Environmental Geology 11

Promises & Problems of a "New" Uranium Mining Method: In Situ Solution Mining

by Robert M. Kirkham

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ABSTRACT

Many new mining techniques are currently being researched and developed by industry and the Federal government. Some of these new mining methods offer considerable economic and environmental advantages over conventional mining methods. One of these new methods is in situ solution mining, a relatively old mining technique that only recently has been successfully applied to the mining of uranium deposits.

The technique involves 1) drilling a series of injection and recovery wells into a uranium ore body, 2) injection of a weak alkaline or acid leach solution and an oxidizer to dissolve and then recombine the uranium with certain desired ions, 3) withdrawal of the "pregnant" uranium-bearing solution, and 4) processing of the solution in a surface plant to recover uranium yellowcake. In situ solution mining and processing have many advantages over conventional uranium mining and milling methods. There is, however, a significant potential for ground-water contamination, but it can be minimized by successful restoration of the mined aquifer, limiting leachate excursions, and control of leakage from waste storage ponds.

Planners should be aware that new mining methods exist and to expect utilization of these methods. Some of these new resource-recovery techniques may be preferable over conventional methods, while others may only create additional problems.

INTRODUCTION

As technology advances and the economy changes, new mining methods are researched and developed by industry and the Federal government. Planners may encounter situations where industry wishes to utilize a new, unfamiliar mining technique to recover a mineral resource. Many of these methods offer considerable socio-economic and environmental advantages over conventional mining and milling techniques. Other of these methods, however, may result in significant impacts that concern planners.

Planners should be aware that new mining techniques are being and will continue to be developed in the future. They should also recognize that in certain cases these new methods may be preferable in many aspects over conventional methods. This paper describes only one of these methods, in situ solution mining, a relatively old technique that recently has been successfully used to extract uranium.

In situ solution mining is defined as the selective mining of a mineral resource in its natural geologic setting by leaching or dissolving the mineral from the surrounding host rock without removal of the host rock. Solution mining technology was first applied to uranium in the early 1960's by Utah Construction and Mining Company, now Utah International, Incorporated (Larson, 1978). Poor ground conditions and high mining costs at an underground mine in the Shirley Basin, Wyoming, convinced the company to consider alternate mining methods. In situ solution mining was successfully applied to the deposit from 1963 to 1969.

As of January, 1978, there were 23 locations in Wyoming, Texas, Colorado, and New Mexico where in situ solution mining of uranium was being conducted on either full- or pilot-scale levels (Larson, 1978). The only operation to date in Colorado is a pilot-scale test operated by Wyoming Mineral Corporation at the Grover site, about 36 mi (57.6 km) northeast of Greeley in Weld County. This test is now complete and the mined aquifer appears to be successfully restored.

Power Resources Corporation has submitted an application for a full-scale in situ solution mine capable of producing 500,000 lb/yr (227,000 kg/yr) of uranium yellowcake. This project is near Keota, about 34 mi (54.4 km) north of Fort Morgan in Weld County. Additional solution mine facilities are anticipated in this area and in other parts of the state such as the Colorado Plateau and Maybell areas, where suitable uranium deposits exist.

In situ solution mining of uranium offers significant advantages over conventional mining methods to industry, environmental groups, local residents, and decision makers in public agencies. Economic advantages include lower initial capital costs, improved cash flow, shorter lead time to production initiation, lower manpower requirements, and ability to mine lower grade, otherwise uneconomic ore bodies. Environmental advantages include minimal surface disturbance, less waste generation and less corresponding needs for waste and tailings disposal, reduced mine-personnel exposure to radiation, minimal air pollution, smaller radiologic releases, and recycling of process chemicals.

There is, however, a significant potential for ground-water contamination by the mining process, by leachate excursions, and by leakage from waste storage ponds. This potential can be minimized by comprehensive, pre-mining environmental and geological studies used for mine design, proper operation of the mine, and extensive post-mining aquifer restoration. Recent tests indicate post-mining restoration of ground water within the mined aquifer can be successfully accomplished on a pilot-scale. Restoration of a large mine site has not yet been attempted.

Not all uranium deposits are amenable to solution mining. To date, only sandstone-type deposits have been mined using this technique. Other types of deposits, such as vein deposits, have permeability, porosity, and transmissivity characteristics not suitable for present-day solution mining technology. The ore body also must be below the ground-water table to allow control of fluid movement.

ACKNOWLEDGMENTS

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The style and content of this paper was significantly improved by colleague review. Reviewers include A. L. Luck of Rocky Mountain Energy Company, J. W. Warner of the U.S. Geological Survey, and L. R. Ladwig, W. R. Junge, and W. P. Rogers, all with the Colorado Geological Survey.

MINING AND PROCESSING TECHNIQUES

An in situ uranium solution mine consists of 1) a system of injection and recovery wells, 2) pipelines to transport barren leach solution (lixiviant) to the injection wells and pregnant, uranium-bearing liquor (leachate) from the recovery wells, and 3) a process plant where uranium is extracted from the liquor and the leach solution is refortified and recycled. Injection and recovery wells are grouped into production cells and a number of production cells constitute a well field. Typically, a mine consists of several well fields. Figure 1 is a vertical cross section through a production cell

