Acid In Situ Leach Uranium Mining : 1 - USA and Australia

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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 the USA and Australia 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.

It is perhaps an historical curiosity as to where the conceptual processes for ISL (as applied to uranium) were first conceived and applied. The Chinese were apparently the first to use solution mining to produce copper as early as 907 AD, with references to the technology dating back to 177 BC (Morris, 1984). In the 1890's, the Frasch process for mining elemental sulphur was invented, and ISL mining of gold was first suggested by Russians (Morris, 1984). The first trials of uranium ISL were developed in the USA and Soviet Union in the early 1960's. It is uncertain who developed the concepts or if they were developed separately (Mudd, 1998).

By the mid 1970's, there were ISL mines across the world as an alternative, low cost method (Mudd, 1998). In the USA, ISL mines generally used alkaline chemistry with only a few sites trialling acid chemistry. In contrast, Soviet mines generally used acid with only a few sites using alkaline reagents. In Australia in the 1980's, two ISL projects in South Australia proposed acid, while a third in Western Australia trialled alkaline chemistry (Mudd, 1998).

The environmental regulation of mining generally requires the restoration of affected groundwater to be returned to its pre-mining quality or use category. In countries controlled by the Soviet block, the need for restoration of contaminated groundwater following mining was ignored during operation, and the problems and magnitude of groundwater contamination now coming to light in the 1990's can only be described as extreme (cf. Mudd, 1998 & 2000).

Indeed, the use of alkaline chemistry in the USA has been partly related to the need to restore affected groundwater and that alkaline mine sites are recognised to be technically easier to restore (Mudd, 1998; Tweeton & Peterson, 1981). In direct contrast, Australian mines - historically and currently - proposed not to restore affected groundwater after acid ISL mining.

The resurfacing of the Australian acid ISL uranium mine proposals in 1996 (due to changes in federal government uranium policy), the lack of acid ISL mines in the USA, the research coming to light through the International Atomic Energy Agency (IAEA) and others of the extent of impacts from acid ISL mines in the Soviet block (cf. Mudd, 2000), led to a detailed review of ISL uranium mining by the author, completed in 1998 (Mudd, 1998).

2 ACID ISL IN THE USA

2.1 *Brief History of ISL*

The initial development of ISL mining in the USA occurred in Wyoming at the Shirley Basin uranium project from 1961-63, by the Utah Construction and Mining Company (UCMC; now Pathfinder Mines Corp.) (Larson, 1981). They experimented with 5 generations of wellfield design and over 100 patterns, using sulphuric acid chemistry (Underhill, 1992). The Shirley Basin ISL project operated on a small scale from 1963-70 to produce 577 MTU, however, the ISL mine was closed in 1970 and converted to an open cut operation (Underhill, 1992).

The late 1960's to mid 1970's witnessed rapid development and promise in ISL mining, principally in Texas, Wyoming, New Mexico and Colorado (Kasper *et al.*, 1979). By May 1980, a total of 18 commercial and 9 pilot scale projects were either in operation or under active development (Larson, 1981). Virtually all of these sites utilised alkaline reagents such as ammonia or sodium carbonate/bicarbonate. The difficulty of restoring ammonia-based sites saw a quick shift in emphasis to sodium- or carbon dioxide-based leaching chemistry by the early 1980's (Tweeton & Peterson, 1981). Despite years of lower production in the late 1980's, ISL mines have gradually increased their share of the uranium market in the USA from about 1.2% in 1975 (Underhill, 1992) to greater than 90% during the mid-1990's (DoE, 1999).

By 1991, a total of 62 ISL projects had been developed, although only 24 of these sites were commercialised (Underhill, 1992), indicating more unsuccessful than successful projects (Mays, 1984). There has been no development of a commercial ISL mine since Shirley Basin using acid chemistry (Mays, 1984). Further detail on all ISL mines is in Mudd (1998). There were several sites in Texas, New Mexico and Wyoming which underwent pilot scale testing of acid ISL, although most were poorly documented in public literature (Mudd, 1998).

Table 1 - Pilot Scale ISL Mines Using Acid Leaching Chemistry [1]

Project / Site	Company	Time Period
Nine Mile Lake (NML), WY	Rocky Mountain Energy Co. (RMEC)	Mining : Nov. 1976 to Nov. 1980 Restoration Suspended : Feb. 1982
Reno Ranch[2], WY	RMEC	Mining : Feb. 1979 to Nov. 1979 Restoration Suspended : March 1981
Irigary, WY	Wyoming Minerals	Unclear - acid trial referred to by Kasper *et al.* (1979)
Jackpile Paguate[3], NM	Anaconda	Early 1970 trial, 2 wellfields, with 2 injection bores & 18 extraction bores, upgraded to 29. Project discontinued.
Dunderstadt, TX	Cities Service	Trial operated between 1969-71. No reports.
Besar Creek, TX	RMEC	Early 1970's ?, details unknown (plant used at NML).

