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IN-SITU LEACH URANIUM MINING IN THE UNITED STATES OF AMERICA: PAST, PRESENT AND FUTURE

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Abstract

Commercial in-situ leach (ISL) uranium mining in the United States began in the mid-1970s. Both acid and alkaline leach systems were evaluated. The difficulty of restoring ground water following acid leaching, led to exclusinve adoption of alkaline leach systems. The low production cost achievable from carefully selected, effectively run projects, was primarily responsible for the adoption and increased use of the unconventional production technology. Today ISL production continues, while production from all conventional uranium mines has been suspended. This paper describes the history of ISL uranium mining in the U.S. While 85 percent of ISL production has come from south Texas, today projects are also operating in Wyoming and Nebraska. Now that most of the ISL amenable reserves in Texas have been mined, most new projects will be in Wyoming, Nebraska and New Mexico. This paper discusses why ISL production costs are relatively low and can therefore compete with low cost, high grade conventional mines. It describes the ore reserves and production capacity of all of the installed, planned and potential U.S. ISL projects. It discusses why ISL mining is expected to be the predominant uranium production technology in the U.S. over the next 10 or 15 years.

1. INTRODUCTION TO IN SITU LEACH URANIUM MINING IN THE USA

Since the start of commercial in-situ leach (ISL) uranium mine production in the USA in 1975, ISL uranium mining has grown from an obscure, experimental technology to the dominant U.S. producer. U.S. uranium production reached its maximum level in 1980 when 16,809 MTU were produced. Of this amount about 1,600 MTU or nearly 10 percent was produced by ISL mining. The 1980 production came from 22 conventional mills processing ore from 303 underground and 52 open pit mines, in addition to 11 ISL projects, 6 phosphate by-product and 4 other producers [1].

At present (October 1992) in the U.S. there are four ISL projects, one phosphate by-product and one mine water recovery plant operating. All conventional uranium mining activity ended earlier this year, with the permanent closure of two open pit mines. Freeport Uranium Recovery Company's phosphate by-product facilities operation produces at it's capacity of about 385 MTU per year. Rio Algom Mining Company's mine water recovery operation produces less than 77 MTU per year. It is estimated that about 795 MTU or over 40 percent of the total 1992 U.S production will come from ISL facilities. In 1993, because of the recent shutdown of non-ISL production centers, it is expected that ISL production will make up an even higher proportion of the total U.S. production.

Since 1975 ISL technology has produced 14,852 MTU or about 10.2 percent of the U.S. production. With the addition of 577 MTU, produced at Shirley Basin, Wyoming between 1963 to 1970, about 15,428 MTU or 4.6 percent of the total U.S. production between 1947 and 1991 was by ISL mining.

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The four operating ISL production centers are producing at only 35 percent of their combined capacity. It is evident that even lowcost ISL operations are not immune to the present low priced uranium market. Although current ISL production is small when compared to the peak 1980 production it is remarkable that ISL production has continued at all in today's market. ISL uranium mining production has survived because the technology is capable of producing at low cost (i.e. $26 to $52 per kgU) from carefully selected projects.

ISL production also continues because the project owners believe that these low cost production centers will be very competitive in the anticipated improving uranium market. Analysis of the U.S. uranium industry indicates that ISL mining will be the dominant production technology over the next 10 to 15 years. Identified reserves with a forward production cost of under $52 per kgU could support the planned development of an annual capacity of over 6,000 MTU.

ISL production will continue to increase in importance primarily because of the relative economic advantage of the lowcost technology. Production from ISL technology will also dominate the U.S. uranium industry because of the limited availability of uranium reserves suitable for lowcost conventional production. Conventional production capacity is also being negatively impacted by the ongoing decommissioning of conventional uranium mills and the increasingly restrictive U.S. regulatory environment.

Successful ISL uranium mining in the early 1990s represents a maturing technology, applied by experienced management and personnel in well defined geologic environments. The current growth in ISL production follows the experimental years of the 1970s and early 1980s, during which there were more unsuccessful than successful ISL projects. Today alkaline leaching systems are used to mine very specific types of orebodies. These are rollfront-type sandstone deposits with favorable geologic and hydrologic characteristics.

Commercial ISL production began in 1975 and had increased to an annual level of about 1,731 MTU by 1982. Following a slow contraction of ISL uranium production, which had decreased to about 538 MTU in 1987, production has stabilized at between 577 and 769 MTU per year over the last few years. Today a refined technology is being employed in the well established ISL uranium mining districts of Texas, as well as in new areas of Wyoming and Nebraska. In the past, projects produced from ore bodies at depths ranging from 75 to 230 meters. Now ISL mining at depths of 300 meters or more is planned in New Mexico.

The most successful operating projects involve selective mining of the better grade ore in favorable geologic environments. More favorable economics are being attained by developing larger projects, which benefit from economies of scale, and automated plants requiring smaller operating staffs. This new generation of projects has in many cases economically benefited by recycling plants and equipment from earlier projects. Some of the projects have extensive ore reserves delineated by former project owners. All of these factors contribute to making ISL uranium mining, with production costs in the $26 to $52 per kgU range, competitive with production from high grade conventional mines.

At a 1978 uranium supply conference, one of the speakers stated that ISL mining of uranium was still in the developmental stage [2]. He indicated that many problems remained to be solved, including questions regarding:

- underground fluid control
- well completion techniques
- selection of the leaching agent

- selection of the oxidizing agent
- non-selective oxidation and leaching
- co-precipitation of uranium after leaching

Although these uncertainties may not have been completely eliminated, experience gained during the 1980s has helped ISL project operators to substantially reduce the risk associated with these issues and/or problem areas. During the last 15 years there have been many changes and developments in all phases of the process. These changes involve property evaluation standards, geohydrology, wellfield development, leach chemistry, plant design and operation, and reclamation technology. Licensing and regulatory practice have also changed.

As a result, today the level of confidence in uranium ISL technology is much greater than it was in the late 1970s. During the early 1980s, not one ISL wellfield had been restored and there was some question whether restoration could be achieved by practical means. By the end of 1987 about 30 commercial and pilot uranium solution mine wellfields had been restored in Wyoming, Texas, Colorado and New Mexico.

In most cases today wellfield restoration is routine. This has helped to assure both federal and state regulators that ISL mining does not significantly impact the environment. As a result, in May 1989, a representative of the U.S. Nuclear Regulatory Commission (NRC) wrote that "Based upon the accumulation of operational data and information, it has become apparent that ISL operations pose no significant environmental impacts." [3]. As compared with the mid-1980s the requirements for permitting and licensing ISL operations have generally become more well defined and the average time required to permit projects has decreased. Today permitting and licensing of a new project takes from two, to more than four years, depending on the location and circumstances.