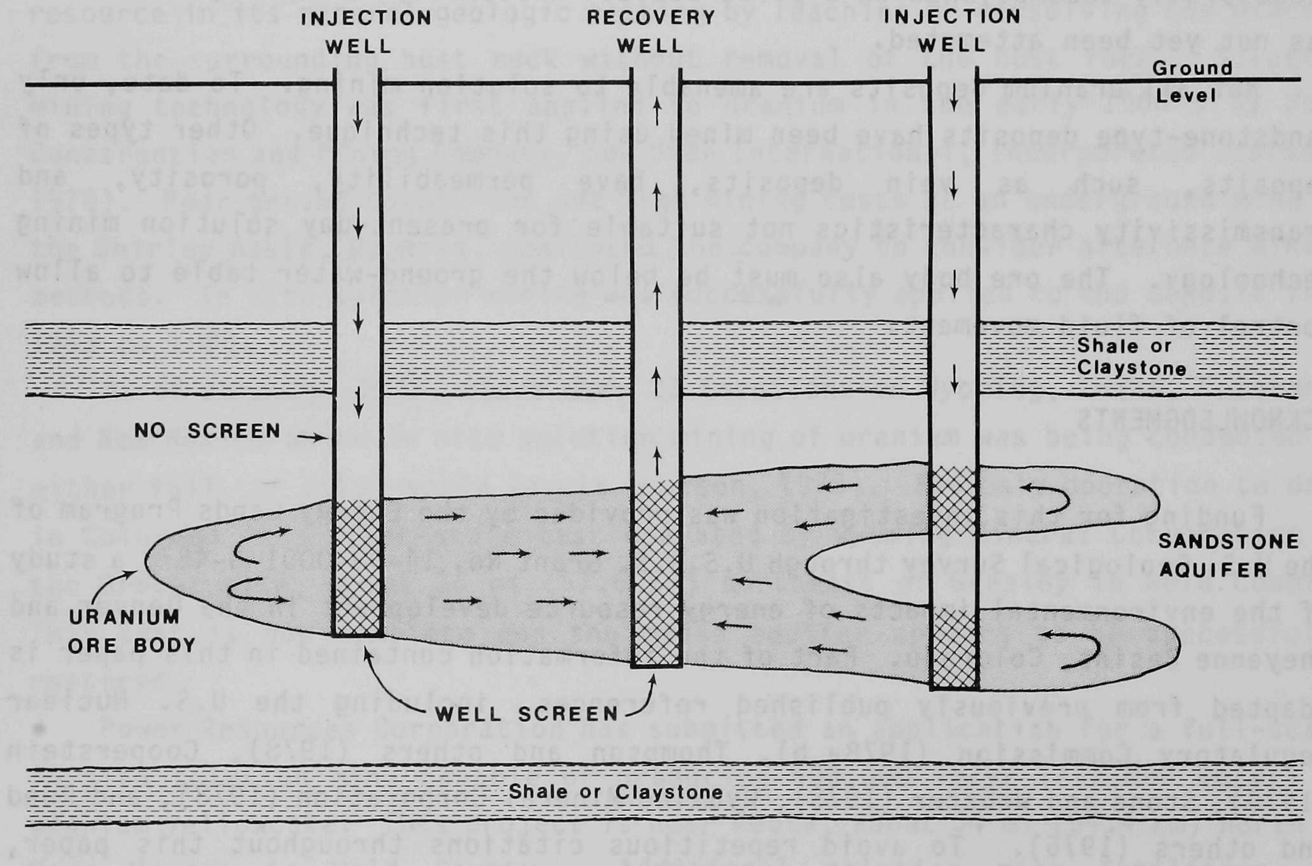


Figure 1. Schematic cross section through a production cell. (from Wyoming Mineral Corporation, 1977; courtesy of Wyoming Mineral Corporation)

illustrating leach-solution flow paths.

A commonly used well-field pattern is the five-spot pattern (Figure 2). It consists of four injection wells, one on each of the corners of a square or rectangle, and one recovery or production well in the center of the square or rectangle. Dimensions of the production cell and well field depend on ore distribution and hydrologic properties of the ore-bearing aquifer. Figure 3 illustrates other types of patterns that have received commercial use.

Special attention must be paid to well-completion techniques to avoid ground-water contamination and loss of leachate. Non-perforated PVC pipe is used from the surface to the top of the mineralized zone and perforated, screened, or slotted PVC pipe is used in the mineralized zone. The area between the non-perforated pipe and drill hole must be grouted to prevent mixing of water from overlying aquifers and mining fluids.

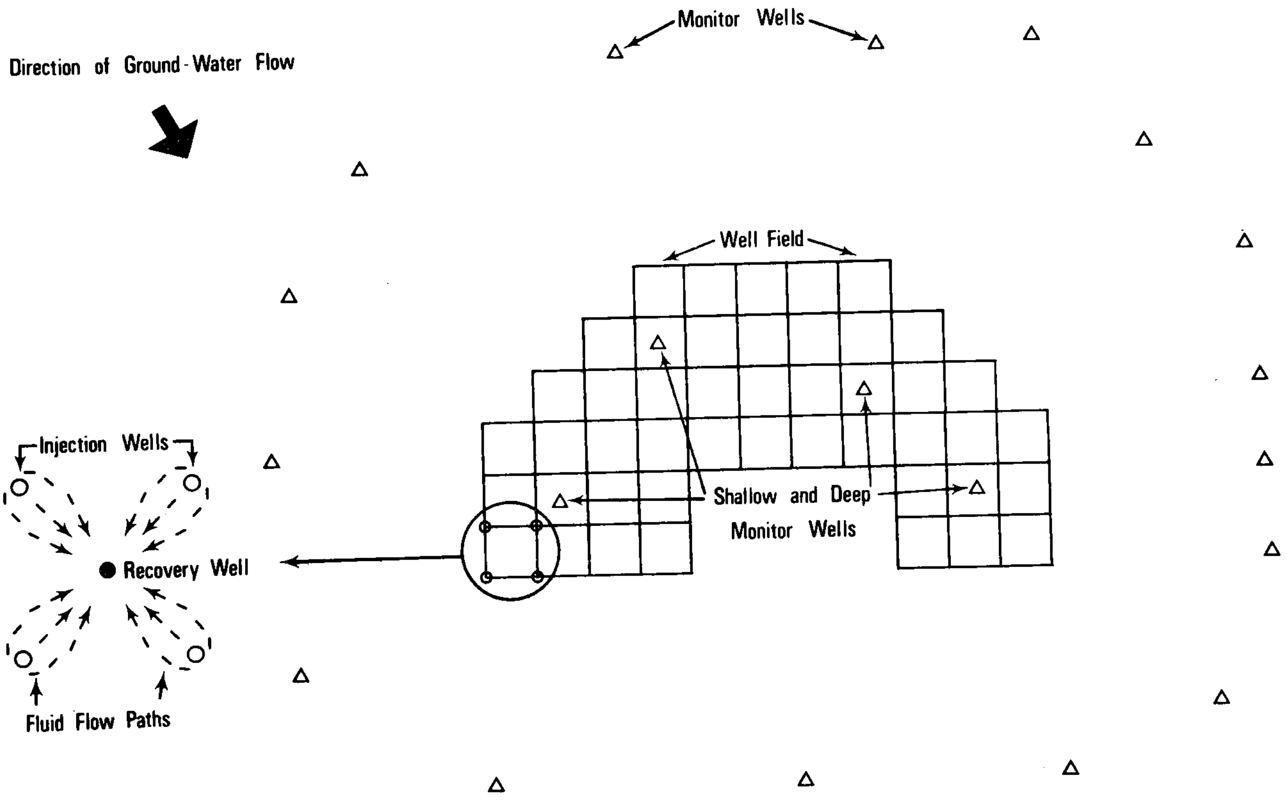
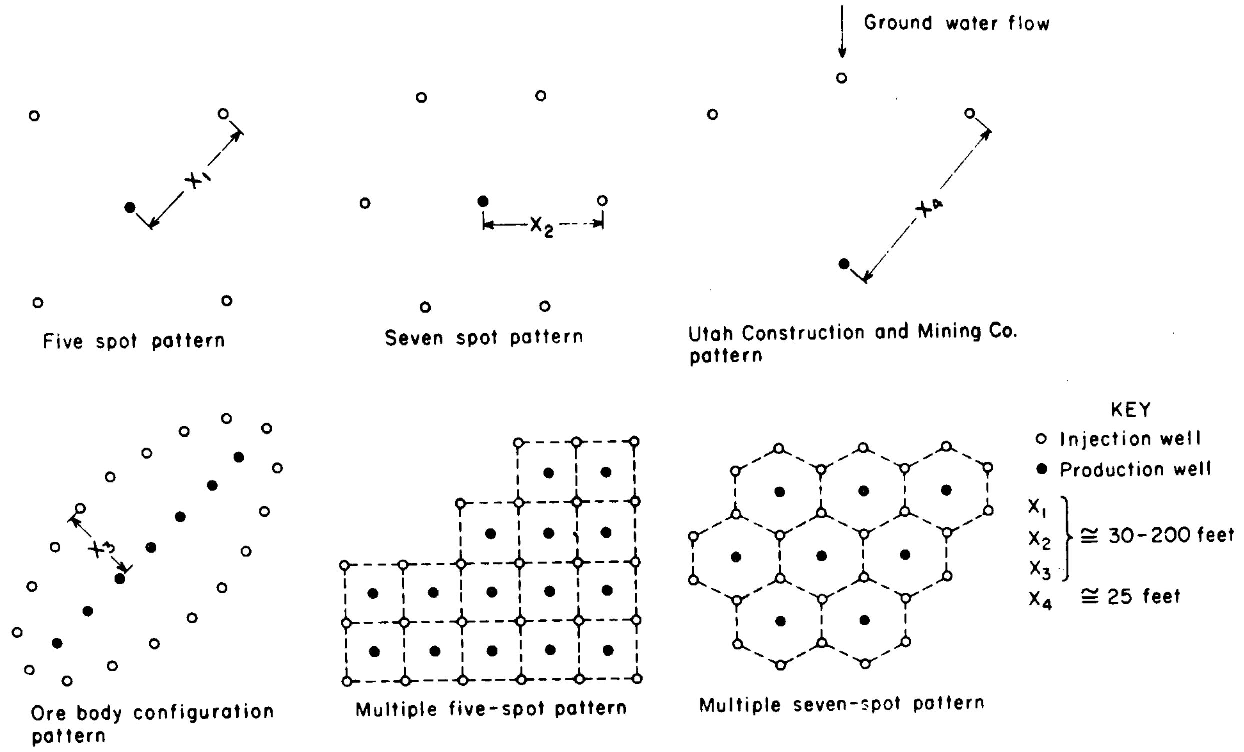