Notes : [1] - Mudd (1998), Underhill (1992) & Staub *et al.* (1986); [2] - also Reno Creek; [3] - North Windup Project.

The best documented acid ISL project is Nine Mile Lake, near Casper, Wyoming. The project was developed by Rocky Mountain Energy Co. (RMEC) in association with research by the U.S. Bureau of Mines. The landmark study was reported in detail by Nigbor *et al.* (1982). RMEC's Reno Ranch trial in Wyoming was the second documented acid ISL trial, reported by (Staub *et al.*, 1986). Further acid ISL trial sites, however, have not been reported widely in the literature. Acid systems were generally considered unsuitable for Texan deposits.

2.2 *Nine Mile Lake, Wyoming*

The geology and hydrogeology of the Nine Mile Lake (NML) site is given by Nigbor *et al.* (1982) and Staub *et al.* (1986). The following discussion is adapted from these references.

It is situated on the southwest flank of the Powder River Basin. The roll-front type uranium mineralization occurs in the Teapot Sandstone within the Mesaverde Formation. The ore body extends over a strike length of 6,100 m in a north-northwest direction and ranges between 15 to 900 m in width, consisting of upper and lower zones. The site is at an elevation of 1,600 m.

The uranium ore at NML was precipitated at the interface of oxidation-reduction boundaries in the Teapot sandstone, due to the presence of carbonaceous material and pyrite. The principal uranium mineral was uraninite, with minor quantities of coffinite. Vanadium was associated with the mineralization (about 1.3%) and was proposed to be extracted from a commercial facility. The ore contained less than 0.1% carbonate, although total carbon content was higher at 0.2-2.0%. The major clay mineral present was kaolinite (2-5%), with minor montmorillonite, although this had a low cation exchange capacity at about 5 meq/100 g.

Due to the low carbonate content of the ore body and the low cost of sulphuric acid, NML was considered an ideal site for sulphuric acid ISL mining. Extensive laboratory tests on core samples suggested that savings in chemical costs would result from the use of acid. A total of four wellfield patterns underwent testing and development at the Nine Mile Lake project site. The chronology and detail for each pattern is summarised in Table 2.

Table 2 - Research and Development Details for Nine Mile Lake

Pattern & Type		Lixiviant Chemistry	Period of Testing[4]	PV[5]
1	7-spot,	4 g/l H_2SO_4 (pH 1.7), 0.5 g/l H_2O_2,	Mining : Nov. 1976 to Aug. 1977	7
	15 m radius	0.15 g/l $FeSO_4$, flow ~2.5 L/s	Restoration : Sep. 1977 to Oct. 1978	12
2	5-spot,	3-5 g/l H_2SO_4 (pH 1.8), 1 g/l H_2O_2,	Mining : Dec. 1977 to Sep. 1978	13
	15 m radius	flow ~2.6 L/s	Restoration : Sep. 1978 to Aug. 1979	12
3	8-spot[6],	H_2SO_4, H_2SO_5 or O_2, flow ~3.8 L/s	Mining : Sep. 1979 to April 1980	5.6
	18 m radius		Restoration : Aug. 1981 to Jan. 1982	6
4	5-spot,	Na_2CO_3 / $NaHCO_3$ with $CO_{2\,(g)}$	Mining : June 1980 to Nov. 1980	?
	15 m radius	(pH ~ 7.5), 0.5 g/l H_2O_2 (later) O_2	Restoration : Nov. 1980 to Aug. 1981	?

Notes : [4] - Restoration refers to initial phase only; [5] - Aquifer Pore Volumes reached during testing; [6] - included 2 central injection and 6 extraction bores (effectively, one 3-spot pattern for each ore zone aquifer).

Pattern 1, completed in the upper ore zone, experienced several problems leading to poor operational performance. These included problems with the PVC well casing, cement baskets and pumps. A buildup of gypsum scale on the injection well screens, possibly related to the degaradtion of the casing cement by the acid, contributed to poor injectivity. Potential channelling and poor injectivity led to disappointing overall uranium recovery.

Pattern 2, completed in the lower ore zone, with a detailed assessment provided by Nigbor *et al.* (1982), was generally considered a good success. Injectivity was good, although plugging problems due to "fungus growth" and gypsum precipitation were encountered in April 1978. No evidence was provided to substantiate the conclusion for "fungus growth".