Probably the single greatest ongoing challenge is the application of ISL technology to economically mine deeper orebodies. Most of the earlier projects mined uranium at depths of 90 to 150 meters. Current ISL projects have extended into the 150 to 250 meter range. Some of the planned projects will operate at depths of 300 meters or more. The Mobil Crownpoint research and development project successfully produced uranium at a depth of 610 meters. While the Mobil pilot project was a technical success no information is available to indicate the level of economic success.

Additional challenges will involve the application of ISL technology in new areas, such as New Mexico, where geologic conditions differ from those of established producing districts. The continuing effort to streamline project design to minimize costs is an continuing challenge. However, with the exception of projects located in New Mexico, all of the installed and planned projects will generally operate within the range of previous ISL experience.

In the United States the record of ISL uranium mining speaks for itself. ISL mining has survived and there are plans for expanding use of the technology. Meanwhile conventional underground and open pit uranium mining has experienced severe cutbacks. While the principal advantages of ISL mining over conventional mining are financial, there are several other advantages. Given favorable conditions, the principal advantages include [4]:

- lower capital and operating costs, improved cash flow, and a generally greater return on investment;
- shorter lead time to production;
- less energy intensive;

- less equipment to maintain;
- very low labor intensity per unit of product;
- substantially reduced personal radiation exposure;
- less surface disturbance and pollution;
- less waste generation and fewer disposal problems;
- lower ore grades can be treated in some cases - recoverable reserves of uranium are therefore increased;
- potential for application to otherwise inaccessible deposits.

As noted above the most significant advantage relates to the favorable economics of ISL production. However, the flexibility of ISL operations is also very important [5]. For example, the short lead times to bring a project into production as compared with conventional projects is a real advantage. The ability to selectively mine and adjust the cutoff grade of deposits is a strategy that all of the current ISL operators are using. The potential for readily adjusting ISL production to match market requirements is a another strength of the technology. These factors have all helped to make ISL uranium producers more competitive in today's market.

1.1 Overview of the ISL Mining Process

In-situ leach (ISL) mining is defined as that mining method where the ore mineral is preferentially leached from the host rock in place, or in-situ, by the use of leach solutions, and the mineral value is recovered. Although this definition can include the use of explosives or hydraulic fracturing techniques to fragment an ore body in preparation for in-situ leaching, these techniques are not employed in current U.S. ISL uranium mining. Uranium dump or heap leaching would not be included.

In general, ISL extraction consists of injecting a suitable leach solution (lixiviant) into the ore zone below the water table; oxidizing, complexing, and mobilizing the uranium; recovering the pregnant solution through production wells; and finally pumping the uranium-bearing solution to the surface for further processing.

In the past various types of injection-recovery well configurations or patterns have been used. A five-spot pattern (a production well surrounded by four injection wells at the vertices of a square or rectangle) is the most commonly used configuration. Other less regular or geometric patterns such as line drives or staggered line drives are used to take advantage of ore body configuration, site-specific hydrology, geology, etc. Seven-spot patterns are also used. Injector to production well spacing normally ranges between 15 and 30 meters.

Proper well construction and completion methods are among the most important aspects of successfully bringing an ISL uranium wellfield into production. If a completed well does not function as was intended and another well must be drilled, extraction costs attributable to that well are doubled. An inoperative production well could mean lower overall uranium recoveries. Various types of well integrity tests are now required to assure that well casings perform according to design specifications.

More specifically, carefully constructed injection wells are used to inject an appropriate lixiviant, usually dilute concentrations of a carbonate-bicarbonate, and a suitable oxidizing agent, usually dissolved oxygen, into the ore zone. The lixiviants are maintained at a near neutral pH of 7.0 to 7.4. The leach solution and oxidizing agent migrate through the permeable sandstone and contact the uranium minerals. The oxidant oxidizes the uranium, changing it from an insoluble

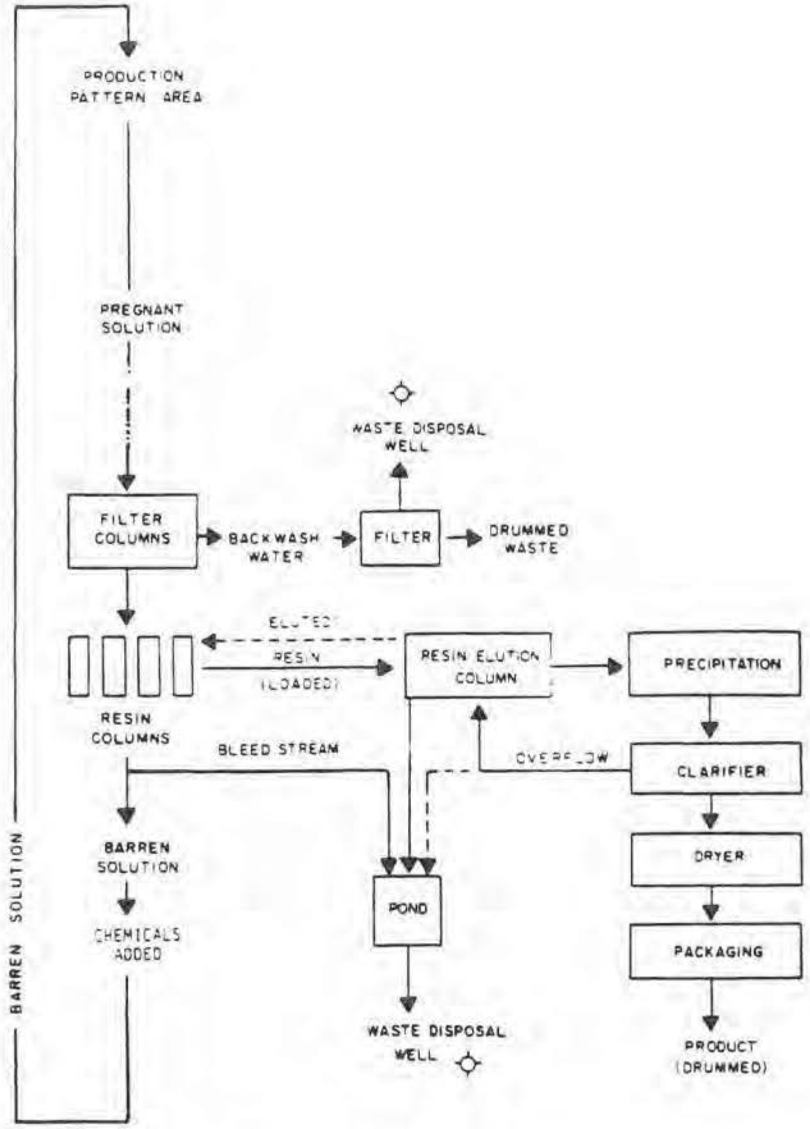

FIG. 1. Flow diagram for an in situ uranium leach mining process.

tetravalent to a soluble hexavalent state. When a carbonate leach solution is used the uranium is mobilized as a soluble uranium carbonate complex.

