Acid In Situ Leach Uranium Mining : 2 - Soviet Block and Asia

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ABSTRACT: The technique of In Situ Leach (ISL) uranium mining is well established in the USA, as well as being used extensively in Eastern Europe and the former Soviet Union. The method is being proposed and tested on uranium deposits in Australia, with sulphuric acid chemistry and no restoration of groundwater following mining. The history and problems of acid ISL sites in countries of the Former Soviet Union and across Asia is presented.

1 BACKGROUND

The unconventional mining technique of In Situ Leach (ISL) is now the primary producer of refined uranium in the United States, with a market share of around 95% in the mid 1990's (DoE, 1999). ISL mines appear set to assume a greater role in Australia's uranium industry. The commercial ISL uranium mines in the USA use alkaline chemistry, compared to the proposed projects in Australia which are based on the use of acid (Mudd, 1998). In contrast, the ISL uranium mines of the former Soviet Union and Eastern Europe have primarily used sulphuric acid, with apparently little consideration given to environmental concerns during operation.

The first trials of uranium ISL were both developed in the USA and the Soviet Union in the early 1960's. It is uncertain who developed the concepts or if they were developed separately (Mudd, 1998). The use of ISL uranium mining continued to expand until the collapse in the late 1980's. It is worth noting that an unnamed Russian first suggested In Situ Leaching of gold by as early as 1896 (Mineev & Shutov, 1979).

The majority of countries with uranium mining under the influence or control of the Former Soviet Union has undertaken ISL projects, although different countries had contrasting success, from an operational perspective. Bulgaria, for example, experienced a major shift in uranium production from conventional to ISL mines, dramatically reducing the workforce and exacerbating already recalcitrant environmental problems.

Since the reunification of Germany and the collapse of the Soviet Union, the extent of the contamination of groundwater is beginning to come to light, mainly through co-operative programs of the International Atomic Energy Agency (IAEA), although other agencies are are becoming involved. There is also increasing interest in the use of ISL methods for the mining of low grade uranium ores in other parts of Asia, most notably China and Pakistan.

The resurfacing of the Australian acid ISL uranium mine proposals in 1996, the lack of acid ISL mines in the USA, the research coming to light through the IAEA concerning the extent of impacts from acid mines in the Soviet block, led to a wide ranging review of ISL uranium mining by the author, completed in 1998 (cf. Mudd, 1998).

2 BULGARIA

This review is based on IAEA (1999), Nedyalkov (1996), Dimitrov & Vapirev (1994), Vapirev *et al.* (1993), Kuzmanov *et al.* (1992) and Tabakov (1992), more detail is given in Mudd (1998).

The ISL technique was first applied in 1967 to low-grade deposits (ranging from 0.006 % to 0.03 %) at Orlov Dol and Selishte (a former conventional mine). Given the success of these sites, a revolution was perceived whereby many previously uneconomic deposits were exploitable. By 1990, the share of uranium production from ISL was 70%.

All uranium mining and milling in Bulgaria was closed down by government decree on August 20, 1992. Activity since has been aimed at cleaning up and rehabilitating the numerous mine sites. The total contaminated area due to all uranium industry activity is approximately 20 km^2, including 6 km^2 from ISL mining and 4 km^2 of contaminated forest.

There has been a total of 19 sites where ISL has been applied, and a further 11 sites where the ISL technique was applied within an underground mine. Most of these sites began operation in the late 1960's to early 1970's, although poor results from initial trials meant some sites were not continued. These are all concentrated in the southern and western regions of Bulgaria (refer to Figure 21). The deposits contain high amounts of organic matter, iron and sulphides.

The ISL mines had a dramatic impact on the workforce in conventional mines, falling from 5,000 workers between 1965 and 1970 to approximately 500 in 1988. The initial chemistry used was sulphuric acid, although this was later switched to sodium-carbonate and ammonium-carbonate leaching chemistry in deposits with a high carbonate content.

The siting and operation of many uranium mining operations across Bulgaria were often neglected to enable fast tracking of projects and minimise the costs involved in establishing a project. Only one mine was closed due to contamination of drinking water.

