NUREG/CR-0311

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ABSTRACT

This report provides methods to collect data and evaluates impacts concerning ground-water elements of production-scale leach mining of uranium. Two overlapping networks of monitor wells are designed to collect pre-mining hydrogeologic and baseline water-quality data and to detect excursions of leaching fluids. The pre-mining data collection network consists of 24 wells completed into the ore-zone aquifer and the water-bearing units above and below it. The excursion-monitor network utilizes two rings of wells encircling the ore body and other wells strategically placed into other water-bearing units. The lateral excursion detection system is keyed to changes in water levels whereas the vertical excursion detection system is keyed to changes in water quality.

Several ground-water restoration methods are evaluated. Mechanical and chemical restoration methods can significantly remove most introduced and mobilized chemicals. Natural geochemical mechanisms should be capable of causing water-quality improvement. Several water-quality constituents, i.e., ammonia, chloride, sulfate, may not be greatly affected by restoration efforts.

Most mining and restoration activities should not greatly affect the availability or usefulness of ground water unless uncontrolled withdrawals from many sources occur. Disposal of leach mining wastes may prove a greater threat to the environment than the mining. Natural conditions and/or current state and Federal regulations limit the types of disposal methods that may be used.

SUMMARY

The investigation summarized herein was undertaken in 1977-78 to assist the U. S. Nuclear Regulatory Commission in protection of ground-water resources at sites where in-situ leach mining of uranium is expected to take place. The major objectives of the investigation were to: (1) provide criteria and a methodology for establishing baseline ground-water quality; (2) evaluate methods of restoration and their potential environmental impacts; (3) evaluate excursion control methods and their environmental impacts; (4) develop criteria for selecting excursion and restoration monitoring programs; (5) assess the potential impact of mining and restoration on water use; and (6) determine the potential impacts of disposal of wastes generated during mining and restoration.

The physical environments of the potential mining areas and the methods used in the in-situ leaching are very similar, and can be briefly summarized as follows:

1. The uranium ore body is found in sand lenses within a much thicker sedimentary sequence of sand, silt, and clay.
2. Ground water in the uppermost part of the sedimentary sequence is under water-table conditions, whereas the beds containing the ore bodies are at least locally confined.
3. Deposition of mineral species that are found in close association with a uranium ore body is controlled by the same oxidation/reduction reactions that localize the uranium.
4. The ground-water system in the mining areas is capable of yielding sufficient water of generally good quality to support individual water supplies, stock watering, small towns, and light irrigation.
5. The uranium is mined using lixiviants that oxidize and complex the uranium and other metals in soluble form.
6. The standard leach field utilizes injection wells as the outer ring of wells and production wells at the center. By pumping at a rate higher than the injection rate, the effects of mining on the ground water are normally confined to within a few tens of feet of the leach field.

CRITERIA AND METHODOLOGY FOR ESTABLISHING BASELINE WATER QUALITY

An analysis of ore-body mineralogy, lixiviants, geochemical reactions, and the ground-water flow regime indicates that several different water-quality conditions may naturally occur in and around the well field. Thus, a comprehensive hydrologic survey must be made to define the ground-water system in three dimensions. For this purpose, 13 observation wells are installed: 9 in the ore zone, 3 in the water-bearing unit

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above the ore zone, and 1 in the water-bearing unit below the ore zone. Water-level measurements taken in these wells are used to determine both horizontal and vertical flow in the ground-water system. The wells are also used to determine the (1) capacity of the system to transmit water, (2) permeability of the ore-zone aquifer, (3) anisotropy of the ore-zone aquifer, and (4) capacity of the confining beds to transmit fluids.

Baseline water-quality data are collected from 22 wells, including: 16 wells installed in two linear arrays through the ore body and perpendicular to the ore-body trend; 3 wells in the overlying water-bearing zone; and 3 wells in the underlying water-bearing zone. Water samples are collected and analyzed for 38 parameters including the major cations and anions, arsenic, selenium, heavy metals, radioactivity parameters, specific conductance, and temperature. Wells used to collect water-quality data can also be used to collect pre-mining hydrologic data and may be converted to excursion monitor wells or injection or production wells. NRC should reevaluate the usefulness of this pre-mining data collection program as guidelines and program decisions are made.