Once a uranium complex is formed and is mobilized in the leaching solution, it moves down the pressure gradient towards a production well. In the well, submersible pumps transfer the uranium-bearing solution to the surface for processing. Ion exchange technology is used to recover the uranium from the pregnant liquor. The residual uranium-barren solution from the ion exchange operation is recharged with leaching chemicals and recirculated into the wellfield through injection wells.

Ion exchange is a cyclic operation that consists of two steps, the loading or adsorption step and the elution step. During the loading step, the pregnant leach solution contacts the ion exchange resin and the uranium is selectively adsorbed. When a suitable uranium loading has been achieved, the resin is cycled to the elution step. During elution, the resin is contacted with a chemical solution that strips the uranium from the resin. The uranium enriched solution is called the eluate. The eluted resin is then cycled back to the loading operation.

The uranium is recovered from the eluate by precipitation. The precipitate is usually ammonium diuranate or uranyl peroxide, both of which are normally termed yellowcake. The yellowcake precipitate is separated from the residual solution by thickening and filtration. The filter cake may be partially dewatered to form a yellowcake slurry, or it may be dried and packaged for shipment. An example of a flow diagram for an ISL uranium mining process is given in Figure 1.

2. HISTORICAL PROJECT ACTIVITIES

In the U.S., experimentation with ISL mining started in the early 1960s led to more systematic development of the technology in the 1970s. In Wyoming the first ISL uranium mine was operated by Utah Construction and Mining Co., (later to become Utah International Inc., and then Pathfinder Mines Corp.) at its Shirley Basin site. Uranium mining started at Shirley Basin in 1959 using conventional underground methods. Following recovery of about 460 MTU, underground mining was discontinued in 1963 because of adverse ground conditions. From 1963 until 1970 patented ISL mining techniques were used to recover about 577 MTU. A sulfuric acid leaching system was used.

Utah Construction reportedly [6] used many of the same principles and techniques currently used, including ion exchange (IX) systems, pattern drilling, and the use of leach solutions with an oxidizer. During 1961-63, Utah Construction experimented with many techniques, including well development procedures and leach solutions. By 1963 the company had experimented with and tried 5 generations of well field designs and had drilled over 100 well field patterns in the attempt to maximize recoveries. From 1963 to 1969 ISL mining was the only method used by this company for uranium production. Open pit mining was started nearby at the site in 1969 and in 1970 the ISL operation was replaced by open pit mining. The open pit mines continued to produce uranium until their final closure early 1992.

In New Mexico ISL mining for uranium was first reported in early 1970, when Anaconda experimented with the North Windup Project at the Jackpile-Paguate mine area near Laguna. Pump tests from two well fields recovered uranium from a depth of 61 to 73 meters in the Jackpile Sandstone Member of the Morrison Formation.

Initially each well field consisted of one injection well surrounded by nine production wells on 60-meter centers. To improve hydrologic control well spacing was adjusted resulting in 2 injection wells and 29 production wells. A sulfuric acid lixiviant was used with uranium recovery by IX resin on the surface. Loaded resin was trucked to the Anaconda Bluewater mill some 80 kilometers west of the site where elution, precipitation, clarification, decantation, drying and packaging were done. Production was not reported and the project was discontinued [7].

Uranium was first produced in south Texas by conventional open pit mining. As exploration progressed, uranium mineralization was discovered at increasingly greater depths and the limits of open pit mining were exceeded. The unconsolidated, saturated condition of the host sands made underground mining impractical. This was one of the reasons that ISL mining was first considered for the recover of uranium in Texas. As experience with ISL mining increased it became apparent that for some deposits ISL mining has economic advantages that can not be equalled by other

Table I

U.S. IN SITU LEACH URANIUM CONCENTRATES PRODUCTION (MTU)

Year	Number of ISL Projects	U.S. Total	ISL	Percent ISL
1975	NA	8,923	106	1.2%
1976	NA	9,805	192	2.0%
1977	NA	11,491	600	5.2%
1978	NA	14,220	1,223	8.6%
1979	NA	14,412	1,346	9.3%
1980	NA	16,809	1,602	9.5%
1981	14	14,798	1,708	11.5%
1982	18	10,334	1,296	12.5%
1983	10	8,138	908	11.2%
1984	14	5,724	700	12.2%
1985	10	4,351	758	17.4%
1986	12	5,195	525	10.1%
1987	15	4,997	560	11.2%
1988	11	5,050	956	18.9%
1989	9	5,322	976	18.3%
1990	5	3,418	560	16.4%
1991	6	3,038	834	27.5%
Total (1975-1991)		146,025	14,850	10.2%
Shirley Basin (1963-1970)			577	
Total U.S.A. (1947-1991)		337,033	15,427	4.6%

Table 2

U.S. ISL URANIUM PRODUCTION THROUGH 1991 AND PROJECT STATUS BY STATE

State	Production (MTU)	Percent	Commercial Projects	Pilot Projects	Planned Projects
Texas	16,872	85.4%	20	30	4
Wyoming	3,483	17.6%	3	25	7
Nebraska	140	0.7%	1	1	1
New Mexico	0	0.0%	0	6	3
Total	19,745	100.0%	24	62	15

mining methods. The technology of in situ leaching of uranium deposits using chemicals was readily accepted in Texas, where many of the uranium industry personnel were familiar with designing and operating fluid handling systems used in the oil and gas industry.

Mays reports [8] that at least six pilot plants operated in the U.S. in the early 1970s. Most of these tests were small and involved only one or a few well patterns. The first large test involved the Dalco, Atlantic Richfield and U.S. Steel In Situ Uranium Project (Clay West), Texas in 1975. This group carried out extensive tests using 13 well patterns with a flow capacity of 25 liter/second. The Clay West commercial project involved scaling up the pilot to 150 liters/second of flow capacity and 96 MTU per year. Clay West operated at this capacity until 1978 when the expanded plant began producing at an annual rate of 385 MTU.

During the same period of time several other ISL projects were developed in South Texas. Several of these projects experimented with and tested various aspects of the technology including leaching systems, oxidants and ion exchange systems. The rising uranium price of the mid-1970s and the success of the Clay West project resulted in intense interest in ISL mining. Mays [9] reports that by 1984, 8 pilot plants and 21 commercial plants had been put into production in Texas, Wyoming and New Mexico.

A summary of ISL production from 1975 through 1991 is given in Tables 1 and 2. Over this period, production rose from a modest 106 MTU to a maximum of 1,708 MTU in 1981. ISL production then decreased to 525 MTU in 1986. Output again increased and has varied between 560 MTU and over 923 MTU per year since 1988. Total production for the period 1975 through 1991 was about 14,852 MTU, or 10.2 percent of total U.S. production for the period. Texas produced 85.4 percent of the total ISL production.

