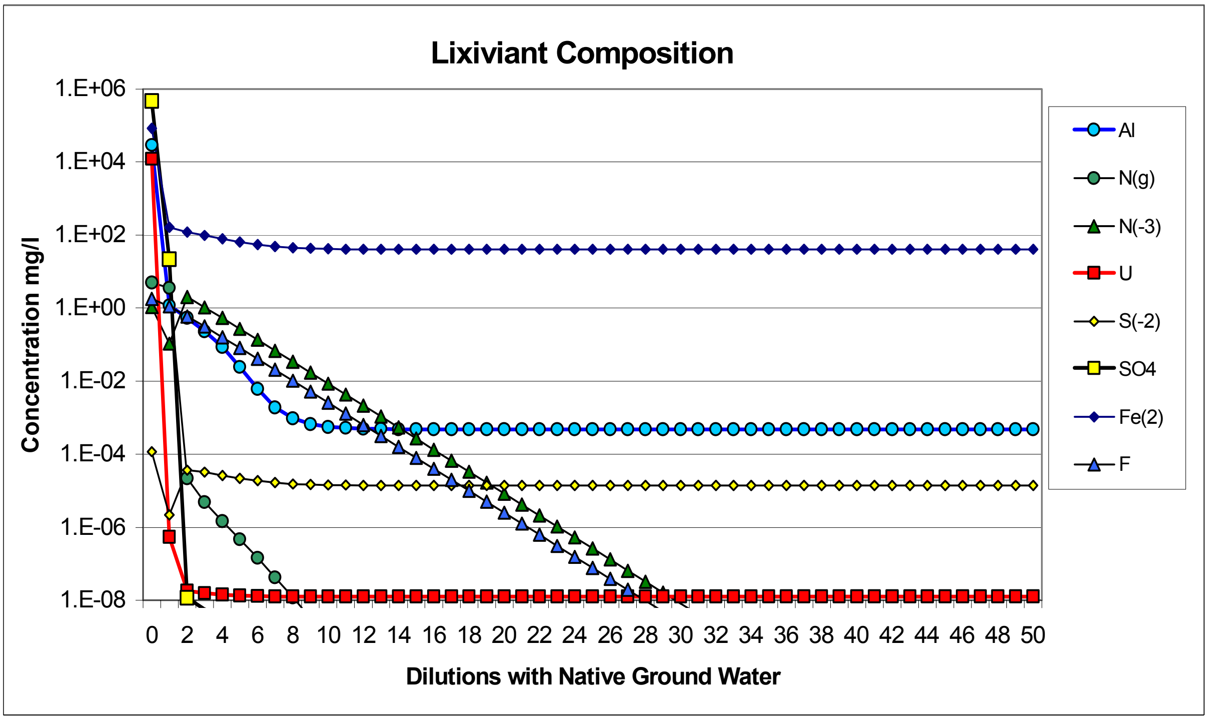


FIG. 3. Successive dilutions with natural ground water

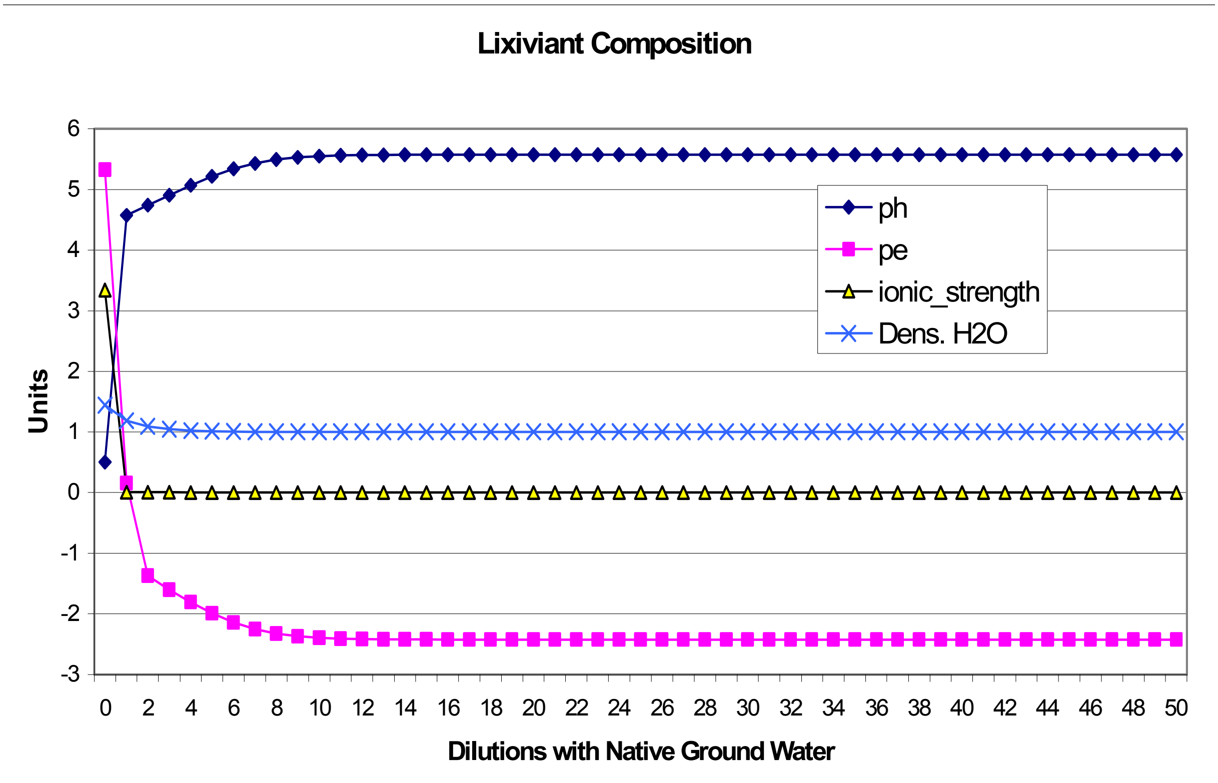


FIG. 4. Modelled pe and pH changes.

16. Conclusions

Natural attenuation processes are an important characteristic for acid ISL mining depending on the forward and backward rates of reactions. Mineral assemblages which include kaolinite and muscovite provide an extensive pH buffering capacity for precipitation of non-redox sensitive reactions involving Al^{+3}, K^{+}, Si, and SO_4^{-2}, as alunite (KAl_3 $(SO_4)_2(OH)_6$), jurbanite ($AlOHSO_4$), and kaolinite ($Al_2Si_2O_5(OH)_4$). Because Fe^{+2} minerals such as pyrite (FeS_2) and siderite ($FeCO_3$) are relatively abundant in the host rock, reducing conditions are quickly re-established following mining, allowing for the precipitation of uraninite.

Most of the uranium (over 99.4%) is maintained in solution as U^{+4} as the neutral aqueous species $U(SO_4)_2$ (aq) and only a small fraction (0.4%) oxidizes to U^{+6}. Almost all soluble uranium precipitates rapidly as the pH is buffered, and redox conditions return to reducing.

Chemical equilibrium modeling of a lixiviant for acid ISL mining and the interaction with ore zone minerals provides insight into the chemical reactions during mining, but is significantly limited because the rates of reactions may not be modeled. Far more acid is required by the model to maintain a pH of 0.5 in the pregnant lixiviant than is actually the case in mining.

The model is in agreement with the mining experience in that the lixiviant solution must retain its acidic characteristics between the injection and extraction wells or uranium will precipitate prior to reaching the extraction well. The rate at which uraninite may go into solution cannot be modeled with PHREEQC. The results of modeling are similar with respect to the precipitated species that the DIAMO modeling has achieved.

An important feature regarding the solubility of Al^{+3} is the presence or absence of F^{-} in solution. The primary aqueous species that control the solubility at distance to the mine site are AlF^{+2} (56%) and AlF^{2+} (34%). These two species control 90% of the solubility.

Recommendations

D. Parkhurst (USGS, Denver) has recently released a new version of PHREEQC (V2.30), which includes features for kinetics of reactions, as a beta-test version. This code would be suitable to compare with the AMMPRQ code prepared by DIAMO as well as the results of the present exercise.