The two injection bores of Pattern 3 were completed in both the upper and lower ore zones to test the feasbility of simultaneously leaching both zones. The extraction bores were completed independently in each ore zone. The pattern experienced sporadic problems with well plugging, frozen lines and equipment failures, leading to poor operational performance. Further problems were encountered in controlling lixiviant distribution to the two ore zones.

Pattern 4, using alkaline chemistry, was intended to give a comparison of alkaline and acid leaching on the same ore body. However, the results of the trial are not available, although RMEC described the test as "disappointing". Thus no comparison can be made of the respective advantages and disadvantages of acid versus alkaline for the same deposit.

There were 5 horizontal excursions (ore zone aquifer) detected at NML during the testing phase, with three in Pattern 3 and two in Pattern 4. All excursions were bought under control by increasing the extraction rate. No monitoring of overlying and underlying bores was undertaken, and determination of any vertical excursions is impossible. This potential exists at almost every ISL site, due to casing failures and abandoned exploration bores (Staub *et al.*, 1986; Marlowe, 1984). The risk increases with the total number of bores and age of a site (Marlowe, 1984).

The restoration of each pattern was undertaken immediately after mining, followed by the regulatory period of stabilization. Post-restoration monitoring is critical in understanding the effectiveness of restoration efforts and long term impacts on water quality at NML. The available baseline, leaching phase and restoration groundwater quality data for each pattern is compiled in Tables 3 & 4, adapted from Nigbor *et al.* (1982) and Staub *et al.* (1986).

The restoration data is averaged from observation and extraction bores, due to the tendency of injection bores to reflect the quality of injected solutions rather than groundwater after mixing. The high sulphate levels of the ore zone were thought to be related to influx from Nine Mile Lake itself, 1.6 km to the south, which is naturally high in sulphate.

Table 3 - Baseline and Restoration Groundwater Quality, Patterns 1 & 3, Nine Mile Lake (all units mg/L, except for pH; EC in mmhos/cm) (Staub *et al.*, 1986)

Pattern	& Phase	TDS	EC	pH	Cl	SO_4	Ca	U (U_3O_8)	V
1	Baseline	2,483	3.16	6.9	3.3	1,240	87	0.384	0.1
	Restoration	7,750	12.0	6.9	93	5,140	300	0.289	0.073
3	Baseline	2,034	2.38	6.9	35	1,244	74	0.060	0.18
	Restoration	1,450	2.50	7.1	26	920	61	0.126	0.57

Table 4 - Average Baseline, Leaching Phase and Restoration Groundwater Quality, with Standard Deviation, Pattern 2, Nine Mile Lake (mg/L, except for pH, EC in mmhos/cm, Redox in mV, As, Mo and Se in µg/L, and Ra^{226} & Th^{230} in pCi/L) (Nigbor *et al.*, 1982)

	TDS	EC	pH	Redox	DO[7]	Cl	SO_4
Baseline	4,300 ± 550	4.10 ± 0.51	6.7 ± 0.3	-120 ± 200	1	46 ± 4.3	2,510 ± 244
Leaching		10.0-20.0	1.5-2.0				up to 8,000
Restoration[8]	3,000 (2,390)	3.25 (3.08)	6.1 (6.9)	-22 to 120	<0.1	29 (37)	1,585 (1,584)

	HCO_3	F	Ca	Mg	Na	K	Al
Baseline	290 ± 30	0.77 ± 0.25	207 ± 43	92 ± 31	830 ± 145	14 ± 3.6	0.13 ± 0.05
Leaching			260				
Restoration[8]		0.6	805 (102)	42	485	6.2	

	As	B	Cr	Cu	Fe	Mn	Hg	Mo	P	Se
Baseline	40	0.67 ± 0.40	0.01	0.01	1.07 ± 0.4	0.31 ± 0.18	0.01	8 ± 18	0.2	2
Leaching					up to 200					
Restoration[8]	24				6.8	0.24			<0.1	13

	Si	U	V	Zn	Ra^{226}	Th^{230}
Baseline	4.2 ± 4.0	0.23 ± 0.10	0.5 ± 0.2	0.02 ± 0.02	510 ± 29	0.084 ± 0.005
Leaching		80-150	up to 800		10,000 ± 170	49,000 ± 3,200
Restoration[8]	14.8	1.05 (0.132)	11.1 (0.986)	1.97		

Notes : [7] - Dissolved Oxygen; [8] - includes additional restoration work undertaken in 1981-82 in brackets. Many elements buildup over time, while others approach a stable concentration - leaching values indicative only.