Certain observations are warranted. Mays reports that there have been more unsuccessful than successful ISL projects. While there were several pilot tests using acid leach systems there have been no commercial ISL operations in the U.S. using an acid leach system. There has been only one acid leach pilot test in south Texas: the Duderstadt project operated by Cities Service in 1969 to 1971.

Test results of both acid and alkaline leach systems showed that in geologic environments with low carbonate content (i.e. less than a few percent) acid systems frequently have advantages. These include high yield and efficient rapid recoveries. Acid systems have particular advantages where the ore mineral is contained or coated by other minerals, or is otherwise leach resistant. The problem with strong acid leach systems is that they solubilize large amonts of other chemical constituents. These must be removed in the surface recovery plant. Restoration of the orebody aquifer following mining is the major problem for acid leach systems. In the U.S., regulators routinely require that the orebody aquifer quality be restored to premining quality.

Table 3 shows the constituents in both acid and alkaline leach solutions tested at the Irigaray, Wyoming pilot plant [10].

Review of the table indicates that with the exception of Radium-226 and arsenic, the concentration of all constituents is higher in the acid than in the alkaline lixiviant. This difference illustrates the more aggressive behavior of the sulfuric acid leach solution.

Table 3

Partial Composition of Recirculated Acid and Alkaline Lixiviants

Constituent	Acid System Concentration mg/liter	Alkaline System Concentration mg/liter
Arsenic	<0.05	<0.05
Copper	1.00	0.04
Zinc	4.30	0.10
Lead	0.70	0.20
Iron	25.40	0.60
Nickel	0.60	0.06
Chromium	0.15	0.07
Strontium	3.70	1.50
Zirconium	3.30	0.90
Selenium		1.60
Manganese	1.20	
Molybdenum		0.90
Radium-226	390 pCi/l	1750 pCi/l
Vanadium	1.00	
Cobalt	0.20	

3. CURRENT ISL PROJECT ACTIVITY

Nuclear Assurance Corporation (NAC) maintains a database including all installed, planned and potential uranium production facilities in its Uranium Supply Analysis (USA) System. The USA System includes technical and financial information for all database projects. The following analysis of installed and planned ISL projects was done using the USA System. A summary of the 20 identified U.S. ISL projects is given in Table 4.

At present there are four operating ISL uranium projects, four shut-in projects and five planned or developing projects. Of the four producing projects; one is in South Texas, two are in Wyoming and one in Nebraska. Three of these projects were started (or restarted) since late 1987. The Crow Butte, Nebraska project is the newest project and came into production in April 1991. The capacity of the operating projects is 1,720 MTU.

With the exception of Crow Butte, each project uses satellite ion exchange equipment to recover uranium and then trucks the resin to a central plant for elution and final concentrate final production.

Both the Smith Ranch and Ruth/North Butte projects in Wyoming, are licensed for operation. Smith Ranch is scheduled to come into production in 1995, but the startup is dependent on market conditions. The startup date for Ruth/North Butte has not been announced. Startup dates for the Alta Mesa, Churchrock/Crown Point and Gas Hills projects range from 1994 to 1997, but will most probably be market dependent. There are no announced startup dates for development of the potential projects.

Table 4

U.S. IN SITU LEACH URANIUM MINING PROJECTS

Operating 1991/1992	State^a	Reserves (MTU)	Capacity (MTU)
Christensen/Irigaray - Malapai Resources	WY	14,800	770
Holiday/El Mequite - Malapai Resources	TX	2,540	300
Highland - Power Resources, Inc.	WY	6,500	770
Crow Butte - Ferret Exploration of Nebraska	NB	13,600	785
Total		37,440	2,225
Installed/Not Operating mid-1992			
Kingsville/Rosita - Uranium Resources, Inc.	TX	2,390	770
West Cole - Total Minerals Corp.	TX	850	77
Hobson/Gruy - Everest Minerals Corp.	TX	230	77
Total		3,470	924
Licensed(1)and/or with Announced Plans			
Smith Ranch(1) - Rio Algom Mining Corp.	WY	9,600	770
Ruth/North Butte(1) - Pathfinder Mines Corp.	WY	4,600	615
Alta Mesa - Total Minerals Corp.	TX	3,500	425
Chruchrock/Crown Point - Uranium Resources, Inc.	NM	8,500	1,150
Gas Hills - Power Resources/UG Mining, Inc.	WY	7,700	385
Total		33,900	3,345
Potential Projects with Producer Owners			
Ruby Ranch - Power Resources, Inc.	WY	1,770	115
Leuenberger - Power Resources, Inc.	WY	1,550	115
Powder River - Pathfinder Minerals Corp.	WY	5,800	NA
Reno Creek - Energy Fuels Nuclear	WY	1,900	150
Benham - Albuquerque Uranium Corp.	TX	390	100
Vasquez - Uranium Resources, Inc.	TX	1,400	NA
Churchrock Option - Uranium Resources, Inc.	NM	6,900	NA
Big Red - Ferret Exploration of Nebraska	NB	7,300	NA
Total		27,010	480
Grand Total		101,820	6,974

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a. TX = Texas; WY = Wyoming; NB = Nebraska and NM = New Mexico

3.1 ISL Plant Capacity and Labor Efficiency

The labor efficiency of ISL operations compares favorably with most conventional uranium production centers. In addition, labor efficiency in current ISL operations, is significantly higher than it was in 1980. Two factors are responsible for these changes. Today's ISL operations have larger capacity's and fewer employees. Both factors have helped reduce ISL production costs.

Payroll costs of U.S. ISL projects make up about 30 percent of operating costs and also account for about 15 to 20 percent of total production costs, including capital. Payroll costs are a major cost center in all types of uranium mining activities. However the labor efficiently of ISL mining is high as compared with most conventional uranium mining operations. For example Stover [11] reports that employee productivity for the Rosita and Highland ISL projects was 6.5 and 7.5 MTU/worker-year in 1989. In comparison, employee productivity in conventional uranium mines ranged from 1.13 MTU/worker-year at Elliot Lake, to 6.5 MTU/worker-year at Ranger. Only Key Lake with 13.0 MTU/worker-year had a significantly higher productivity.

Over the last 15 years the ISL uranium mining industry has achieved higher productivity per worker by using more efficient project design and automation, as well as through economy's of scale achieved in larger projects. The increase in the size of present day installed and planned projects is readily apparent compared to earlier projects. In 1980 there were 15 commercial ISL projects with an average annual capacity of 148 MTU. Individual annual project capacities ranged from 38 to 385 MTU. In 1992 the 12 installed and planned projects have an average annual capacity of 615 MTU. The annual capacity of these 12 projects ranges from 77 to 1,154 MTU.