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Appendix I:

Primary Reactions during ISL Mining

Host Rock	Reaction	Log K_d	Reacted	Precipitated after Dilution	S.I.
Quartz	$SiO_2 + 2H_2O = H_4SiO_4$	-3.98	46%	√	
Kaolinite	$Al_2Si_2O_5(OH)_4 + 6H+ = 2Al^{+3} + 2H_4SiO_4 + H_2O$	7.435	100%	√	
Kmica	$KAl_3Si_3O_{10}(OH)_2+10H+=K+ +3Al^{+3} +3H_4SiO_4$	12.703	100%	√	
Pyrite	$FeS_2 + 2H^+ + 2e- = Fe^{+2} + 2HS^-$	-18.479	49%	√	
Siderite	$FeCO_3 = Fe^{+2} + CO_3^{-2}$	-10.89	100%	√	
Uraninite	$UO_2 + 4H^+ = U^{+4} + 2H_2O$	-4.8	100%	√	
Products	**Precipitated Species**				
Alunite	$KAl_3(SO_4)_2(OH)_6 + 6H+ = K^+ + 3Al^{+3} + 2SO_4^{-2} + 6H_2O$	-1.4		√	
Jurbanite	$AlOHSO_4 + H^+ = Al^{+3} + SO_4^{-2} + H_2O$	-3.230		√	
Hematite	$Fe_2O_3 + 6H+ = 2Fe^{+3} + 3H_2O$	-4.008		√	
Other	**Not Precipitated**				
Diaspore	$AlOOH + 3H^+ = Al^{+3} + 2H_2O$	6.879			**0.82**
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2 + 12H_2O = 2Al(OH)^{4-} + 4H_4SiO_4 + 2H^+$	-48.314			**2.46**
Boehmite	$AlOOH + 3H^+ = Al^{+3} + 2H_2O$	8.584			-0.88
Gibbsite	$Al(OH)_3 + 3H+ = Al^{+3} + 3H_2O$	8.11			-0.42
Gas Phases					
$CO_2(g)$	$CO_3^{-2} + 2 H^+ = CO_2 + H_2O$	16.681		√	
$N_2(g)$	$2 NO_3^- + 12 H^+ + 10 e- = N_2 + 6 H_2O$	207.08		√	
Redox					
$N_2(g)$	$2 NO_3^- + 12 H^+ + 10 e- = N_2 + 6 H_2O$	207.08		√	
Pyrite	$FeS_2 + 2H^+ + 2e- = Fe^{+2} + 2HS^-$	-18.479	49%	√	
$U^{+6} \rightarrow U^{+4}$	$UO_2^{+2} + 4H^+ + 2e- = U^{+4} + 2H_2O$	9.04			
$Fe^{+2} \rightarrow Fe^{+3}$	$Fe^{+2} = Fe^{+3} + e-$	-13.020			
$N^{+5} \rightarrow N^0$	$2 NO_3^- + 12 H^+ + 10 e- = N_2 + 6 H_2O$	207.08			
$N^{+5} \rightarrow N^{-3}$	$NO_3^- + 10H^+ + 8e- = NH_4^+ + 3H_2O$	119.077			