METHODS OF RESTORATION

Several techniques have been tested or proposed for restoration of ground water affected by mining. The restoration techniques have only been applied at the research and development project level where extrapolation of results to production-scale operations is particularly difficult because of differing geologic and geochemical frameworks.

The restoration technique being considered most widely today involves pumping residual fluids from the well field and drawing uncontaminated ground water from outside the field to displace the residual fluids. Pilot-project tests indicate that the total dissolved solids concentration in ground water within the well field can be restored to the average baseline level. However, concentrations of trace metals, ammonia, arsenic, and selenium may not be returned to average baseline conditions.

To expedite restoration, simultaneous pumping of the well field and injecting of specifically tailored fluid into the well field has been suggested. Natural ground water and treated leach-field water may be injected to displace and dilute residual lixiviant fluids. This technique may achieve reduction of total dissolved solids concentrations to acceptable levels, but the effect on any one constituent is unknown. The introduction of oxygen into the ground-water system by the injected water will allow continued mobilization of uranium and other oxidizable metals.

Another restoration technique utilizes the injection of special chemical solutions to remove certain bothersome constituents from the well-field ground water. Theoretically, the injection of reducing agents, such as hydrogen sulfide, will convert the soluble uranium and heavy metals to insoluble forms which will be naturally removed in-ground by precipitation. The solution left in-place will remain high in the major ions that are not affected by the reducing agents. This restoration approach has not been field tested. Ammonia desorption and removal has been field tested using salt solutions. Results indicate that some ammonia can be removed from the system but that baseline water-quality conditions are not restored.

Although it appears likely that natural geochemical processes can remove objectionable minor elements, the amount of time for natural restoration cannot be predicted based on current knowledge. Natural restoration may not be effective in the removal of ammonia to baseline levels.

EXCURSION CONTROL METHODS

The movement of lixiviants outside the mining zone in either a lateral or vertical direction is considered to be an excursion. Lateral excursions will occur only when the hydraulic gradient associated with the mining operation is away from the well field. This may occur locally even though the net hydraulic gradient is toward the well field. Flow away from the field is slow except where unusual geologic conditions, such as high permeability zones or fractures, allow rapid excursion.

Upon confirmation of a lateral excursion, corrective action should be taken. If the excursion is relatively small, correction can be achieved by re-establishing an inward hydraulic gradient in the area of the excursion. If the excursion is extensive, restoration-type measures must be taken.

Lateral excursions have been documented using water-quality monitoring techniques. Available data indicate that the best water-quality indicator of an excursion is an increase in total dissolved solids concentration, which is attributable to large changes in concentration of calcium, magnesium, sodium, chloride, and sulfate.

Vertical excursions occur when lixiviants escape into water-bearing rock above or below the ore body. Escape may occur through natural weak points in the confining beds or around improperly completed or abandoned wells. To minimize the impact of the vertical excursion, it is necessary to eliminate the pathway of escape, if it can be located. Natural paths cannot be closed but artificial avenues of escape may be. Restoration-type measures can be used to control and clean up a vertical excursion.

MONITORING PROGRAM

A monitoring network, developed to detect excursions in a timely fashion, is installed in the ore-zone aquifer and other water-bearing units. The network of monitoring wells is arranged in two rings around the ore body, located 50 ft (15 m) and 250 ft (75 m) from the well field. Wells in each ring are spaced 200 ft (60 m) apart. In addition, three monitor wells are installed in the water-bearing unit above or below the ore body.

The hydraulic properties of ore-zone aquifers are such that excursions are expected to move slowly. Ground-water quality changes resulting from an excursion will be noted in monitor wells only after large volumes of ground water are affected. On the other hand, pressure changes caused by injection and production imbalances are transmitted instantaneously throughout the system. Water-level measurements in a system of monitor wells can provide sufficient data to rapidly determine excursion events.

The type of monitor system needed to determine the effects of aquifer restoration is dependent upon the standards for restoration finally determined by NRC. A sufficient number of monitor wells, injection wells, and production wells should be in place at the time of restoration to facilitate any post-operation monitoring program. The restoration-monitoring program is water-quality oriented, and continues until the regulatory goal is achieved.