During the same period the productivity of ISL project workers has also increased. In 1980 it was reported [12] that a typical ISL operation with a capacity of 193 MTU per year required 60 to 100 people. Today the Highland project produces 385 MTU per year with a staff of about 50. Smith Ranch plans to operate at up to 769 MTU per year with a staff of 65 to 75. The 1980 personnel level equates to a productivity of between 1.9 to 3.2 MTU per worker-year. Productivity at the Highland project is 7.7 MTU per worker-year, while Smith Ranch is expected to achieve a productivity of between 10.2 and 11.5 MTU per worker-year.

4. GEOLOGY AND HYDROLOGY

All of the installed and planned U.S. ISL uranium projects are located in Wyoming, Nebraska, Texas and New Mexico. Figure 2 shows the location of these areas. All of the installed and planned ISL projects will mine sandstone hosted uranium deposits. With the exception of New Mexico, the ore forming mineralization consists of uraninite and/or coffinite. A description of the regional geology of the ISL uranium mining districts follows.

4.1 Wyoming and Nebraska

The Wyoming and Nebraska uranium mineralization occurs in major rollfront-type deposits in sandstone of Tertiary age in intermontane basins of the Rocky Mountain foldbelt. The basins are filled with clastic sedimentary rocks and lie between (or as in Nebraska, adjacent) to mountain ranges, with granitic cores of Precambrian age. The basins are products of Laramide orogeny of late Cretaceous and Paleocene time. Tectonic forces were responsible for basin formation and sedimentary filling. The host basins for installed or planned ISL projects include the Wind River Basin (i.e. Gas Hills project), the Denver Basin (i.e. Crow Butte project) and the Powder River Basin for the other Wyoming projects.

The Powder River Basin is a structural basin open to the north, bounded on the south by the Laramie Range and Hartville uplift, on the east by the Black Hills, and on the west by the Big Horn Mountains and the Casper Arch. The Basin includes an area of nearly 31,000 square

FIG. 2. In situ leach uranium mining districts.

kilometers and has been a prolific uranium producer. In the past several open pit and a few underground mines produced uranium, while today only the Highland and Christensen-Irigaray ISL mines are in production.

4.2 Texas

The south Texas uranium province consists of rollfront-type deposits located in sandstones that occur in a mixed fluvial-shallow marine sedimentary sequence. The province occurs on a broad flat coastal plain located along the northwest margin of the Gulf of Mexico. The sedimentary basin is located on the margin of a continental plate adjacent to a spreading ocean basin. It is located to the east of a volcanic field occupying the Big Bend region and adjacent areas.

The coastal plain is underlain by more than 15,200 meters of interbedded Tertiary marine and non-marine sediments. The depositional history of these rocks reflects inter-relationships between migrating shorelines, relative and eustatic changes of sea level, and structural deformation.

In response to sea level changes during the Tertiary, the position of shorelines in South Texas have fluctuated, with deposition gradually extending out into the subsiding Gulf. This pattern has been even more well developed since the Oligocene.

The regional geology is characterized by a series of easterly dipping continental sediments that gradually increase in thickness toward the east. The sediments are composed of major sand systems that grade laterally into clay and siltstone. Post-depositional tilting toward the Gulf of Mexico has resulted in truncation of the sediments from Eocene through Oligocene in age.

4.3 New Mexico

In New Mexico the planned ISL uranium operations are located in the northwest corner of the state in the Grants Uranium Region on the south flank of the San Juan Basin. The San Juan Basin is a large basin, about 160 kilometers by 110 kilometers, that has been the site of recurrent differential vertical tectonic movement since late Paleozoic time. The basin contains up to 3,350 meters of sedimentary rocks ranging in age from Pennsylvanian to Late Cretaceous (some volcanic intrusive and extrusive rocks are also present).

Most of the uranium deposits occur within the main sandstone bodies of the Westwater Canyon and Brushy Basin Members of the Morrison Formation of Upper Jurassic age. They are generally localized near the thickest part and in the most permeable parts of the sandstones. These fluvial sandstones were formed as alluvial fan deposits and most commonly consist of medium to fine grained feldspathic sandstones. The Westwater Canyon reaches a maximum thickness of about 90 meters.

The Grants Uranium Region has been a prolific source for uranium production by conventional methods. In this area the Morrison Formation has been the source for 98 percent of the 130,800 MTU produced in the state. More than 99 percent of New Mexico's remaining reserves of about 282,300 MTU are sandstone-type uranium deposits that occur in the San Juan Basin. There are, however, characteristics of these remaining resources that may prevent extensive production using ISL technology. Two principal factors will be critical in determining to what degree uranium deposits in the San Juan Basin may be amenable to ISL mining: ore deposit type, and depth.

While some of the uranium ore deposits are of the roll-front type, a large portion of the deposits are uniquely classified as tabular, uraniferous humate deposits. The uranium minerals are intimately associated with humate (i.e. a carbonaceous precipitate from humic acid) which coats and is intergrown with the uranium minerals. In addition most of the uranium resources of the San Juan Basin occur at depths greater than 300 meters.

4.4 Geology of Current ISL Operations

All significant ISL uranium production in the U.S. has been from paleochannel sands of Tertiary age. Planned New Mexico ISL production will be from paleochannel sands of Upper Jurassic age. While all of the planned ISL production is from rollfront-type sandstone deposits, geologic characteristics are somewhat different in each district. See Tables 5 and 6.

With the start-up of six commercial ISL uranium operations during the mid-1970s, South Texas was the only significant ISL uranium producer. The principal ISL uranium production units in Texas are the Goliad sand, Oakville sandstone, Catahoula and the Jackson Group. All current and

Table 5

GEOLOGY OF IN-SITU LEACH URANIUM RESERVES IN THE USA

State	Recoverable Reserves (MTU)	Formation	Epoch	Age (Host rock) (10^6 years)
Wyoming	54,200	Fort Union and Wasatch, Wind River	Paleocene Eocene	38-63
Texas	11,200	Catahoula and Goliad	Eocene Miocene	5-54
Nebraska	20,900	Chadron	Oligocene	24-38
New Mexico	15,400	Morrison	Upper Jurassic	138-205

Table 6

CHARACTERISTICS OF U.S. IN SITU LEACH DEPOSITS

State	Depth Range, Meters	Characteristics	Special Problems
S. Texas	60-245	- High permeability	- Low levels of Mo in some ores
		- Thicker ore intercepts	- Faulting
		- Clean sands	- Saline water in some areas
Wyoming & Nebraska	60-300	- Lower permeability	- Varying levels of vanadium
		- Thin, high grade ore intercepts	- Insufficient groundwater levels in some cases
		- Good ground water quality	- Winterization required and remote locations
New Mexico	245-760	- Intermediate to high permeability	- Deep ore
		- Very thick host sand (30m plus)	- High Mo concentration in some areas
		- Multiple mineralized intervals in one sand	- High humate concentrations in some areas

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Source: Montgomery, A.H. 1989, Adopting Uranium In Situ Mining Technology for New Commercial Operations, p. 75-96, in Proceedings of a Technical Committee Meeting, IAEA Vienna, November 3-6, 1987, TECDOC-492.

planned ISL production will be from the Goliad and Catahoula Formations. They are characterized by clean, very well sorted sands with high permeability. Rollfronts are characterized by thick ore intercepts. South Texas has been the source of about 85 percent of the uranium produced by ISL mining. Geologic favorability has been a major factor contributing to this. However, identified south Texas reserves of 11,231 MTU are limited and producers have gradually sought new districts in Wyoming, Nebraska and New Mexico where large ISL amenable uranium reserves are known to occur.