Almost no preventive measures or counter measures were implemented during the whole period of mining for the environmental protection of water, soil and air from mechanical, chemical and radioactive pollution. The secrecy of the uranium and nuclear industry was identified as a key reason behind this philosophy.

The leaching of uranium was generally progressed in three stages - first, acid was introduced at levels up to 10 g/L (lasting for a few months); second, the base period of acid leaching at 4-6 g/L (lasting for over two years); and third, the closeout period at 0.5-1 g/L. The overall time for a wellfield was between 3 to 5 years and the recovered uranium was about 60% to 80%. The Ra levels of leaching solutions was generally low.

Table 1 - Typical Lixiviant Components (mg/L) (summarised from 13 ISL sites)

pH	TDS	Na	K	Ca	Mg	SO_4	V
1.4-2.0	15,000-20,000	30-900	30-200	140-600	140-330	10,000-12,000	1.0-18
Al	Fe	Mn	Zn	$HSiO_4^-$	U	Ra (Bq/L)	
310-840	700-2,200	6-61	2.1-7.3	210-350	5-30	1-2	

The pre-mining quality of groundwater in the ore zone aquifers was typically 500-2,000 mg/L TDS, pH of 6.3-8.8, iron 0.1-648 mg/L, and sulphate 24-758 mg/L; good quality water.

There has been significant contamination of groundwater at most ISL sites, with major concerns arising from chemical, radiological and bacterial contamination. For the combined underground-ISL sites, Fe, Cu, Co, Ni, Mo, As and some rare earth elements are several times higher than allowable limits. In the Deveti septemvri ISL mine, Mo reaches 13.4 mg/L (regulatory limit 0.5 mg/L, 27 times higher), and Mn reaches values up to 13 mg/L in groundwater and 4.2 mg/L in the retention pond; quantities of B and Hg have been detected.

At the Orlov Dol site, after six years of monitoring, the acidity of the ore zone aquifer was declining from 1,300 mg/L to 10 mg/L, although the groundwater still contained elevated levels of uranium despite the associated small increase in pH.

The concentration of sulphate can be very high in surface waters and even in water supply wells of private owners as a result of accidental spilling of solutions at ISL sites. The average chemistry of contaminated groundwaters ranges in TDS from 15-20 g/L, SO_4 from 10-12 g/L, U between 5-20 mg/L, other salts and the presence of heavy metals and rare earths.

For the Cheshmata (Haskovo) site, in the valley downstream, SO_4 concentration is 1,400 mg/L (limit 300 mg/L), free sulphuric acid 392 mg/L and the pH is 2.2 (over 1,000 times more acidic than the surrounding aquifer). The private wells of residents of the area have also been affected with significantly high concentrations of SO_4 being noted, demonstrating that the leaching solutions have migrated into drinking water supplies.

A similar case has been recorded in Navusen, where in a valley the SO_4 concentration is 13,362 mg/L and almost 5 g/L free sulphuric acid, indicating the water is actually lixiviant or leaching solution. The groundwater quality of such sites has a TDS (salinity) level of greater than 20 g/L, of which SO_4 is 12-15 g/L. Heavy and rare earth elements were detected in some cases, such as V, W, Mo and La, due to recycling of the solution.

There were also noted problems due to bacterial contamination, although their exact effects were not able to be predicted and were not studied. It was thought that they were beneficial in the leaching process.

There remains concern that solutions at the various ISL sites could contaminate the deeper groundwater systems, as well as the shallow systems. For the deep systems, which contain the ore being mined, the U content can reach 20-30 mg/L and Ra 1-2 Bq/L, with U content in shallow aquifers around 3-4 mg/L and Ra 0.5 Bq/L, despite dilution effects during migration through the aquifer.

At some sites, where there were surface spills due to failure of distribution pipes, the U and Ra content of soils is 10 and 2-3 times the background level, respectively.

At most of the ISL sites undergoing restoration, the solutions were continually recycled through the mined aquifer without adding acid, and this led to deposition of salts within the pipes. These salts contained increased and significant levels of radioactivity. This process has been now been stopped.