The methods for restoring each pattern differed slightly. Pattern 1 was restored using a groundwater sweep, while Pattern 3 involved a groundwater sweep combined with reverse osmosis treatment and mixed with "clean" formation water before reinjection into the ore zone.

The post-restoration monitoring of Pattern 1 from early 1978 to 1981 indicated substantial deterioration of water quality, due to gypsum dissolution increasing salinity levels. Reverse osmosis treatment of approximately 2.5 pore volumes of recirculated groundwater was undertaken in 1981, although later monitoring again showed a deterioration and stabilization at a high salinity level. The water quality, with salinity 4 times higher at 7,750 mg/L and SO_4 3 times higher at 5,140 mg/L, is now unsuitable for stock purposes - it's pre-mining use category.

The restoration of Pattern 2, however, proved to be more recalcitrant. The first phase of restoration involved four months of a modified groundwater sweep with reinjection of process water and barren production fluid. Restoration using reverse osmosis treatment was then undertaken for a month. From May to mid-August 1979, a high pH, sodium hydroxide solution was injected to promote ion exchange and speed restoration. Clean water recycling with reverse osmosis continued for the next three weeks, by which stage nearly all major parameters were restored to pre-mining ranges, and active restoration ceased.

Post-restoration monitoring of Pattern 2 during late 1979 and early 1980 detected scattered areas of contaminated groundwater around the pattern interior, migrating slowly down gradient. Pumping resumed in August 1980, with the groundwater being treated with a lime/barium chloride precipitation process, and reinjected into the wellfield. The total quantity was about 3.5 aquifer pore volumes. Little improvement was apparent and by May 1981, water quality was again deteriorating. As of June 1984, V, ^{226}Ra and TDS were above pre-mining levels.

The restoration of Pattern 3 returned most parameters to baseline values or better but failed to restore U, V and ^{226}Ra to pre-mining levels. The lack of published data for Pattern 4 precludes a direct comparison of the efficacies of an acid to an alkaline leached site.

The Nine Mile Lake acid ISL trial demonstrated that acid was indeed an effective alternative leaching reagent to the alkaline chemistry prevailing at the time, albeit non-selective. However, other issues raised by the trial include the difficulty in scaling laboratory test results to the field.

The column leaching tests performed on NML core samples suggested significantly lower reagent consumption than required in the field. The restoration of the laboratory columns indicated that about 13 pore volumes would be required to restore the water quality, whereas in the field it was closer to 20 and still experienced deterioration following treatment efforts. Nigbor *et al.* (1982) concluded that, due to greater reagent consumption and the difficulty and expense of restoration, that acid leaching was no more cost effective than alkaline leaching.

The expansion of the NML site to commercial scale by RMEC proposed to use a 7-spot production pattern with a radius of 21 m. The lixiviant was 3-5 g/L H_2SO_4 and 1 g/L H_2O_2, with recovery of the vanadium by-product. As of June 1984, the RMEC had no plans for commercialisation, and to the best of the authors' knowledge, the site is yet be developed.

2.3 *Reno Ranch, Wyoming*

The Reno Ranch (Reno Creek) uranium deposit in Wyoming, although lesser known than the Nine Mile Lake site, underwent trials of acid ISL about the same time period. An alkaline 5-spot trial was also developed. However, unlike NML, the geology, hydrogeology and information on the ISL trials at Reno Ranch was published by Staub *et al.* (1986).

Reno Ranch is situated on the eastern flank of the Powder River Basin. The roll-front type uranium mineralization occurs in the Wasatch Formation, consisting of fluvial sandstones, siltstones, shales, claystones and coal seams. The ore zone contains high quantities of carbonate minerals, although quantitative data is unavailable. The site is at an elevation of 1,590 m.

Two wellfield patterns were developed and tested, the first being a conventional 5-spot pattern and the second being a 6-spot pattern with 2 injection and 4 extraction bores. Pattern 1 was leached with acid while Pattern 2 with alkaline reagents, details are in Table 5.

Table 5 - Research and Development Details for Reno Ranch

Pattern & Type		Lixiviant Chemistry	Period of Testing	PV
1	5-spot,	5 g/L H_2SO_4 (pH 1.8), H_2O_2,	Mining : Feb. 1979 to Nov. 1979	?
	12 m radius	flow ~2.5 L/s	Restoration : Nov. 1979 to Oct. 1981	?
2	6-spot[9],	Na_2CO_3 / $NaHCO_3$, H_2O_2,	Mining : Sep. 1980 to Dec. 1980	?
	15 m radius	flow ~1.6 L/s	Restoration : Dec. 1980 to April 1981	6.5

Notes : [9] - included 2 central injection and 4 extraction bores.