With the exception of one planned project in the Gas Hills District, all installed and planned Wyoming ISL projects are located in the Powder River Basin. Here the principal uranium bearing units are the Wasatch and Fort Union Formations, respectively of Eocene and Paleocene age. Results of ISL test work indicate that, while some areas of the Power River Basin may not be amenable for ISL operations, much of the Basin has favorable geologic properties.

The Gas Hills uranium deposits are rollfront-type and are hosted by fluvial sandstones of the Eocene Age Wind River Formation. Information regarding the ISL amenability of these deposits is very limited as the one ISL project in the Gas Hills District is in the early planning stage.

In general, the Wyoming uranium deposits exhibit lower permeability than do South Texas deposits. This characteristic may restrict economic ISL production of some Wyoming uranium deposits. Most of the identified uranium resources occur at depths that should be amenable for ISL operations. As compared with Texas deposits, the ore is characteristically thick and high grade. Rollfronts frequently occur in more than one sand unit, distributed one above the other, named "stacked" ore. The rollfronts may be narrow and rapidly change direction.

The opportunity for successful ISL uranium mining in Wyoming is best illustrated by the operation of the Highland project. The project has produced over 1,540 MTU since its start-up in January 1988. Wyoming has identified ISL amenable reserves of 54,231 MTU, or 53 percent of the U.S. total.

Substantial reserves of ISL minable uranium have been identified near Crawford, in northwestern Nebraska. In the combined Crow Butte and Big Red projects, up to 20,923 MTU reserves are reported to occur in the Tertiary Basal Chadron member of the White River Group. This is 21 percent of the total U.S. ISL amenable reserves.

In the Crow Butte project area, 13,615 MTU are reported. The ore averages 0.9 to 4.6 meters in thickness and occurs at a depth between 185 and 256 meters. Permeability is high and the principal geologic and hydrologic factors that effect ISL operations are reported to be favorable [13]. Results of two pilot tests and over 18 months of Crow Butte production demonstrate the ISL amenability of these deposits.

Holen and Hatchell have evaluated the ISL potential of New Mexico's uranium deposits and report the following conclusions:

> "The Morrison Formation, and to a lesser extent, the Dakota Sandstone, account for the bulk of the reserves amenable to exploitation by ISL. The Todilto Limestone, which has accounted for about two percent of New Mexico's uranium production, is probably unsuitable for ISL production.

> Two general types of deposits occur in the Morrison Formation: primary and redistributed. Uranium in primary deposits is coextensive with an amorphous high-carbon organic material commonly called humate. Although specific leach effectiveness data are lacking, the association with humate results in a reduction in host rock permeability and in uranium mobilization that would be expected to have an adverse effect on recovery. In contrast, the ratio of humate to uranium in redistributed deposits is highly variable and in some deposits humate is virtually absent. In many respects redistributed deposits are similar to the roll-type deposits that have been exploited successfully by ISL in Texas and Wyoming.
>
> About 83 percent of the remaining reserves in New Mexico are at depths exceeding 1,000 feet (305 meters) and extend to depths over 4,000 feet (1,220 meters), but most of the more amenable redistributed deposits are at depths of 2,000 feet (610 meters) or less. Primary ore is the dominant ore type in most areas except Church Rock where redistributed ore is dominant. Subequal mixtures occur in deposits at Crownpoint. There has been no commercial-scale ISL production in New Mexico and recovery factors at several pilot operations are largely unknown. Mobil's South Trend Development Area project at Crownpoint has been the most extensively tested and is reportedly considered to be successful from the standpoint of recovery as well as groundwater restoration. The Crownpoint deposits are at a depth of 2,000 feet (610 meters) compared to depths of less than 800 feet (244 meters) for Texas and Wyoming deposits." [14]

Uranium Resources, Inc. plans to bring New Mexico's first commercial ISL uranium mine into production near Churchrock and Crownpoint. The area hosts large reserves of relatively shallow ore where ISL pilot tests have been completed. Reserves associated with the planned Churchrock/Crownpoint and potential Churchrock Option projects are 15,385 MTU, or 15 percent of the total identified U.S. reserves. Reserves at the initial Churchrock site are at a depth of 245 meters. Additional reserves are at a depth of 300 meters or more.

4.5 Factors of Geologic and Hydrologic Favorability

The two most important factors in determining the economic feasibility of any ISL project are the flow rate per well and the concentration of uranium in fluid produced from the well. Given an optimal design of the ISL mine system, the geology then becomes the fundamental control of what flow rates and uranium head grades are achievable.

The success of the current U.S. ISL uranium industry depends on the ability of the project operators to define favorable geologic environments that consistently provide physical and chemical conditions amenable to economic ISL recovery using alkaline leaching systems. The industry currently mines only rollfront-type sandstone uranium deposits. These deposits are uniquely amenable to ISL exploitation since ISL mining relies on physical and chemical processes similar to those that originally deposited the uranium orebodies.

Geological requirements for ISL mining are:

- Orebody located below water table
- Uranium mineral amenable to oxidative dissolution with proposed leaching system
- Permeability that will permit required flow, with a minimum in the .15 to .37 meters per day range
- High correlation of permeability to uranium ore to allow intimate contact of leachant to ore
- Overlying and underlying continuous permeability barriers for fluid confinement
- Groundwater with chloride content less than 2.5 grams/liter

These elements define the minimum requirements for ISL operation. The more successful ISL operations exploit orebodies that have the most favorable ISL amenable characteristics. Several characteristics that improve the amenability for ISL mining are:

- Rollfront-type deposit, continuous and wide (width not less than 30 meters)
- High average grade with minimum thickness of 1 meter or more and high Grade times Thickness (GT) product
- High permeability ranging up to 3.7 meters per day or more
- Artisan water table with minimum hydrostatic head of about 15 meters
- Depths from 60 to 180 meters
- No by-product metals

Geologic characteristics that may prevent economic development include:

- Excess presence of unfavorable gangue minerals (metal sulfides, calcite, organics, clay, etc.)
- Uranium mineralization encapsulation in clays or silts
- High molybdenum or vanadium concentration
- Thin, sinuous, and deep mineralization
- Poor vertical solution confinement
- Highly faulted or dipping formation

The presence of groundwater around the orebody is critically important to ISL mining of uranium. The aquifer water has four functions in the leaching/restoration process:

- Forms leach solution
- Moves the leach solution within the deposit
- Allows control of the leach solution, including control of possible solution excursion outside of the operating wellfields.
- Natural flow of the aquifer helps restore the chemical properties of the aquifer and host formation once leaching is terminated.