A principal problem of the restoration work currently in progress is that the environmental requirements are quite strict, making uranium production unprofitable. It was argued that achieving an acceptable level of environmental protection required that preventative measures, planning and funds are set aside during the early stages of a project, and during the operational phase of a particular project. As this was not done, the necessary funds are not available and restoration work is thus significantly impaired.

Only one third of the land used by ISL operations has been remediated, and as the land will be returned to the original owners for agricultural purposes, there are grave concerns for public health and environmental safety. Some of the ISL sites (such as Bolyarovo, Tenevo, Okop and Gorna Trakiiska nizina) are close to areas where potable quality groundwater is extracted by local communities or the groundwater is considered to be an important future water resource.

2 CZECH REPUBLIC

This review is based on IAEA (1999), Tomas (1996), Andêl & Pribán (1994), Andêl & Pribán (1993), Fiedler & Slezák (1992), Khün (1992) and Benes (1992), more detail is in Mudd (1998).

The Bohemian Massif mining district in the Czech Republic has been an important source of uranium for the Russian military and nuclear power programs, with uranium ore from the Jáchymov mine being used to manufacture the first Soviet atomic bomb. A total of more than one hundred uranium mines were developed, including shallow investigation mines.

The Stráz Pod Ralskem district consists of sandstone-type uranium deposits, and acid ISL has been applied as the mining method since 1968 after successful trials during 1967. The associated mineralisation is also unusual, with zircon, titanium and phosphorous present.

The Stráz region is characterised by complex and unfavourable hydrogeological and biological conditions that make the application and success of ISL extremely difficult. The dissolution rates of uranium are quite slow. This causes two principal problems - firstly, large doses of chemicals are required (sulphuric acid at about 5% with nitric acid and nitrate as the main oxidants); and secondly the leaching periods are very long, ranging from 15 to 25 years. The total uranium production by ISL was 16,470 t U_3O_8.

The Hamr deposit was developed at the Hamr and Luzice mines with both underground and combined ISL techniques. The Hamr mine is only 5 km from the Stráz mine, exacerbating the technical problems at both sites, leading to higher production costs and greater environmental impacts. A principal problem for many of the sites is the density of population across the Czech Republic, with 40,000 people living near the Stráz mine, for example.

After detailed evaluation of the negative impact of uranium mining and milling, a progressive program of declining production from uranium mining has been adopted and an extensive remediation programme implemented by the Czech Government.

2.1 *Stráz Pod Ralskem*

The hydrogeology of the Stráz region is complex, but can be thought of as two distinct aquifers - the Cenomanian and the Turonian. The Cenomanian is a deep, confined and artesian aquifer, and the Turonian lies above this, separated by up to 100 m of thick low permeability clays and siltstones. The Turonian is designated as an important high quality drinking water reserve with a calcium bicarbonate (Ca-HCO_3) type of water quality, and is known to discharge to the Ploucnice River at about 40 L/s. The Cenomanian was known to contain elevated levels of Ra.

For the Stráz deposit, every tonne of uranium (t U) produced :

- 274 t of sulphuric acid injected;
- 7.9 t of ammonia injected;
- 19.3 t of nitric acid injected;
- 1.79 t of hydrofluoric acid injected;
- 7,260,000 L of contaminated groundwater in the Cenomanian aquifer;
- 1,500,000 L of contaminated groundwater in the Turonian aquifer.
- 0.95 t of sulphuric acid released to the air;
- 1.18 t of nitrous oxides released to the air;
- 53 GBq of radium released to the air;

By contrast to experience in the USA, the Stráz ore deposit required 50-70 g/L of sulphuric acid and a leaching period of 15-20 years to reach a yield of 60-80% of the uranium. This was due to the lower permeability of the aquifer materials.

By 1994, a total of 32 ISL sites had been commissioned covering a total of 6 km^2 consisting of 7,000 wells. The Stráz mining district, has seen approximately 3,800,000 t of sulphuric acid, 270,000 t of nitric acid, 103,000 t of ammonia and 25,000 t of hydrofluoric acid injected into the wellfields. The interactions between the leaching solutions and aquifer sediments are not well defined, and the speciation of many heavy metals and radionuclides remain unstudied. The Stráz site ceased producing uranium on April 1, 1996.