Figure 2. Typical plan view of a five-spot well-field pattern. (after Stone and Webster Engineering Corporation, 1978)



Five spot pattern

Seven spot pattern

Utah Construction and Mining Co. pattern

Ore body configuration pattern

Multiple five-spot pattern

Multiple seven-spot pattern

Figure 3. Plan views of common well-field patterns. (from Larson, 1978)

Choice of the proper lixiviant is based on factors such as ability to selectively dissolve uranium, recirculation suitability, environmental considerations, and maintenance of hydrologic properties. Both alkaline and acidic lixiviants are currently utilized by industry. Popular alkaline lixiviants include ammonia, sodium, and alkaline earth carbonate-bicarbonate complexes. The only commonly used acidic lixiviant is sulfuric acid. Hydrogen peroxide is often employed as the oxidizing agent.

Injection and circulation of the lixiviant and oxidizer through the ore-bearing aquifer first dissolves the uranium and then allows it to combine with desirable ions. The mobilized uranium complex thus formed is pumped from the subsurface by the recovery wells and piped to a surface processing plant. Figure 4 illustrates the steps involved in processing the uranium-bearing solution. In the first part of the process, the uranium complex is treated in an ion exchange operation consisting of two steps: 1) a loading or adsorption step and 2) an elution step.

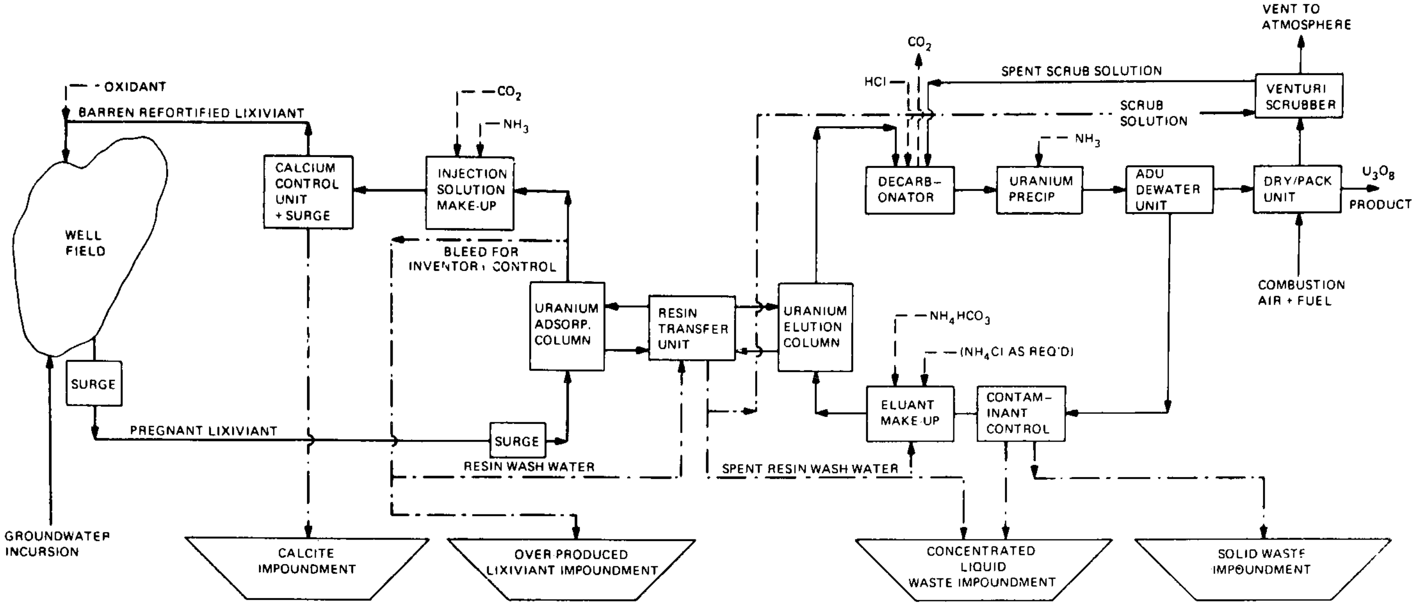


Figure 4. Schematic flow diagram of a typical in situ solution mine using an ammonia bicarbonate lixiviant. (after U.S. Nuclear Regulatory Commission, 1978a)