Although this paper is primarily concerned with the use of acid in ISL mining, it is of great value in comparing the acid and alkaline trial at Reno Ranch. The groundwater quality from each trial is compiled from Staub *et al.* (1986). The results from Pattern 1 are in Table 6, although space in this paper does not allow full data from Pattern 2 (see Staub *et al.*, 1986).

After mining was initiated in Pattern 1, problems with gypsum precipitation and "fungus growth" reducing the efficiency of well field circulation. No evidence was provided to substantiate the conclusion for "fungus growth". The uranium recovery rates were low and the carbonate minerals in the host sandstone consumed high quantities of acid. Leaching was terminated prematurely and restoration began immediately, consisting of water treatment by ion exchange, groundwater sweeping, and treatment with potassium carbonate to raise the pH and facilitate further removal of calcium, heavy metals and radionuclides. The restoration sequence, although aggressive compared to other efforts at ISL mine sites, encountered many difficulties.

The ongoing restoration efforts of Pattern 1 failed to reduce free acidity, SO_4 and Ra levels. The RMEC suggested the use of a high salinity solution to displace the hydrogen ions from clay lattice structures, enabling these to be removed during the restoration process. The regulatory agencies refused this technique due to uncertainties and possible adverse effects on the aquifer.

Very little post-restoration water quality improvement has occurred at pattern 1. During the first quarter of 1983, groundwater monitoring indicated that : 1) pH levels in the aquifers have not changed significantly; 2) Ca and SO_4 concentrations have not changed significantly (270 and 1,500 mg/L, respectively); 3) U levels have decreased marginally to less than 1.0 mg/L; & 4) TDS (~ 2,650 mg/L) remains almost twice that before mining.

Pattern 2, leached with alkaline reagents, proved less problematic from an operational and restoration perspective, however, post-restoration monitoring indicated a significant inrcease in

U levels to around 3.7 mg/L. This pattern of increasing uranium after restoration has been noted at many former ISL sites, although the mechanism remained unclear without more research.

Table 6 - Average Baseline, Injection, Extraction and Restoration Groundwater Quality, Ore Zone, Pattern 1 (acid), Reno Ranch (mg/L, except for pH, and EC in mmhos/cm)

	TDS	EC	pH	HCO_3	CO_3[10]	Alkalinity[10]	SO_4		
Baseline	970-1,566	1,220-2,000	6.4-11.2	ND-190	ND-48	ND-225	486-1,006		
	Cl	F	NH_4	NO_3	Ca	Mg	Na	K	Fe
Baseline	6 - 62	ND-0.57	ND-0.74	ND-7	72-182	9-51	145-323	7-25	0-3
	As	B	Mn	Se	SiO_2	U	V		
Baseline	ND-0.03	ND-2.6	ND-0.22	ND-0.05	ND-8.7	0.007-0.27	0-8		
	TDS	pH	SO_4	Ca	Fe	U	V		
Restoration[11]		4.8	1,385	230	29.1	1.1	0.2		
Post-Rest.[12]	1.267	9.3	764	102		0.059			
Post-Rest.[13]	2,551	5.3	1,551	263		0.64			

Notes : [10] - as CO_3; Alkalinity as $CaCO_3$; [11] - groundwater quality at the cessation of restoration efforts, February 1981; [12] - Post-Restoration groundwater quality, March 1983; [13] - Post-Restoration groundwater quality of extraction bores, March 1983. ND - Not detectable.

There were no reported excursions at the Reno Ranch site, although it was questionable whether the control limits were sensitive enough to detect such an event, especially for a vertical excursion. As with Nine Mile Lake, the Reno Ranch site is yet to be commercialised, and new interest in the developing the deposit has been recently abandoned.

2.3 *Acid ISL in the USA - Summary*

The experience with acid In Situ Leach uranium mining at Nine Mile Lake and Reno Ranch has shown that it can be an alternative, albeit non-selective, to alkaline process. However, the choice presents two major potential problems : 1) precipitation of gypsum on well screens and within the aquifer during mining, plugging wells and reducing the formation permeability (critical for economic operation); and 2) gradual dissolution of the precipitated gypsum following restoration, leading to increased salinity and sulphate levels in groundwater. The further effects of the release of heavy metals and radionuclides, especially Ra, that were co-precipitated with the gypsum have not been assessed or quantified. A critical issue is that acid leaching was not found to be more cost effective than alkaline, when taking restoration into consideration. No commercial acid ISL uranium mine has been approved nor developed in the USA.