Table 2 - Typical Lixiviant Composition at Stráz Pod Ralskem (mg/L)

Free Acid (H_2SO_4)		SO_4		NH_4	NO_3	F		P	SiO_2
15,000-38,000		40,000-65,000		1,000-2,000	200-800	100-300		50-150	100-200
Na	K	Ca	Mg	Al	Fe	Cr	Ni	U	V
10-15	40-70	200-300	20-30	4,000-6,000	500-1,500	5-15	20-30	20-500	10-15

The leaching solutions from the Stráz wellfields were not operated with a bleed system to maintain a cone of depression around active wellfields, and this led to solutions being dispersed widely through the Cenomanian aquifer in the area, as well vertically into the Turonian aquifer. The excursions occurred mainly through production bores, but significant excursions also occurred at liquid waste disposal bores.

The contaminated water in the Turonian aquifer alone is spread over 245 hectares (43% of the area of the wellfields). A total of 200 billion L of groundwater has been affected, covering a total area of 6 km^2 and the volume of aquifer material affected is thought to 720 billion L. Approximately 50% of the contaminated water is thought to be residual leaching solutions, with sulphate higher than 20 g/L and salinities between 35-70 g/L. The remaining 50% is thought to be dispersed solutions, formed by migrating leaching solutions mixing with native groundwater, with a salinity level of 4.5 g/L.

Table 3 - Groundwater Quality Before and After ISL mining at Stráz Pod Ralskem

	pH	TDS	SO_4	NO_3	F	U	Ra	H_2SO_4
	units	g/L	g/L	mg/L	mg/L	mg/L	Bq/L	g/L
Lixiviant	0.5	50-100	33-80	600-1,400	150-250	1-30	50-90	15-20
Cen. Before	6.7	0.14	0.033	<1	<1	0.02	8.74	NA
Cen. Affected	1.8-2.8	5-20	3.3-13	5-100	5-50	0-15	30-70	0.5-5
Tur. Before	6.7	0.1	0.035	5.2	<1	0.01	0.07	NA
Tur. Affected	2.5-7.0	0.5-5.5	0.05-3.3	5-1,000	0.5-25	<1	0.1-1.0	<0.5

The urgent need for restoration is governed by the extremely high concentrations of radionuclides and heavy metals in the various solutions and the large volumes of contaminated water involved. The most critical factor is that the Cenomanian aquifer is artesian, and the pressure difference between the Turonian and Cenomanian aquifers will always ensure groundwater flow is vertically upwards, as was the case before ISL mining began.

The presence of known excursions through boreholes highlights the above problem, and if the bores are not effectively sealed during restoration, there will remain a pressure gradient for new excursions of contaminated groundwater from the Cenomanian into the Turonian aquifer.

The contaminated groundwater in the Cenomanian aquifer is approaching the sanitary protection zone of the Mimon water supply (70 L/s). The contaminated groundwater in the Turonian is within 1.2-1.5 km of the sanitary protection zone of the Dolánky water supply (200 L/s). The region presently utilizes 1,500 L/s of groundwater for drinking supplies.

The restoration of the groundwater is proving a difficult task, with 1 pore volume of groundwater only removing about 70% of the contaminated groundwater and 5 pore volumes required for 90% removal. This equates to about 940 billion L of water. While regulators in the USA require a proven pilot-scale test to demonstrate effective groundwater quality restoration, the Stráz mine only received approvals for liquid waste disposal and restoration requirements in the mid 1990's after three decades of operation.

Currently, restoration programs are aimed at determining the optimal strategy for long term remediation of groundwater quality. The technology being used for restoration involves pre-treatment, reverse osmosis, volume reduction by evaporation, crystallisation and processing of the concentrated saline solutions or brines. Some components are re-utilised, such as sulphuric acid (H_2SO_4), aluminium oxide (Al_2O_3), ammonia (NH_3), and gypsum ($CaSO_4$). The presence and removal of Ra and other metals of concern is a significant barrier to these programs.