During the loading step, the complexed uranium ions are sorbed from the solution to the ion exchange resin, displacing chloride ions sorbed to the resin. The resulting uranium-barren solution is refortified with lixiviants and oxidants and is recycled to the well field for reinjection. In many operations the recovered solution is saturated with calcium carbonate and it is necessary to cycle the solution through a calcium control unit to prevent calcite precipitation. Such precipitation could plug well openings and pipelines and reduce hydraulic conductivities in the ore body.

Uranium-loaded resin is transferred to the elution circuit and an equal volume of eluted resin is returned to the loading circuit. During elution the resin is stripped of uranium by a chemical solution consisting of ammonia chloride, sodium chloride, ammonia bicarbonate, or other similar eluents. The resulting uranium complex may be treated with acid to form the uranyl ion. The solution is transferred to a precipitation unit where ammonia diuranate (ADU) is precipitated. The ADU is then dryed, converted to yellowcake, and packaged.

WASTES AND EFFLUENTS

In situ solution mining generates only a small amount of atmospheric emissions and solid wastes, but a considerable volume of liquid waste results from restoration activities and well-field overpumping during mining. Part, but not all of these wastes and effluents are radioactive. Non-radioactive wastes may contain toxic or hazardous chemicals, but some are harmless.

Atmospheric emissions, though minimal compared to conventional methods, are emitted from the recovery process plant, waste storage ponds, well field surge tanks, calcium control unit, and yellowcake drying and packaging unit. Table 1 lists the typical emissions from the recovery circuit of a 500,000 lb/yr (227,000 kg/yr) solution mine using an ammonia bicarbonate lixiviant.

Table 1. Typical atmospheric emissions from the recovery circuit of a 500,000 lb/yr (227,000 kg/yr) uranium solution mine using an ammonia bicarbonate lixiviant. (after U.S. Nuclear Regulatory Commission, 1978a)

	Emission Rate[a] (thousands of lb/yr)				Radioactive Releases[b] (Ci/yr)	
SOURCE	NH_3	CO_2	NH_4Cl	H_2O	U-238	Rn-222
Uranium Recovery Process Facility (excluding calcium control unit and waste storage ponds)	6-9	1500-3000	30-54	-	0.141	-
Calcium Control Unit (based on 1,000 ft^2 of exposed solution surface containing 0.75g NH_4, 1.5g total CO_3, and 0.75g Cl/L)	2-4	6-9	0.06-0.09	390-470	-	0.04
Calcite storage pond (based on complete evaporation of 2.04 gpm of supernate containing 0.75g NH_4, 1.5g total CO_3, and 0.75g NH_4	2.5-3.5	9-10	9.5-10.5	∽8000	-	1.36
Liquid waste storage ponds (based on 1 acre of exposed solution surface containing about 7.0g NH_4, 1.0g total CO_3, and 16g Cl/L)	9-11	7-8	27-31	∽9300	-	-
Well field Surge Tanks	-	-	-	-	-	76

a) based on data supplied by WMC and a net evaporation rate of 42 in/year

b) NRC estimates

Small amounts of fugitive dust and vehicular emissions from gasoline- and diesel-burning equipment, such as carbon monoxide, nitrogen and sulfur oxides, unburned hydrocarbons, and suspended particulates, are released during mine construction, operation, and restoration. Solution mines generate fugitive dust and vehicular emissions similar in volume to underground mines, but an order of magnitude less than open-pit mines.

Radioactive and non-radioactive solid waste is generated by four principal sources: 1) the calcium removal unit, 2) the contaminant control unit in the process plant, 3) precipitated waste in liquid waste storage ponds, and 4) water treatment methods used in post-mining aquifer restoration. The total volume of radioactive and non-radioactive solid waste from a solution mine is several orders of magnitude less than that produced by conventional mining. This is a major factor when the environmental and economic problems associated with tailings disposal are considered.

Calcite (calcium carbonate) precipitated from the calcium control unit is one of the major solid wastes from the solution mining process. Estimates suggest that 1 lb (0.454 kg) of calcite may be produced for every 1 to 3 lb (0.454 to 1.362 kg) of yellowcake recovered. A typical 500,000 lb/yr (227,000 kg/yr) mine could produce up to 500,000 lb (227,000 kg) of calcite waste every year containing up to 500 to 1500 pCi of radium-226 per gram of calcite and other hazardous elements.

The contaminant control unit in the elution and precipitation unit may generate solid waste containing sulfate and vanadium. Removal of sulfate and vanadium from the eluant is accomplished by vanadium adsorption on activated carbon and sulfate precipitation utilizing barium salts, resulting in vanadium-saturated activated carbon and barium sulfate. Precipitated solids from evaporative concentration of impounded waste solutions is another type of solid waste resulting from solution mining. This waste consists of ammonia and alkaline chlorides, sulfates, and carbonates which likely contain radioactive materials.

Additional solid waste will be generated during the restoration process by evaporation of withdrawn contaminated water during ground-water sweeping and by water purification efforts such as reverse osmosis. Water from the restoration process will contain about 10 to 20 g/l total dissolved solids and high concentrations of salts such as ammonia chloride, sodium chloride, and sodium sulfate. Over 100 pCi/l of radium and smaller quantities of uranium, calcium, magnesium, selenium, arsenic, and other trace elements may also occur in the brine.

Principal liquid wastes result from 1) ground-water restoration, 2) well field overpumping, 3) resin wash water in the contaminant control unit, 4) well cleaning, 5) building and equipment cleaning, 6) eluant bleed for contaminant control, 7) monitor well sampling, and 8) yellowcake slurry wash water. The total volume of liquid wastes is significant, but many conventional mines produce similar amounts of liquid waste and in certain situations mine dewatering may generate even greater amounts of liquid waste that must be properly disposed.