3 ACID ISL IN AUSTRALIA

3.1 *Brief History*

The history of the technique of ISL uranium mining in Australia coincides with the litmus paper of public concern regarding the environment, nuclear issues and indigenous land rights. There has been no commercial ISL uranium mine in Australia by 1999. Only three sites have had pilot scale testing - two with acid, at Beverley and Honeymoon, South Australia, and one with alkaline chemistry at Manyingee, Western Australia (see Mudd, 1998).

There has never been a commercial acid ISL copper mine, although several sites near Mt Isa, Queensland, have undergone trials (mostly in the late 1960's) and more recently at the Gunpowder (Mammoth) mine. A small experimental acid ISL copper project was trialled at the old Mutooroo mine, 100 km south of Honeymoon, during 1981-82. All projects proved difficult and sub-economic, and thus acid ISL copper mining is yet to be.

A different site of note was the western world's first proposed ISL gold mine at Eastville, Victoria, in the early 1980's. The regulators and community, however, were not convinced about the safety of cyanide leaching and expressed grave concerns about groundwater contamination problems in the rural farming area. The project was quickly abandoned by (then) CRA Ltd.

The Beverley and Honeymoon uranium deposits, situated in the Lake Frome Embayment east of the Gammon Ranges in northeastern South Australia, were both discovered in the early 1970's, at a time when the prospects for nuclear power and uranium mining seemed endless. The deposits were actively being developed towards commercial scale in the late 1970's.

The Beverley deposit was originally planned as an open cut operation, but with the rapid drop in uranium prices in the mid-1970's, the project was shelved by 1974. The Honeymoon deposit, however, was recognised to be uneconomic by conventional mining from the outset, and by the late 1970's, ISL was being investigated as a possible economic alternative.

The Joint Venture developers of the Honeymoon deposit first conducted alkaline push-pull tests in 1977 using ammonia-bicarbonate solutions, however the results were discouraging (Mudd, 1998). A second push-pull test using sulphuric acid was undertaken in 1979 with positive results, and the partners committed to commercial development (Mudd, 1998).

The environmental impact assessment (EIA) process was undertaken (MINAD, 1980, 1981) with federal government approval being obtained in late 1981 for pilot testing before commercial scale operations could proceed (Mudd, 1998). A semi-commercial scale pilot plant, with a capacity of about 115 t/yr U_3O_8, was built and operated briefly in 1982, but was plagued with severe operational problems due to jarosite precipitation and other issues (Mudd, 1998).

The joint venture partners developing the Beverley deposit, first investigated the use of ISL in about 1980, releasing their Draft Environmental Impact Statement (EIS) in 1982 (cf. SAUC, 1982). The EIA process was not completed, however, and final approvals were not given.

Both projects proposed not to restore affected groundwater following operations at each site.

In March 1983, the recently elected government of South Australia refused to issue mining leases for commercial operations at Beverley and Honeymoon, citing these reasons (Mudd, 1998) : 1) many of the economic, social, biological, genetic, safety and environmental problems associated with the nuclear industry were unresolved; 2) endorsement of the Government's position by a wide range of community organisations; 3) commitment to the Roxby Downs (Olympic Dam) project; and 4) community disquiet at the nature of the ISL process.

The later introduction of the "Three Mines Uranium Policy" by the federal government in 1984 saw no further development until the election of a new federal government in 1996 and the removal of the (infamous) policy (Mudd, 1998). With new owners, fresh plans for their development are now being actively pursued. The Honeymoon site was joined with all nearby deposits, including Gould's Dam 75 km northwest, to form the "Honeymoon Project".

The geology of the Lake Frome region is given in Curtis *et al.* (1990), Morris (1984) and Brunt (1978). The following discusion uses these references, except where noted.

3.2 *Beverley ISL Project*

The Beverley deposit was originally discovered by the OTP Group of companies in 1969, with further drilling in 1970 confirming economic uranium grade (Mudd, 1998). After nearly three decades and two unsuccessful attempts, the Beverley uranium deposit finally began development towards commercial operation in 1996 through new owner Heathgate Resources Pty Ltd (HR), a wholly-owned Australian subsidiary of US-based General Atomics Corporation.

The geology and hydrogeology of Beverley is given in HR (1998a) and SAUC (1982) . The deposit consists of three ore zones - North, Central and South, each with increasingly higher salinity, respectively. The total size is about 21,000 t U_3O_8 (HR, 1998a).

A series of new bores were constructed in 1996 and 1997, including two 5-spot patterns, and hydrogeological pump testing was completed. HR applied for operation of an acid Field Leach Trial (FLT) in late 1997 with no proposed restoration of the pilot patterns. Approvals were quickly forthcoming from the South Australian government. The trial began on January 2, 1998 - before public release of a revised Draft EIS for the project. The trial was to leach the 5-spot patterns in the Northern and Central ore zones each for about 6 months. Due to the unexpected success of the Northern pattern, the FLT apparently used this pattern until the end of 1998.