Further options for groundwater quality restoration are being investigated with a view to a compromise between environmental demands and economic feasibility. It is intended to return the Turonian aquifer to it's original quality (as much as possible). Recent modelling studies indicate that restoring the Cenomanian groundwater to a salinity of 3 g/L can cause undesirable impacts on the Turonian aquifer, due mainly to structural and tectonic conditions and the instability of the groundwater regime after returning to natural flows.

For the Cenomanian aquifer, though, it appears impossible to achieve restoration to it's original good quality. The philosophy being adopted is to ensure that any escape of Cenomanian groundwater will disperse to an appropriate quality and not impact on potable or surface waters.

The region, once covered by pine forests, underwent deforestation for mining purposes. This was undertaken hastily with many trunks left in the ground, dead and rotting. The surface soils, devoid of tree cover, were therefore exposed to accelerated rates of weathering, sheet erosion and wash-down of the poorly cohesive sandstones and deep furrows. This was exacerbated by the movement of heavy machinery across the site. In the low-lying areas near the Ploucnice River, the alteration of surface drainage patterns, together with the removal of vegetation, led to a gradual rise in the water table and the formation of lagoons and wetlands.

In the areas where pine trees had been left, to try and preserve some of the remnant forest, it was found that the forest was weakened and unsustainable since it was no longer continuous. This led to increased exposures of the wells and piping systems and high incidences of dead, falling trees. In the hill areas, wells and piping systems were often built partly on benches and partly on platforms. Together with the spills of solutions from pipes and surface runoff, the siting of these parallel to slopes led to significant rates of erosion and the prevention of further vegetation growth due to the lack of suitable soil. Attempts were made from the mid 1980's to address these problems, such as hydromulching, different seed species and other techniques, but they were of varying short duration and thus limited success.

Due to the intransigence of the chemical and physical changes caused by ISL mining at the Stráz site, the restoration efforts are anticipated to last several decades, or even centuries.

3 GERMANY

This review is based on Biehler & Falck (1999), Diehl (1999), Ettenhuber (1996) and Hähne & Altmann (1992).

The rich pitchblende uranium deposits of East Germany were one of the former Soviet Union's first targets for supplying uranium during the late 1940's and 1950's for weapons and nuclear power programmes. Simultaneous work was carried out on all types of uranium deposits in the area. Most uranium mines and mills in East Germany were underground, although Königstein and to a lesser extent Ronneburg, also had underground ISL applied for the extraction of uranium. Underground uranium leaching began in 1968 to take advantage of low grade ores and increasing conventional costs, since in-situ leaching costs were only 60-70% of conventional methods.

3.1 *Ronneburg*

Although a less prolific producer of uranium by ISL, repeated attempts were made to increase uranium recovery from 1970. The leaching solutions used included sulphuric acid or alkaline reagents. Between 40-70% of the uranium reserves were recovered at concentrations of sulphuric acid from 3-10 g/L, pH of approximately 1.5-2.5 and uranium content between 20-100 mg/L. A total of 3,203 t of U_3O_8 was produced by heap and waste pile leaching, with 106 t of U_3O_8 produced by underground ISL techniques.

3.2 *Königstein*

From 1971 both underground and in situ leach mining was being used, until ISL mining took over in 1984. The extraction of uranium with ISL operated until 1990, with the total uranium production from the life of the mine being 22,711 t of U_3O_8, 6,517 t by sulphuric acid ISL.

The aquifers at Königstein generally contain excellent quality water, with salinity less than 200 mg/L and pH near neutral. The heavy metal content is typically quite low. The uranium mineralisation at Königstein is found within the fourth aquifer of a regional groundwater system. The clay layer separating the third and fourth aquifers was intersected by the underground mine workings. The third aquifer is used by residents of the region for their water supply, as well discharging into the Elbe River 600 m east of the mine site. The dewatering of the fourth aquifer for the mine led to a decrease in water level of the third aquifer.