By far, the largest volume of waste water at a solution mine results from the aquifer restoration program. The U.S. Nuclear Regulatory Commission (1978a,b) estimates about 40 to 60 acre-ft (48,560 to 72,840 m^3) of concentrated brine will be produced for every 10 acres (40,470 m^2) mined. Obviously, these numbers depend on thickness of the ore body, mining methods, lixiviants, and restoration problems. The brine may contain ammonia, sodium, calcium, and magnesium carbonates, bicarbonates, and sulfates. Uranium and radium-226 concentrations likely will exceed, respectively, several parts per million and 50 to 150 pCi/l. Trace contaminants, such as molybdenum, arsenic, and selenium may also be present. Other types of liquid waste will contain similar ions and toxic elements, but these sources produce significant less volumes of waste water than does restoration.

WASTE DISPOSAL AND CONTROL

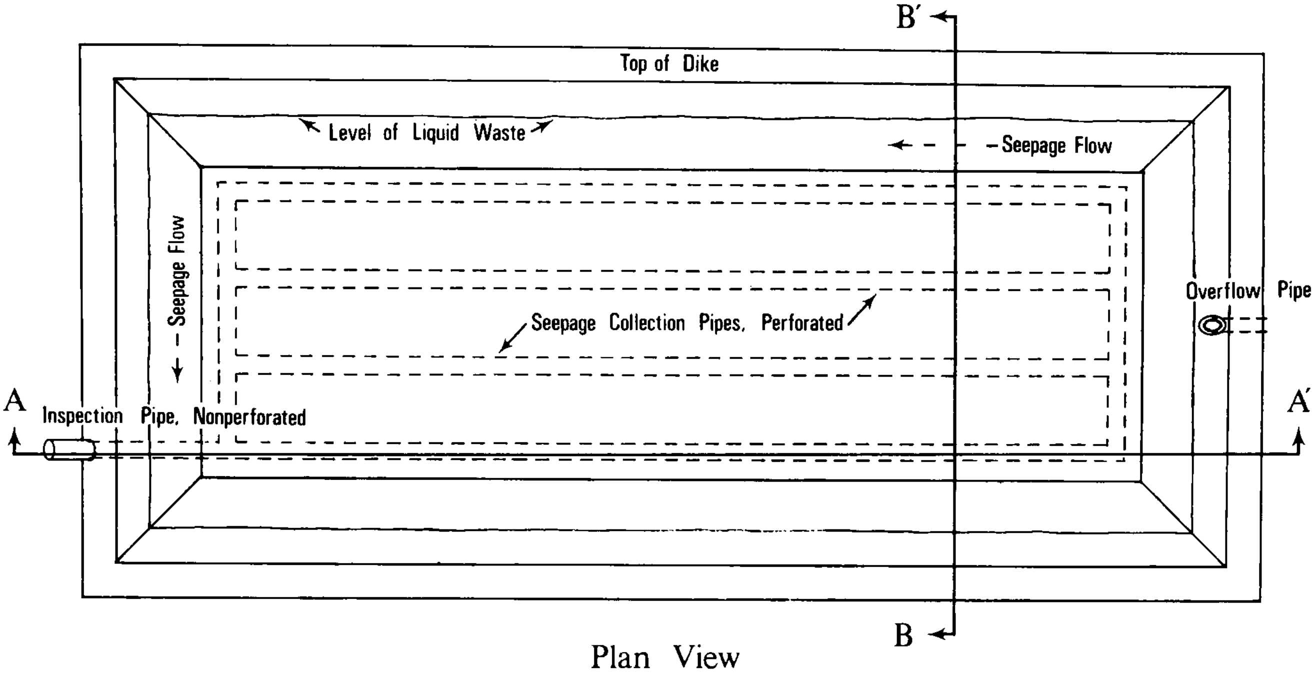
Gaseous vehicular emissions and particulate matter are released into the atmosphere directly from the mine. All vehicles should be equipped with the most up-to-date pollution control devices. Fugitive dust can be lowered by watering or oiling disturbed land during mining and rapid revegetation and reclamation. Scrubbers on the vent stacks of the drying and packaging unit minimize the escape of particulate yellowcake. Liquid seals on all solid waste storage ponds limit atmospheric emissions from this source.

Solid waste from the calcium removal unit should be stored in properly designed solid waste storage ponds. These ponds should be constructed similar to the liquid waste ponds described later in this paper. If the storage ponds fill, the calcite should be moved to an approved tailings pond, either on or off site. Solid waste from the contaminant control unit should be treated similar to that from the calcium removal unit. Precipitated waste in liquid storage ponds should be removed as necessary and placed in an approved tailings pond. Solid waste from the restoration program should also be handled similar to calcite waste.

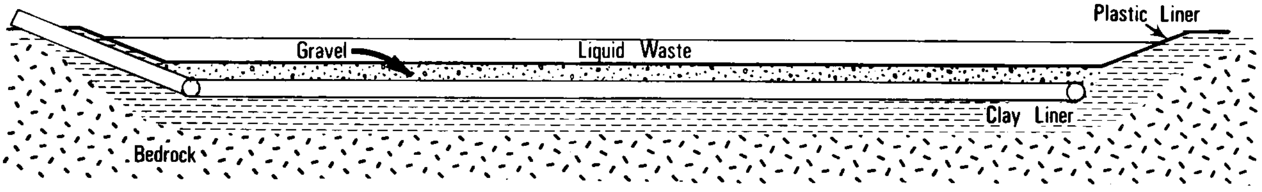
Liquid wastes should be placed in properly designed liquid waste storage ponds or possibly deep disposal wells. Deep disposal wells are satisfactorily used at solution mining facilities in Texas, but they may not be environmentally sound in all of Colorado. Liquid waste storage ponds should be lined with impermeable layers of clay and/or plastic to minimize contaminant leakage. Some ponds, such as those planned by Wyoming Mineral Corporation (1978), have built-in monitoring systems to detect leakage. Other ponds are surrounded by shallow monitor wells. Figure 5 illustrates the construction details of the waste storage ponds proposed for Power Resource Company's Keota project. The ponds will be constructed as rectangular basins in relatively flat, high areas with a continuous detention dike on all four sides of the pond. A gravel layer and system of perforated plastic pipes are placed at the base of the pond to collect seepage and serve as a built-in leak detection system. A thin layer of impermeable clay and an impermeable polyethylene liner, such as hypalon, overlie the detection system.