The development of methods to control wellfield fluids is one of the advances that has made current ISL operation successful. Today greater care is taken to assure that wells are carefully constructed to prevent vertical migration of solutions along the well bore. Regulators now require that the integrity of each well be tested prior to operation, thereby substantially reducing the risk of leakage. The risk of lateral excursions from the wellfield has also been reduced. This is done by pumping between one and three percent more fluid than is injected, thereby inducing a net flow of ground water into the wellfield.

Some of the early ISL operations were attempted where the groundwater level extended only a few meters over the orebody. Today all operators are mining orebodies with a head of 15 meters or more over the orebody. Selection of orebodies located well below the water table provides several benefits. Less control is required to assure that pumping does not excessively lower water levels. Higher flow rates can be achieved under conditions of high water pressure. Higher water pressures permit an increased concentration of dissolved oxygen, which is used as the oxidant in all current operations.

Formation permeability is the most significant control of wellfield flow rate. While ISL mining may be carried out with low permeability, successful operations require higher permeabilities that permit rapid movement of fluids through the aquifer. The minimum required permeability is in the .15 to .45 meters per day range. Several of the Texas ISL operations have been carried out in aquifers where permeabilities are .75 meters per day or greater.

Table 7

Hydrological Criteria for ISL Extraction

Criteria	Character/or Reported Values	Effect of ISL Extraction
Permeability of production zone (meters/day)	0.22-7.5	High production rate requires high permeability
Type of groundwater occurrence	Below water table: artisan; some water table	Feasibility
Position of ore zone below water level	Normally 15 to 75 meters or more	Oxidation/production rate increases with water pressure
Confining strata present above and below ore aquifer	Normally required	Feasibility; restrict solution to production zone
Horizontal continuity or ore aquifer	Poor to excellent	Feasibility/production rate
Geologic structure of strata	Gently dipping	Simple structure enhances feasibility
Baseline water quality	Water quality standards	Restoration guidelines less difficult for low quality; very poor quality will interfere with leaching
Well efficiency	Low to 90%	Flow/production rate improves with high efficiency
Status of drill hole plugging or status of other man-made conduits	Holes should be plugged. Other openings should not enter ore zones	Open holes or mine workings may result in excursions or make solution control difficult or impossible
Regional influence on groundwater operations use	Normally located in remote areas but conflicting water use may occur	Water use conflicts may restrict or prevent operation

Most of the present day operations are developed in orebodies with high flow rates. If projects with lower permeabilities are to be successful, it is necessary to have consistently high solution grades. High solution grade can make up for low flow rates.

Most Tertiary age sandstones that host rollfront-type uranium ores exhibit high permeability. These sandstones are characteristically moderately compacted and have relatively little cement between the sand grains. Permeability decreases as compaction occurs or as intergranular cements have been introduced. These features are common in older formations that have sustained longer periods of burial, often at increased depth. Well compacted and/or cemented formations may therefore not be amenable to ISL mining. See Table 7 for a summary of hydrogeologic criteria for ISL mining.

Orebody depth is another factor that has a significant impact on ISL amenability. In the past most ISL uranium mines have operated at depths of 60 to 150 meters. Although most production is still coming from moderate depths several current projects have some portion of their orebodies located as deep as 210 to 290 meters.

As operators turn to new projects, such as the extensive New Mexico reserves, ore depths will increase to between 300 and 760 meters. Exploration, development and construction costs increase rapidly with depth. Operating costs will be higher because of increased pumping costs. It is known however, that the efficiency of uranium dissolution rises with increasing pressure because of the increasing solubility of oxygen in water. It is also argued that it is possible to increase pressure differentials between injection and production when operating at greater water pressures. This is believed to improve fluid velocities and to allow greater distances between wells.

As early as 1980, Hunkin argued that the high cost of well completion at deeper levels is more than offset by greater efficiency of leaching and greater separation of injection and production wells [15]. The technical feasibility of ISL uranium mining at depths of 610 meters has been demonstrated by Mobil's pilot test on Section 9 at Crownpoint, New Mexico. There is however, insufficient information about the tests to indicate the economic viability of ISL mining at these depths [16]. The fact that Mobil has abandoned the project and returned the properties to the original owners suggests that a high uranium price will be necessary to justify this project.

4.6 Ore Reserves

The ore reserves of the 20 identified ISL projects are in most cases in the proven and probable (RAR) category and have been adjusted to account for a 75 percent recovery. Recoverable reserves for the currently operating and shut-in ISL projects are about 40,925 MTU. See Table 4. Licensed and planned projects add an additional 33,845 MTU. Potential projects add another 27,000 MTU. It should be noted that all of the potential projects are owned by companies still active in the uranium industry. Total ISL recoverable reserves are 101,770 MTU.

Ore reserves in currently operating or shut-in projects have the following characteristics:

- Average uranium Grade times Thickness Product (GT) ranges from 0.55% ft. (0.14% m) to greater than 2.0% ft. U_3O_8 (0.5% m U).
- Average thickness ranges from 0.9 to 4.5 m
- Average grade ranges from 0.04 to 0.26% U
- Individual project reserves vary from 230 to more than 14,800 MTU
- Average ore depths of less than 300 m

These parameters are also generally typical of the planned and potential projects. However, the average grades are in nearly all cases closer to .08% U than to .04% U. The average ore thickness is typically 3 to 4.5 m. With the exception of the New Mexico deposits the average ore body depths are less than 300 m.

The distribution of the ISL recoverable reserves by state is given in Table 8. The distribution of recoverable reserves is 53, 11, 15 and 21 percent respectively, for the states of Wyoming, Texas, New Mexico and Nebraska. Table 9 provides an insight into the relative significance of ISL amenable reserves in the U.S. For comparison the table gives the U.S. Energy Information Administration's 1990 estimate of all reserves with a forward production cost of $30/pound and

Table 8

PRODUCTION CAPACITY AND RECOVERABLE RESERVES BY STATE (MTU)

State	Capacity	Percent	Reserves	Percent
Wyoming	3,692	53%	54,229	53%
Texas	1,750	25%	11,230	11%
New Mexico	1,154	17%	15,384	15%
Nebraska	385	6%	20,922	21%
Total	6,980	100%	101,765	100%

Table 9

ISL RECOVERABLE RESERVES AND TOTAL RESERVES BY STATE (MTU)

State	Forward Cost Reserves[1]		ISL Recoverable[2] (Installed and Planned)	Percent
	$78/kgU ($30/Lb)	$130/kgU ($50/Lb)		
Wyoming	27,307	102,050	54,230	43
Texas	8,846	18,077	11,220	62
Nebraska	NA	NA	20,923	NA
New Mexico	32,692	135,000	15,385	11
Others	33,077	76,154	0	0
Total	101,922	255,203	101,768	29

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1. Source: Energy Information Administration/Uranium Industry Annual 1990, Washington, DC

2. This report

$50/pound U3O8 ($78 and $130/KgU) for each state[17]. ISL amenable reserves of the 20 identified projects described above account for 29 percent of the total reserves with a forward production cost of $50/pound U3O8 ($130/KgU).