One of the most difficult problems associated with remediating the contaminated groundwater is that at the time of closure a new underground block had just been prepared for leaching. The prevailing unsaturated conditions allowed the pyrite to oxidise, generating significant quantities of sulphuric acid, further mobilising heavy metals, uranium and radionuclides and adding to the contaminant load to remediate.

The average concentrations of leaching solutions was 2-3 g/L sulphuric acid, pH 1.5-1.8, salinity (TDS) 10-14 g/L and uranium 10-150 mg/L. The uranium recovery was generally about 65-75% within three years. A total of 100,000 t of sulphuric acid was injected into the mine. The leaching process has chemically affected more then 55 million m^3 of rock and aquifer, while approximately 1.8 billion L containing 1.2-1.7 g/L sulphuric acid and more than 30 mg/L uranium remains circulating or trapped in the pore space of the rocks. A further 850 million L are circulating between the leaching zone and the recovery plant. Expressed as multiples of applicable German drinking water standards, the trapped liquids have levels 400 times higher in Cd, 280 times higher in As, 130 times higher in Ni and 83 times higher in U.

The principal concerns for restoration of the site are centred around the flooding of the underground mine workings that will occur after the mine is closed down. There is potential for contamination of surrounding groundwater and surface water streams with U, Ra, SO_4, Fe and heavy metals. Although small scale flooding trials are currently being conducted, restoration is still not complete and the mine still represents a threat to the surrounding aquifer, an important potable groundwater resource for the region.

4 FORMER SOVIET UNION

A general overview of the use of ISL in the Former Soviet Union is presented. A more detailed review of each new republic (the "stans"), however, will be treated separately. This review is based on Skorovarov & Fazlullin (1992) and Skorovarov *et al.* (1987).

There has been active development of ISL-type mines across former Soviet block countries such as Ukraine, Uzbekistan, Kazakhstan and Russia, since the early 1960's. The ISL technique was typically applied to low grade deposits between 0.03-0.05%. Sulphuric acid was the more popular leaching agent, although alkaline carbonate-bicarbonate agents were used at some sites, depending mainly on the carbonate content of the ore. The wellfield patterns used were quite variable, including 10x10 m, 10x20 m, 25x50 m and up to 10x100 m spacings.

The concentration of sulphuric acid ranged from 2-5 g/L, with the stronger the acidity the greater the recovery of uranium and shorter the period of leaching. The average acid consumption per 1 kg of uranium recovered as an end product varied widely from 18-150 kg. The recovery rate of uranium was generally between 70 and 90%. No oxidant was needed to ensure dissolution of the uranium. Associated metals were also thought to be extractable, such as V, Re, Se, Mo, Sc, Yt and rare earths.

Some of the main problems of using sulphuric acid was the necessity to use acid-resistant materials and equipment, deterioration of the ore zone permeability due to chemical and gaseous plugging, and the very high salinity levels during mining (ranging from 15-25 g/L).

Table 4 - Typical Acid and Alkaline Leaching Solution Composition (mg/L; Ra in pCi/L)

	Cl	SO_4 (g/L)	Na + K	Ca	Mg	Al	Fe^{2+}	Fe^{3+}	Ra
Acid	400-600	17-25	100-200	400-600	300-500	500-800	800-1,500	400-1,000	100

	HCO_3	NH_3	SO_4	Cl	Na + K	Ca	Mg
Alkaline	500-2,500	400-600	2,000-3,000	500-1,200	500-1,000	700-800	100-300

For ores with a carbonate content higher than 1.5-2.5%, alkaline solutions were used consisting of ammonium bicarbonate. The concentrations generally varied from 500-5,000 mg/L. On some sites sodium bicarbonate was also applied. The alkaline ISL sites used oxygen as the oxidant. The recovery rate of uranium was generally between 50 and 60%. The use of alkaline agents also tended to show much smaller increases of salinity during mining. The main recognised problems of alkaline ISL were the high degree of solutions escaping outside the mining zone (often due to gaseous oxygen plugs forming), compulsory pre-treatment to soften the water and restoration difficulties following completion of ISL.