MONITORING PROGRAMS

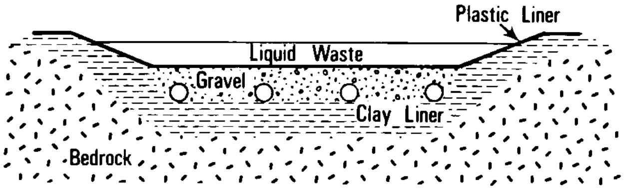
Prior to establishment of an in situ solution mine, meteorological, hydrological, soil, and vegetation surveys should be conducted to determine baseline concentrations of contaminants in the undisturbed environment. Meteorological surveys should determine climatic and wind conditions. Air samples should be analyzed at least for uranium, thorium, radium, and gross alpha. Natural radon-222 emanation from the soil should also be determined. All streams and surface water impoundments should be sampled prior to mine construction. Natural pre-mining ground-water quality must also be determined during the baseline data acquistion program. All wells used for monitoring or as trend wells during mining must be sampled during this phase and during mining as new wells are constructed. In certain cases, production wells should be sampled prior to initiation of mining in that particular production cell. Table 2 lists the primary physical and chemical parameters of the surface and ground water which should be analyzed during baseline studies. During mining it may not be necessary to analyze for all parameters in that some parameters serve as lead indicators of contamination. Soil and vegetation samples collected as a part of the baseline program should be analyzed for radioactive elements and heavy metals.



Plan View



Section View, A - A′



Section View, B - B′

Figure 5. Waste storage pond construction details of a pond with a built-in monitoring system. (after Wyoming Mineral Coporation, 1978)

Table 2. Physical and chemical parameters of surface and ground-water monitoring programs.
(from U.S. Nuclear Regulatory Commission, 1978a)

- Ammonia (as NH_4)
- Arsenic
- Barium
- Bicarbonate
- Boron
- Cadmium
- Calcium
- Carbonate (as CO_3)
- Chloride
- Chromium, hexavalent
- Conductivity
- Copper
- Fluoride
- Gross alpha and beta
- Hardness (as $CaCO_3$)
- Iron
- Lead
- Magnesium
- Manganese
- Mercury
- Molybdenum
- Nickel
- Nitrate (NO_3)
- Nitrite (NO_2)
- pH
- Potassium
- Radium-226
- Selenium
- Silica
- Silver
- Sodium
- Sulfate
- Total dissolved solids
- Thorium-230
- Vanadium
- Uranium (U_3O_8)
- Zinc

Monitoring programs should be continued during mining and additional surveys initiated. Air quality sampling stations should be located on the mine site and downwind from the mine. Stack gases from the yellowcake dryer and emissions from the well field surge tank need to be regularly sampled. Air samples should also be collected from near the calcium removal units, waste storage ponds, and other selected sites in the mine and process plant that may contain significant levels of hazardous elements.

In order to detect accidental contamination of the ground water, it is necessary to employ two primary monitoring systems. One system monitors leakage from waste storage ponds as described previously. A second system involves a series of monitor wells which encircle the well field. This system detects lateral excursions of contaminated mine water in the ore-bearing aquifer and defines an area of leachate containment. It may also be necessary to monitor for vertical excursions into overlying and underlying aquifers. These wells should be within the well field. Use of trend wells may be desired by the mine operator for production control purposes. These wells are a type of monitor well located bwetween the well field and the outer ring of monitor wells which encircle the well field. Variation of water quality within a trend well may indicate the beginning of an excursion.

Monitor wells should be completed such that individual wells sample either the ore-bearing aquifer or the first aquifer above or below the ore-bearing aquifer. Monitor wells completed in the ore-bearing aquifer should be located about 200 ft (60 m) from the periphery of the mined area. If trend wells are utilized, this distance may be increased up to 400 ft (120 m). Specific monitor-well spacing depends on the hydrogeologic conditions of each site. If vertical excursions endanger other important aquifers, it may be necessary to maintain at least one shallow and one deep monitor well completed in overlying and underlying aquifers for each five acres (20,235 m^2) of well field.

Monitor wells should be placed to maximize excursion detection capabilities and to allow for control of the leachate within the production zone. The U.S. Nuclear Regulatory Commission (1978a) recognizes three major factors to be considered in the spacing of monitor wells: 1) local variations in geologic and hydrologic conditions, such as flow rates, flow directions, stratigraphy, and structure, 2) placement of wells to create overlapping zones of influence, and 3) placement of wells to avoid interception of normal operating fluid flows. These factors play a significant role in excursion detection and must be considered when designing the monitoring programs.

All monitor wells should be sampled periodically and analyzed for parameters such as pH, water depth, specific conductance, chloride, bicarbonate, carbonate, hardness, sulfate, ammonia, uranium, sodium, etc. The suite of parameters to be monitored for depends in large part on the lixiviant used. An upper control limit (UCL) must be established for each selected indicator to allow for natural fluctuations of ground-water quality. A possible excursion and need for corrective action is signalled whenever two or more parameters exceed their designated UCL.

If an excursion occurs, corrective actions should be rapidly employed. Primary corrective actions include well-field overpumping, well reordering, reducing or halting injection, reducing leachate concentrations, establishment of a water fence, and, if all else fails, restoration.

After completion of mining and restoration in all well fields, a period of post-mining monitoring is necessary to verify successful restoration and quality stabilization. All monitor wells and well-field wells used to establish baseline water quality should be sampled periodically for six months to one year after completion of restoration to verify stabilization.

ENVIRONMENTAL EFFECTS OF ACCIDENTS

Serious environmental consequences may result from accidents during the operation of an in situ uranium solution mine. Accidents can be minimized by proper design, manufacture, and operation of process equipment, strict adherence to safety procedures, and establishment of a quality assurance program designed for safe operations in accordance with all applicable regulatory guidelines. Table 3 lists the potential surface and subsurface accidents that could occur at a solution mine. Only the more significant types of these accidents are described in this paper.

Table 3. Potential environmentally hazardous accidents at an in situ solution mine.

Subsurface Accidents	Surface Accidents
subsurface pipeline rupture	surface pipeline rupture
waste pond leakage	failure of chemical storage tanks
well casing failure	explosions and fires
leachate excursions	tornados
production well failure	seismic effects
leakage through improperly abandoned drill holes	
hydraulic fracturing	

Surface and subsurface pipeline rupture resulting from poor construction methods, deterioration, freezing, or physical damage may release harmful elements to the environment. The degree of impact depends on the amount and quality of chemicals within the pipeline and the operator reaction time. Feeder trunk lines and injection lines contain barren lixiviant. Return trunk lines and production lines carry numerous toxic and radioactive elements. Rupture of the latter type would result in a more serious release. Both surface water and ground water could be affected by pipeline rupture.