4.7 Resource Estimation for ISL Mining

As indicated above ISL amenable uranium ore reserves must meet several well defined criteria. ISL recoverable ore reserves estimates must take into account the highly selective nature of the ISL process. ISL mining can only extract those resources that lie directly beneath or within a few tens of feet from each well pattern, and within or immediately above and below the screened well interval. Only those resources exposed to direct contact with the leaching fluid can be recovered.

Ore mineral grains occuring in zones of low permeability are not leached during normal operations. This includes uranium minerals in very fine grained rocks, such as clay and siltstones, or zones where clays or mineral cements surround the ore minerals. Ore reserve calculations should discount resources occuring in these environments.

Initial ore reserve calculations for ISL projects have been made using a variety of estimation techniques. However, in the U.S., detailed well pattern, or wellfield, estimates are usually calculated using some type of Grade x Thickness (GT) contour method.

Today most ISL projects are designed using a recovery factor of 65 to 75 percent. The recovery factor is defined as the amount of uranium recovered compared to the amount of uranium in the reserve estimate. Over the years, the recovery factor for ISL uranium mining has been subject to much discussion. The low recovery achieved in some of the early projects were partly to blame for this uncertainty.

Actual recoveries are difficult to document. However, various studies reported in the literature provide some insight. Everest Minerals Corporation reported an overall recovery of only 27 percent from their first project completed in 1982 (Hobson Project in Karnes County, Texas). They indicate that several geological, hydrological and geochemical factors were responsible for this low value [17]. In particular, the uranium was restricted to low permeability sands, channelization of leaching solutions occurred and an appreciable amount of uranium occurred in a mineral phase that is difficult to dissolve.

More recently, Everest and other operators have been able to achieve much higher average recoveries. In 1991, Power Resources, Inc., (PRI) operator of the Highland project, reported that they were recovering an average of 86 percent of the calculated reserves at the Highland Project [18]. In a report entitled "In Situ Leaching of South Texas Uranium Ores Part 3 - Post Leach Assessment of Recovery and Sweep Efficiency", Mobil indicated that overall recovery from a 12 m thick mineralized zone was 70 percent based on analysis of a core drilled after leaching was complete [19].

It should be noted that under conservative estimation practice only those reserves are included that fall within the boundaries defined by the 5-spot well patterns. No allowance is given for mineralization swept by leaching fluids but located outside of limits defined by straight lines connecting the injection wells. Other estimation methodologies assign some reserves to this area.

Based on a review of current and past operations, it is concluded that a properly designed wellfield will recover a minimum of 65 to 75 percent of estimated reserves. This assumes that the reserve estimate is made using appropriate considerations for ISL amenability of the ore. Recovery may be higher if a conservative approach is used in estimating reserves. This would include deducting all reserves in zones of low permeability and restricting the ore inventory to the area within the boundaries of the well patterns.

5. FUTURE OUTLOOK FOR THE U.S. ISL URANIUM INDUSTRY

There are twelve licensed and planned ISL uranium projects in the U.S. See Table 4. The estimated forward cost of production for these projects ranges from about $26 to $52 per KgU. With a total planned annual capacity of 6,346 MTU and recoverable reserves of about 74,615 MTU, ISL mining should be the dominant U.S. uranium production technology during the next 10 to 15 years. This capacity could be increased by 20 to 30 percent through the development of 8 additional potential projects with identified uranium reserves of about 26,923 MTU. The total reserves associated with NAC's identified ISL projects include 101,769 MTU.

NAC's reserve estimate may be compared with the total estimated ISL amenable reserve base of the U.S. Based on it's 1990 annual survey of all industry participants [20], the U.S. Energy Information Agency (EIA) reported an estimated 127,308 MTU producible by ISL technology at a Forward Cost of up to $50 per pound U_3O_8 ($130/KgU). This includes 32,308 MTU producible at a forward cost of up to $30 per pound U_3O_8 ($78/KgU). NAC's inventory of ISL projects equals 80 percent of the U.S. ISL reserves producible at a Forward Cost of up to $50 per pound ($130/KgU) and therefore includes most of the identified ISL reserves in this cost category.

While there are substantial uranium reserves amenable to ISL mining in the U.S., there is an apparent practical limit to ISL uranium mine development because of the finite limit of these reserves. As shown in Table 9, based on its industry wide survey the EIA reports an estimated 356,154 MTU of reserves recoverable at a Forward Cost of $50 per pound ($130/KgU) using all mining methods. ISL recoverable reserves make up about 36 percent of this total. While some additional portion of the national reserve base will be minable using ISL technology there is a practical limit because of the stringent geologic and hydrologic requirements for economic production.

The probable future dominance of ISL mining of the U.S. uranium production industry becomes even more clear when considered in perspective with the decreasing capacity of conventional projects. This year's permanent closure of the Shirley Basin and Rhode Ranch open pit mines and the start of decommissioning of the Shirley Basin and Panna Maria mills marks the end, at least for the time being, of the U.S. open pit uranium mining industry. The closures remove 992 MTU per year of U.S. uranium production capacity. At present there are no plans for developing new open pit mines in the U.S.

The future of uranium production from underground mining is somewhat more positive. However, with the exception of the relatively high grade breccia pipe hosted deposits of the Arizona Strip there is relatively little potential for development of underground mines amenable to lowcost production. The Green Mountain project may be one possible exception to this case. While NAC's database includes eight existing or planned projects with a cumulative annual capacity of 6,769 MTU, most of these projects will not be able to compete in a market with uranium selling for $52 per KgU or under.

The ongoing decommissioning of uranium mills motivated by the increasingly restrictive regulatory requirements of the U.S. Environmental Protection Agency (EPA), as implemented by the U.S. Nuclear Regulatory Commission (NRC), will further diminish the potential for reactivation of shut down and development of new conventional uranium mining projects in the U.S. In addition, the added cost of meeting new, lower radiation exposure limits for workers, particularly in mines with medium to low average grade, may make it uneconomic to develop new underground mines.

The future of U.S. ISL uranium production therefore depends not only on the economic advantages of the technology, but also on the relatively small amount of uranium resources amenable to lowcost conventional production.

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