After the release of the revised EIS in mid-1998, further studies were required by the federal and state governments to address significant inadequacies in the EIS, such as the degree of isolation of the Beverley mineralised aquifer, long term impacts on groundwater quality, and especially the potential to contaminate surrounding groundwater systems. HR still proposed not to restore affected groundwater following current and future mining operations at Beverley. With completion of these extra studies, final government approval was received in April 1999.

Table 7 - Beverley Groundwater Quality (average) : North (N), Central (C) and South (S) Ore Zones, Northern Field Leach Trial data (Injection - I, Extraction - E; averages March to July 1998) and Retention Pond (P; July 1998) (units as noted; m - mg/L; b - µg/L; na - not available) (adapted from HR, 1998a & b, SAUC, 1982)

	pH	TDS	S	SO_4	Cl	F	Na	K	Ca	Mg	U	Ra^{226}	Rn^{222}
	units	g/L	g/L	g/L	g/L	m	g/L	m	m	m	m	Bq/L	Bq/L
N	7.3	3-6	na	1.6	2	0.85	1.2	42	380	198	0.076	22-967	500-2,000
C	7	6-10	na	2.1	na	na	na	na	610	na	1.91	1.2-3,100	5-32,140
S	6.8	11-13	na	2.6	na	na	na	na	850	na	0.70	13-111	20-585
I	1.93	11.5	1.6	4.79	2.0	7.67	1.43	59	610	337	2.9	8414	na
E	1.97	11.7	1.6	4.84	2.0	7.33	1.43	59	600	337	162	9881	na
P	2.10	62.1	9.8	29.5	6.1	5.50	15.1	105	460	369	272	1713	na

	Al	B	Ba	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Se	Si	SiO_2	V
	m	m	b	b	m	b	b	m	m	m	b	b	m	m	b
N	0.2	1.6	53	0.2	0.1	20	30	0.7	0.2	0.004	40	1	48	na	1
I	91	1.0	37	117	20	100	200	109	0.7	8.47	160	410	138	294	1,100
E	91	1.1	39	116	20	580	200	105	0.8	8.33	790	410	133	283	1,130
P	39	3.4	76	49	6.6	260	180	39	0.9	2.48	70	310	99	211	780

Note - This is a compilation only, many parameters display a buildup over time. Complete trial data unavailable. No measuered Rn^{222} analyses available from the Field Leach Trial.

It is worth pointing out some significant outcomes of the approvals process for Beverley : 1) it is the western world's first commercial acid ISL uranium mine; 2) it proposes to re-inject all liquid wastes back into the mineralised aquifer rather than deep re-injection (»1 km; as per some US-sites) or evaporation (as per most US-sites); 3) the extent of the palaeochannel system is underexplored beyond the surrounds of the three ore zones; and 4) it is the first mining project in modern Australian history not required to restore the majority of it's environmental impacts after cessation of operations (that is, groundwater contamination).

HR (1998a & b) argue that following mining, the levels of radionuclides, heavy metals and pH will return to pre-mining conditions given several years; no mechanism is provided. This deserves critical assessment. The ore contains low sulphide (0.13%), organic carbon (0.05%), carbonate (0.06%), Fe, Mn and clay content (HR, 1998a). Buma (1981) argued that natural geochemical processes within aquifers can restore ISL-contaminated groundwater, thereby saving valuable chemical, energy and financial resources. The processes include precipitation of reduced compounds; scavenging of of heavy metals by pyrite, organic matter, calcite and ferric oxyhydroxides; adsorption by quartz, feldspars and clays. The key was for active reductants to be present. The conditions at Beverley, therefore, fail to provide any geochemical mechanism for natural restoration following acid ISL mining. The current trial, now two years old, if the data were to be released publicly, might be able to shed important light on such behaviour.

Of further significance is that Morris (1984) stated clearly that "reliance on this process (natural restoration) has never been tested". The time and rates at which natural processes could attenuate such levels of pollution are yet to be established. The extreme levels of groundwater contamination wrought at acid ISL uranium mines across the Former Soviet Union suggests natural restoration appears to be spurious at worst, ineffective at best (Mudd, 2000).

The potential for excursions due to abandoned exploration bores (when an open cut was intended) still remains, as well as excursions due to well casing failures (Marlowe, 1984). Curiously, final approvals for Beverley included provisions that liquid waste reinjection only occurr in the Northern zone - the zone of least exploration drilling and, importantly, the region of the best quality groundwater. This zone has similar water quality to pastoral use in the region (excluding radionuclide content), although gold mines in Western Australia often operate with much more saline groundwater (TDS up to 250 g/L).