Environmental problems resultant from leakage of chemical storage tanks are not unique to solution mining. Chemical storage tanks may be inside and around plant buildings and in the well field. Any leakage from tanks within buildings will be collected by the building sump and pumped to appropriate evaporation ponds. Two types of storage tanks, pressurized gas and liquid, are kept outside of the plant building. Leakage of pressurized gas tanks create short-term toxic hazards and explosive or flammable conditions. Liquid storage tanks contain hazardous chemicals such as hydrochloric, nitric, and sulfuric acid, hydrogen peroxide, surge fluids, gasoline, and diesel fuel. These tanks should be in areas enclosed by a dike or berm and lined with impermeable materials to contain and limit any leaks.

Leakage from waste storage ponds is minimized by proper construction techniques. Should leakage occur, it would be detected by the built-in leak detection system or nearby shallow monitor wells. As soon as the leak is discovered, the contents of the pond should be removed to another intact pond and the damaged liner repaired. Liquid waste escaping from a leaking pond will migrate vertically and horizontally through the subsurface with the rate and direction of flow depending on the geometry and permeability of the underlying materials.

Leakage through cracked or improperly set casing in wells used by the mine may contaminate aquifers and dry formations which overlie the ore-bearing aquifer. Leaks in recovery wells probably will not cause significant contamination because withdrawal pressures in the well force fluids out of the formation and into the well. Contaminant escape in injection wells is more likely because fluids are injected under pressure into these wells. Most leaks probably will result from poor well construction techniques and leakage will occur almost immediately upon initiation of production. These leaks can be detected by circulating natural water through the production cell and close monitoring of injection pressures and recovery flow rates. During production, leaks will be detected by comparing injection and recovery pressures and flow rates, and by chemical sampling of water from shallow monitor wells. Generally, only the first aquifer above the ore-bearing aquifer is monitored; additional overlying aquifers are not monitored. Leakage into these aquifers would not be detected by the shallow monitor wells completed in the first overlying aquifer.

Vertical and lateral excursion or migration of leachate during mining is possible because of geologic inhomogeneities, anisotropic aquifer permeabilities, differential hydraulic gradients, poor well spacing, incorrect injection/recovery rates, and equipment failure. Excursions are one of the greatest potential environmental impacts of solution mining. Most excursions will be of limited extent and will only affect areas very near or within the mine area. Ocassionally, however, excursions may extend for several thousand feet from a mine. In rare situations where fractures and faults act as hydraulic conduits, fluid may travel a few miles. The exact shape, chemistry, and size of an excursion is controlled by 1) ability of the well field to confine and then remove leachate and mobilized constituents from the ore-bearing aquifer, 2) direction and rate of ground-water flow, 3) geochemical characteristics of the ore-bearing aquifer and the adsorptive and ion-exchange capacity of clay minerals in the aquifer, 4) mobility and chemical reactivity of contaminant ions, 5) lithologic and hydrologic variations of the aquifer, 6) excursion detection lag time, and 7) mitigation measures employed by the mine operator (U.S. Nuclear Regulatory Commission, 1978a,b). The chemistry of the excursion will depend on the mine lixiviant, mobilized ions from the ore body, and ability of the aquifer to selectively remove certain ions from solution.

Failure of a production well to recover pregnant lixiviant because of plugging or power loss could cause a localized excursion into adjacent production cells. Regular monitoring of injection and recovery pressures and flows should minimize lag time between failure and detection. Flow rate readjustment in nearby wells should prevent further leachate migration and balance well-field flow rates.

Migration of leachate through abandoned, improperly cased, or damaged drill holes not utilized by the mine may result in vertical excursions. Contaminated fluids may circulate within the drill hole and mix with ground water in aquifers above and below the ore-bearing zone, depending on hydraulic conditions. In areas where this type of well is anticipated, it may be necessary to pump test certain production cells prior to production initiation to determine if leakage through drill holes may occur. During mining, water level and quality changes within monitor wells may indicate contaminant migration in aquifers tapped by monitor wells. Excursions into other aquifers may be detected because of imbalance in production and recovery wells. Adjustment of flow rate, plugging or repair of the leaking well, and aquifer restoration are measures which will remedy the problem.

RESTORATION

Following completion of mining, affected water within the ore-bearing aquifer must be restored to original baseline quality or to a quality level specified by mine permits. Restoration may also be necessary to clean up contaminated aquifers after leachate excursions. Selection and implementation of a proper restoration program is absolutely necessary to assure maximum aquifer restoration. Some of the restoration methods currently considered for use include ground-water sweeping, clean-water recycling, and chemical restoration.

Establishment of restoration criteria is the initial step of any restoration program. Restoration criteria should be developed prior to mining and modified during mining as new quality data becomes available. In simplest terms, restoration criteria specify which parts of the ore-bearing aquifer will be returned to what specified quality levels.

The U.S. Nuclear Regulatory Commission (1978a,b) define three water quality zones within the ore-bearing aquifer at a solution mine: 1) the mining zone, 2) the containment zone, and 3) the undisturbed zone. Area within the ore-bearing aquifer that is mineralized and will be mined by the operator is the mining zone. The perimeter of the mining zone is defined as one well spacing or approximately 40 ft (12 m) beyond the outermost injection wells. An area within the ore-bearing aquifer between the mining zone and the ring of outermost monitor wells is the containment zone. The undisturbed zone is beyond the ring of outermost monitor wells.

Water within the mining and containment zones may originally have mineral contents in excess of quality standards for drinking water or livestock water. If pre-mining water quality is within either standard, the U.S. Nuclear Regulatory Commission (1978a,b) requires that the water be restored to appropriate federal or state standards. Restoration to original baseline conditions may be a reasonable requirement at some mines. If pre-mining water chemistry exceeds either standard, water quality should be returned to a satisfactory use category.

Ground-water sweeping is the most widely used restoration technique. It involves pumping and extraction of ground water from the ore-bearing aquifer and proper disposal of contaminated water. Uncontaminated ground water is drawn into the mining area and displaces and dilutes contaminated water. Ideally, all contaminated water will be replaced by uncontaminated water. Unfortunately, certain cations, especially ammonia, may form very strong bonds with clay minerals in the aquifer and cause significant restoration problems. Ground-water sweeping has been successfully used on a pilot-scale, but the consumptive use of ground water is very high. To minimize consumptive water use, it may be necessary to employ clean-water recycling methods. In such a process, extracted contaminated water may be purified by reverse osmosis, electrodialysis, ion exchange, ultrafiltration, or chemical precipitation and be reinjected near the perimeter of the mining zone. Restoration stabilization should be verified by collecting and analyzing water samples every 45 days for a period of six months to one year after completion of mining.