Appendix II: PHREEQC Input File

```
TITLE Straz ISL simulation
SELECTED_OUTPUT
-file C:\WRDAPP\PHRQCI1.03\DATA\STRAZ01A.OUT
-totals     Al Ca F Fe Fe(2) Fe(3) N(3) N(0) N(-3)
            U U(4) U(6) S(-2) S(6)

PHASES 1 # Do not change this number it is used by the
programme!
Fix_H+
            H+ = H+
            log_k 0.0
Lime
   CaO + 2H+ = Ca+2 + H2O
   log_k  32.797
   delta_h -46.265 kcal

IX
            UO2X2 + 2Na+ = UO2+2 + 2NaX
   log_k  0.0


# UO2(CO3)2-2
# UO2(CO3)3-4
# UO2CO3
# UO2SO4
# UO2(SO4)2-2
# ##########################################
# =====================================
# Create a solution from DI water containing H2SO4 and
HNO3
# Use the couple C(-4)/C(+4) to control redox
# =====================================
# =====================================
# Create a solution from DI water containing H2SO4 and
HNO3
# Use the couple C(-4)/C(+4) to control redox
# =====================================
SOLUTION 1      Lixiviant
            temp      25
            units     mol/l
            pH        7.0       charge # pH balance from
NO3 addition
            redox     Fe(+2)/Fe(+3)
            Fe(+2)    1.80E-07
            Fe(+3)    3.92E-11
            N(+5)     2.0       as NO3
            F         1.2E-4
            K         1.2E-4 # to balance the Fluorine

# =====================================
# Rock composition:
# Porosity25%
# Density 2.5
# Trace             NaCl in solution and 5 mg/l F
concentration
# Minerals composition per liter of H2O (55.55 moles)#
=====================================
# Mineral Composition                 Gmw
            Percent           Moles
# Quartz  SiO2                        184.2351 61.3%
            33.27262
# Kaolinite         Al4[Si4O10](OH)8  516.2638 30.0%
            5.810983
# Muscovite         KAl2[AlSi3O10](OH)2
                    398.2938 5.0%
            1.255355
# Pyrite  FeS2                        119.979
            2.0%              1.666958
# Siderite(d)       FeCO3
            115.8562 1.5%             1.294708
# Uraninite         UO2
            270.0277 0.2%             0.074066
# ========================================
EQUILIBRIUM_PHASES 1
            Fix_H+    -0.5      H2SO4     30.0
            Quartz              0.0       33.27262 #
44.086      61.3%
            Kaolinite 0.0       5.810983 # 254.13  30.0%
            Kmica               0.0       1.255355 #
398.2938 5.0%
            Pyrite              0.0       1.666958 #
119.978     2.0%
            Siderite  0.0       1.294708 # 115.8562
            1.5%
            Uraninite(c)        0.0       0.074066 # 270.0
                      0.2%
#    CO2(g)                     -2.5      0.0
            N2(g)               -0.155    0.0

            Jurbanite 0.0       0.0       # AlOHSO4
            Hematite  0.0       0.0       # Fe2O3
            Alunite             0.0       0.0       #
KAl3(SO4)2(OH)6

SAVE solution 1
END

SOLUTION 2      # Natural Ground Water
            temp      25
            units     mol/l
            pH        7.0       charge
            redox     Fe(+2)/Fe(+3)
            Fe(+2)    1.80E-07
            Fe(+3)    3.92E-13

EQUILIBRIUM_PHASES 2
# ========================================
# Bring the solution into equilibrium with rock
# ========================================
Quartz                0.0       33.27262 # 44.086
            61.3%
Kaolinite             0.0       5.810983 # 254.13
            30.0%
Kmica                 0.0       1.255355 # 398.2938
            5.0%
Pyrite                0.0       1.666958 # 119.978
            2.0%
            Siderite  0.0       1.294708 # 115.8562
            1.5%
            Uraninite(c)        0.0       0.074066 # 270.0
                      0.2%

            Jurbanite 0.0       0.0       # AlOHSO4
            Hematite  0.0       0.0       # Fe2O3
            Alunite             0.0       0.0       #
KAl3(SO4)2(OH)6

SAVE solution 2
END
MIX         1
            1         0.5
            2         0.5
EQUILIBRIUM_PHASES 3
==========================================
# Bring the solution into equilibrium with rock
==========================================

            Quartz              0.0       33.27262 #
44.086      61.3%
            Kaolinite 0.0       5.810983 # 254.13  30.0%
            Kmica               0.0       1.255355 #
398.2938 5.0%
            Pyrite              0.0       1.666958 #
119.978     2.0%
```

```
        Siderite    0.0         1.294708 # 115.8562
        1.5%
        Uraninite(c)            0.0         0.074066 # 270.0
                    0.2%

        Jurbanite   0.0         0.0         # AlOHSO4
        Hematite    0.0         0.0         # Fe2O3
        Alunite                 0.0         0.0         #
KAl3(SO4)2(OH)6

SAVE solution 1
END
MIX     2
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     3
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     4
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     5
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     6
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     7
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     8
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     9
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     10
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     11
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     12
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     13
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     14
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     15
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     16
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     17
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     18
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     19
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     20
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     21
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     22
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     23
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     24
        1       0.5
        2       0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX     25
        1       0.5
        2       0.5
USE equilibrium_phases 3
```

```
SAVE solution 1
END
MIX	26
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	27
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	28
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	29
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	30
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	31
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	32
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	33
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	34
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	35
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	36
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	37
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	38
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	39
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USE equilibrium_phases 3
SAVE solution 1
END
MIX	40
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USE equilibrium_phases 3
SAVE solution 1
END
MIX	41
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	42
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	43
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	44
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	45
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	46
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	47
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	48
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	49
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	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
MIX	50
	1	0.5
	2	0.5
USE equilibrium_phases 3
SAVE solution 1
END
```

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