The high Ca and SO_4 levels of the Beverley ore zones, especially the Central and Southern ore zones, create the potential for gypsum precipitation. A geochemical saturation analysis of the data in Table 7 can demonstrate this. This creates potential problems, similar to Nine Mile Lake and Reno Ranch, both operationally and for post-mining geochemical conditions. By August 1999, HR had apparently begun leaching of the Central trial pattern, although the full results from the Northern trial are yet to be publicly released, nor are they likely to be. This is in contrast to the USA regulatory process, where the results and restoration of a pilot scale facility form the permit basis of a commercial mine (Mudd, 1998). The construction of the commercial operation at Beverley is proceeding rapidly during 1999, presumably to avoid potential changes in government policy to reflect community opposition to uranium mining in Australia.

3.3 *Honeymoon ISL Project*

The Honeymoon deposit was Australia's first attempt at developing an ISL uranium mine, and had it succeeded in the early 1980's, would have become the first commercial ISL mine.

The deposit is located within the Yarramba palaeochannel, which consists of three distinct aquifer sand layers, separated by thin, discontinuous clay layers. The upper aquifer is used by pastoralists in the region, while the lower sand contains the uranium deposit.

The deposit has several unique features related to the use of ISL, including pyrite content at 5-15%, compared to less than 2% in USA deposits; higher salinity; low organic content (0.3%); high background radon activities (Rn^{222} at 6,000 Bq/L); and direct hydraulic connections between the three aquifers in the palaeochannel due to gaps in the clay confining layers. The leaky nature is confirmed by pressures rising to the same level. The high Rn, in disequilibrium with Ra, is anomalous but may be related to basement features.

Table 8 - Honeymoon Groundwater Quality : Upper (U), Middle (M) and Basal (B) (ore) Sands and predicted Lixiviant (L) composition (Fe in mg/L for B, g/L for L) (adapted from MINAD, 1980, 1981; Morris, 1984)

	pH	TDS	SO_4	HCO_3	Cl	F	Na	Ca	Mg	Fe	U_3O_8	Ra^{226}
	units	g/L	g/L	mg/L	g/L	g/L	g/L	g/L	mg/L	-	mg/L	Bq/L
U	-	10	1.4	-	5	1-2.5	-	0.5	280	-	-	0.13-1.5
M	-	12-15	1.6	-	6	2.8	-	0.6	320	-	-	2-100
B	6.8-7	16-20	1.8-2	135	8-10	0-2	3.8-5	0.95	410	<0.5	0.1	90-445
L	1.8-2.5	16-36	6-20	-	7-10	-	-	1.05	450	1-5	150	740-3,400

By 1982, the pilot plant (using solvent extraction) and four 5-spot patterns drilled had been consutrcted, although the fourth pattern intersected silt lenses with little mineralisation, and a field leach trial staretd using sulphuric acid and ferric sulphate. The trial encountered significant operational failure, due principally due to jarosite precipitation. The details have never been published, although it is known that jarosite was difficult to control.

A new trial at Honeymoon was approved in March 1998, relying mainly on previous approvals, with work beginning in April 1998. The information from both the 1982 and new trials are presumably to be incorporated in the new EIS for the project, which SCR are due to release in late 1999. The new trial is evidently trialling oxygen, which should avoid jarosite formation, although ferric sulphate is apparently still being used.

The approvals for Beverley has set important precedents for ISL in Australia that have critical implications for the Honeymoon project : 1) the project proposes to re-inject all liquid wastes into the palaeochannel distant from the ore zone, but still into the lower aquifer which is known to be hydraulically connected to important aquifers used by pastoralists; 2) the potential for "natural restoration" is questionable, although this depends on the extent of pyrite remaining after mining; and 3) the Yarramba palaeochannel is the only groundwater resource in the region (the velocity is about 18 m/year). The potential for post-mining impacts on groundwater are quite significant, especially if restoration is again not required by government regulators.

4 DISCUSSION AND CONCLUSIONS

The use of acid ISL in the USA was considered problematic and has never been approved or used on a commercial scale, despite the lengthy research at Nine Mile Lake and Reno Ranch, Wyoming. If Beverley and Honeymoon succeed where they previously failed, Australia will be forging a new, more profitable method of ISL - acid leaching with no restoration of groundwater. This is more akin to practices in Eastern Europe and the former Soviet Union than the demonstrable experience in the USA (cf. Mudd, 1998 & 2000). This is not considered an acceptable approach for an arid region that is almost entirely dependent on groundwater.

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