Restoration, however, has never been attempted on a full-scale basis. Several factors, including aquifer inhomogeneity, cation adsorption capacity of clay minerals in the ore-bearing aquifer, and chemical disequilibrium may lead to problems during the restoration of a large mine site. This problem is probably the most significant environmental question about solution mining which must be faced by the uranium industry.

Restoration appears to have been successful at the only uranium solution mine facility in Colorado. Table 4 lists the results of restoration of the Grover test site, a pilot-scale operation. Water analyses represent pre-mining, post-mining, and post-restoration water quality levels. Post-mining analyses indicate a marked increase in the concentration of many ions. This increase results from injected chemicals contained in the lixiviant and ions dissolved from the host rock by leaching. The Grover restoration program, which involved ground-water sweeping, clean-water recycling, chemical restoration, and residual TDS reduction, appears to have successfully restored the mined aquifer. Unfortunately, post-restoration analysis for many of the trace elements were not conducted. Therefore, the successful removal of these ions is not documented. Furthermore, a considerable amount of time, money, and effort was expended in the restoration of a relatively small test area. It is unlikely that industry will conduct such an extensive restoration on a full-scale project. Post-restoration analyses at Grover suggest restoration stabilization was achieved.

CONCLUSION

In situ solution mining of uranium favorably compares with conventional mining and milling techniques, both on an economic and environmental basis. Solution mining can be accomplished with lower initial capital outlays, shorter lag time before production initiation, rapid return of capital investments, and lower manpower requirements. The only significant detrimental economic factor is that uranium recovery is low. Commonly, 50 to 60 percent or less of the total uranium present is recovered. The importance of this, however, is lessened when one considers that many deposits suitable for solution mining can not be economically mined using conventional techniques.

Table 4. Restoration data from the Grover test site, Colorado (from Wyoming Mineral Corporation, 1979 and Webb, K., 1979, pers. comm.)

Constituents	Pre-Mining Samples [a]	Post-Mining Samples [b]	Post-Restoration Samples [c]		Restoration Stabilization Period [c]			
					45-days		90-days	
			WMC	CDH	WMC	CDH	WMC	CDH
Calcium	9.1	75.8	11.5	-	10.1	-	9.9	-
Magnesium	1.1	22.4	2.2	-	2.2	-	2.3	-
Sodium	85.2	237.5	-	-	-	-	-	-
Bicarbonate	220.1	1127.3	-	-	-	-	-	-
Sulfate	38.3	311.0	-	-	-	-	-	-
Chloride	7.0	75.5	-	-	-	-	-	-
Nitrate	1.4	5.2	N/A	0.018	0.005	<0.003	0.009	<0.1
Fluoride	0.7	0.1	-	-	-	-	-	-
TDS	295.0	763.0	275	240	268	260	267	270
pH	8.45	8.07	8.2	8.7	7.3	8.5	8.4	8.55
Arsenic	0.01	0.01	-	-	-	-	-	-
Barium	0.03	0.16	-	-	-	-	-	-
Cadmium	0.002	0.004	-	-	-	-	-	-
Chromium	0.003	0.005	-	-	-	-	-	-
Copper	0.06	0.08	-	-	-	-	-	-
Iron	0.70	1.25	-	-	-	-	-	-
Lead	0.02	0.03	-	-	-	-	-	-
Manganese	0.02	0.16	-	-	-	-	-	-
Mercury	0.0002	0.000	-	-	-	-	-	-
Molybdenum	0.02	0.31	-	-	-	-	-	-
Nickel	0.20	0.02	-	-	-	-	-	-
Selenium	0.01	0.59	-	-	-	-	-	-
Silver	0.003	0.002	-	-	-	-	-	-
Zinc	0.04	0.06	-	-	-	-	-	-
Boron	0.10	0.16	-	-	-	-	-	-
Vanadium	0.03	0.30	-	-	-	-	-	-
Ammonia	0.25	304.00	14.9	14	14	16	11	15
Uranium	0.086	12.48	0.62	0.59	0.61	0.57	0.65	0.68
Ra^{226} (pci/L)	13.4	259.8±3.9	-	N/A	-	13.0	-	14.7
Potassium	4.43	13.10	-	-	-	-	-	-
Carbonate	4.31	11.60	-	-	-	-	-	-
Silica	5.45	13.03	-	-	-	-	-	-
Conductance (umho)	380.7	2705.0	530	520	546	580	565	540
Alkalinity	154.7	1692.8	189	180	165	190	203	200
Aluminum	0.537	0.05	-	-	-	-	-	-
Phosphorus	0.050	0.15	-	-	-	-	-	-
Gross Alpha (pCi/L)	87.67	5255±132.6	347±30	579±36	262±25	499±34	348±31	454±30
Gross Beta (pCi/L)	15.23	1256.6±124.8	27±57	99±18	79±167	92±19	63±67	247±25
Lead (pCi/L)	0.37	9.9±2.3	-	-	-	-	-	-
Thorium (pCi/L)	0.7417	10.6±1.4	-	-	-	-	-	-

a) based on the average of twelve analyses; in ppm unless indicated otherwise
b) based on the average of seven analyses; in ppm unless indicated otherwise
c) based on analyses of samples from well G-2; WMC designates analyses by Wyoming Mineral Corporation; CDH designates analyses by Colorado Department of Health; in mg/L unless indicated otherwise

Atmospheric emissions from a solution mine are significantly lower than emissions from open-pit mines and are approximately equal or slightly lower than those from underground mines. Personnel exposure to radiation is greatly reduced by solution mining. Compared to open-pit mining, land impacts from solution mining are very insignificant. Tailings and solid waste disposal, a serious problem associated with conventional mining and milling, is virtually eliminated by solution mining.

Contamination and consumptive use of ground water are very real problems associated with solution mining. Conventional mining and milling methods, however, are also prone to ground-water contamination, as is documented at Grants, New Mexico and Canon City and Uravan, Colorado. Many conventional mines also have high consumptive use of ground water because of mine dewatering. When all aspects are considered, in situ solution mining of uranium compares very favorably with conventional methods. It should be considered a viable mining technique which environmentally and economically is often preferable over conventional mining and milling techniques.

Additional new mining methods are constantly being researched and developed by industry and the Federal government. Many of these methods may also be economically and environmentally preferable over conventional mining and milling. Planners should be aware that new mining techniques are available and should expect to see utilization of these new methods in their area of interest.

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