Numerous techniques were being trialled to restore the quality of the groundwater, including lime pulp treatment, hyperfiltration and electrosorption. The success of these technologies on restoring contaminated groundwater is not known. The production costs of ISL were 40-45% of conventional costs, with significantly lower energy and capital costs and reagent consumption.

5 KAZAKHSTAN

This review is based on Catchpole (1997) and Carroll (1997).

The uranium resources of Kazakhstan are considerable, of which a large proportion are amenable to ISL extraction. As with many former Soviet-controlled states, the use of ISL in Kazakhstan began in 1970 and continued to increase in importance, centred around the large amenable deposits in southern Kazakhstan. The large scale ISL mines began in 1978. All ISL mines utilise sulphuric acid leaching chemistry.

By 1990, ISL technology had displaced conventional mines as the predominant uranium production method. The large ISL-amenable resources are seen as the future of the Kazakhstan uranium industry. There are several operating ISL projects, although an accurate assessment of current and prospective projects is not an easy task. Some operating sites include Stepnoye, Centralia and Chiili. Further sites being assessed and/or developed are the Inkai, Mynkuduk and Moynkum sites. The environmental impacts and operational issues are yet to be published, although given the history of the nuclear industry in Kazakhstan, it is likely to be similar to other parts of the Former Soviet Union.

6 UKRAINE

This review is based on Chernov (1998), Rudy (1996) and Molchanov (1995). In-situ leach uranium mining was carried out on the Deviadovskoye, Bratskoye and Safonovka deposits.

The Deviadovskoye ISL mine operated from 1966 to 1983, using sulphuric and nitric acids. The surface area of the mine is 12 ha, with the ore body about 218 ha and the area for underground storage is 120 ha. As a result of ISL mining, groundwater was contaminated at a depth of 80 m. The residual solutions are distributed a distance of 1.7 km along the flowpath and for 0.35 km against the upstream gradient.

The nearest settlement down gradient is 4 km only distant. The volume of residual solutions after the ISL mining of uranium in the Buchak aquifer is 7.09 billion L. The volume of tailing ponds water is 1 billion L with contaminated silt in ponds-collectors about 40,000 m^3. Leakage from pipelines has contaminated surface soils, totalling about 50,000 m^3.

The Bratskoye ISL mine site operated from 1971-84, using sulphuric and nitric acids. The orebody area is 95.5 ha. At the end of mining, the leaching solutions within the orebody were simply abandoned. The 5.2 billion L of contaminated groundwater is distributed 3 km down gradient and 1.2 km up gradient, to a depth of 50 m.

The Safonovka ISL site was mined from 1982-93. The surface area of the mine site covered 5 ha, although no further information is available on the extent of groundwater impacts and future management and remedial programs.

The severe lack of financial resources has led to the freezing of restoration activities in 1996.

7 UZBEKISTAN

This review is based on Venatovskij (1992). The state of Uzbekistan has numerous uranium deposits that host operating or potential ISL mines, concentrated within the large Central-Kizilkum province. They are generally around 300 m in depth and contain uranium ore in several distinct layers. The ore grades vary from 0.03-0.70%. Many contain low carbonate content less than 2.5% although some deposits are rich in carbonaceous matter (higher than 5%). Various leaching agents are used, with sulphuric acid being the preferred acid. Information on the extent of operational and environmental impacts is not presently available.

8 CHINA

This review is based on Xu *et al.* (1998) and Jian & Ning (1992), except where noted.

Approximately 61% of Chinese uranium is contained within deposits smaller than 3,000 t U_3O_8, mostly below a 0.2% grade. The In Situ Leach technique, for underground mines and the more traditional solution mines, has been viewed as the preferential method for economically extracting uranium since the early 1980's, with trials on all types of mineralisation being conducted. Two main ISL projects are currently being actively developed or operated at Tengchong and Yining (Diehl, 1999).

The Tengchong uranium deposit is hosted in sandstone with gangue minerals including pyrite and carbonaceous matter. A trial of sulphuric acid ISL lasting 42 days was undertaken on a pattern of 31 wells, with the uranium content reaching a maximum of 150 mg/L and an effective yield of 62%. The deposit is being developed as a commercial facility.

In Situ Leaching at Yining, also known as Deposit No. 512, began in 1994 uranium using sulphuric acid and a hydrogen peroxide oxidant. The deposit is hosted in sandstone being up to 20 m thick and is 0.011-0.17% in grade. Sulphuric acid levels were initially injected at 2% (20 g/L) and gradually increased to 8% (80 g/L) with hydrogen peroxide concentrations up to 0.55 g/L. The acid was later reduced to 4-6 g/L. The ISL trial ran for 92 days, with the injection of 9.8 million L of lixiviant, 41.59 t of sulphuric acid , 2.11 t of hydrogen peroxide, and the extraction of 11.7 million L of solutions (18.7% bleed rate) with uranium at 40-75 mg/L.

Table 5 - Typical Lixiviant Composition at Deposit No. 512 (Yining) (mg/L; Eh in mV)

pH	Eh	SO_4	S^{2-}	Cl	CO_2[1]	PO_4	F	Na	K	Ca	Mg	Fe^{2+}	Fe^{3+}	Al^{3+}	U
1.26	652	22,800	2.7	762	0.99	22	5.2	172	28	17	140	377	440	323	75

As	Cd	Cu	Cr^{6+}	Cr_T[2]	Mo	Mn	Ni	Pb	Re	Sb	Sc	Se	Ti	V	Zn
0.1	0.04	0.5	0.1	0.74	2.4	8.4	1.3	0.67	3.1	0.4	1.86	0.001	<1	4.8	0.88

Notes : [1] - Free CO_2; [2] - T is Total Cr.

9 DISCUSSION AND CONCLUSIONS

The experience of acid In Situ Leach uranium mining in areas controlled by the Former Soviet Union provides a stark contrast to experiences in America and Australia. In most applications of the technique, there has been extreme occurrences of groundwater contamination. At some sites, this contamination has migrated considerable distances to impact on potable drinking water supplies. For other sites, the potential for contamination to reach an undesirable receptor remains significant. The problems at these sites were severely exacerbated by the prevailing paradigm of uranium production without regard for environmental damage. Apart from Asian nations such as Kazakhstan, Uzbekistan and China, all countries are in the process of closing down and developing remedial action programs. The restoration of groundwater is proving difficult, both technically but also due to a lack of financial resources within these countries.

Morris (1984) noted that reliance on natural attenuation processes has never been tested for restoration of ISL. The former ISL sites across Eastern Europe and the Former Soviet Union allow some insight into the use of "natural restoration" as a remedial technique.

Buma (1979) argued that natural geochemical processes within aquifers can restore contaminated groundwater from ISL mines, thereby saving valuable chemical, energy and financial resources. The processes he outlines include precipitation of reduced compounds; scavenging of of heavy metals by pyrite, organic matter, ferric oxyhydroxides and calcite; adsorption by quartz, feldspars and clays. The key was for active reductants to be present.

At many ISL mines outlined above, there was high organic, iron or sulphide content, such as Bulgaria and the Czech Republic. The contamination at these sites, including the high concentrations of major ions, heavy metals and radionuclides, has not attenuated significantly over time, and instead migrates away from the mine sites, up to several kilometres in some instances. The geochemical mechanisms controlling this migration are unclear, although co-precipitation, which may give rise to higher solubilities for species such as $(Ca.Ra)SO_4$, and the complete oxidation of reducing agents during ISL mining with no active agents remaining after mining, are likely to be significant, key issues.

It would appear, therefore, that "natural restoration" is not a desirable approach in the slightest, even given the complex hydrogeochemical conditions known to exist at some sites across Eastern Europe and the former Soviet Union.

10 ACKNOWLEDGEMENTS

There are a great many people who have contributed to the comprehensiveness of this paper. Of special note is Peter Diehl (Germany), David Noonan and Dennis Matthews (South Australia), Paul Robinson (New Mexico, USA) and several supportive colleagues from around Australia (eternal thanks). This is independent and voluntary research undertaken by the author, and thus cannot be taken to represent the views of any other person, entity or organisation except those of the author. It is trusted this paper makes a valuable contribution on the topic.

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