POTENTIAL IMPACTS ON WATER USE

The general quality of ground water found in aquifer systems that contain leachable uranium is very good, so that the water is usable for most water-supply purposes. High radium levels, however, may make water that is in direct contact with the ore body unusable. The excursion monitoring program will help prevent water-quality impacts from extending beyond the immediate vicinity of the well field.

The aquifer systems in which the ore bodies occur cover thousands of square miles and are thousands of feet thick, thereby storing billions of gallons of water for use. Because the in-situ leach mining operation uses only small amounts of water, the overall availability of ground water will not be affected during mining. Water-intensive restoration techniques, however, may have a greater impact on the availability of ground water because thousands of gallons may be pumped each minute. Nevertheless, after restoration has been completed, the system will replenish itself.

The current demand for water in areas subject to in-situ leach mining is not large, but is expected to increase as uranium, coal, and oil recovery increases in these areas. Severe impacts may be expected if the ground-water system is not adequately managed to meet these energy demands.

IMPACTS OF WASTE DISPOSAL

Improper disposal of wastes produced during the day-to-day operation and during restoration at an in-situ leach mining site may pose a threat to the environment. Because leach mining wastes are in liquid or slurry form, common methods of disposal include disposal wells and evaporation ponds to handle the entire waste stream. The waste may also be treated to remove objectionable material prior to release to the environment.

The use of disposal wells has proven to be environmentally safe when they are constructed and operated according to state and Federal regulations. Injection wells are used to dispose of leach mining wastes in Texas, but geologic and hydrologic conditions in other leach mining areas do not appear suitable for this practice.

Mining companies planning to use evaporation ponds to dispose of the liquid waste line the ponds to prevent seepage of the waste to the shallow ground water. Lined ponds can be used in all uranium mining areas; however, it may be impractical to use ponds to handle the large volumes of wastes produced by some restoration techniques. In addition, it is difficult to monitor the integrity of a liner to assure that leakage will not occur, and also, evaporation of waste water will leave large volumes of solids at the bottom of the ponds to be disposed in an NRC-accepted manner. Lined evaporation ponds to handle process wastes, wastes prior to well disposal, and reverse osmosis wastes may be used successfully in all mining areas.

Restoration waste can be treated to remove objectionable dissolved solids, including radium, arsenic, and selenium, so that the treated fluid should meet all applicable drinking water, agricultural, or livestock water-use standards. However, because EPA effluent guidelines prohibit the release of any wastes from uranium mills to streams, the treated water should be used only for irrigation purposes.

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1. INTRODUCTION

The U. S. Nuclear Regulatory Commission (NRC) presently has the responsibility of issuing licenses for in-situ leach mining of uranium in several western states. This mining practice is a relatively new one, and only nine research and development operations have been licensed by NRC thus far. Because the mining calls for the injection of chemical mixtures into subsurface geologic formations that contain usable water, NRC must evaluate the applicant's programs to monitor such injection and to restore the natural chemical quality of the ground water after the leach mining is terminated. In addition, NRC must take into account potential impacts of pumping of ground water and of waste disposal on the natural environment and on other water uses in the mining areas.

This report, prepared under a contract with NRC, evaluates (1) criteria and a methodology for establishing baseline ground-water quality; (2) methods of restoration and their potential environmental impacts; (3) excursion-control methods and their environmental impacts; (4) bases and criteria for selecting excursion and restoration monitoring programs; (5) the potential impact of mining and restoration on water use; and (6) the potential impact of disposal of wastes generated during mining and restoration. Few data are available on ground-water conditions at mining sites, and consequently, the findings in this report are based heavily on general scientific principles, case histories of ground-water impacts from similar activities of man, and evaluation of the regional occurrence and movement of ground water in potential mining areas. Data from on-going research and development and production scale operations in Texas and Wyoming have been utilized to support a number of the findings.

2. DEFINITION OF THE PHYSICAL SYSTEM

To date, NRC has been evaluating license applications on a case-by-case basis, first taking into account the geology and hydrology of the proposed mining site and impacts upon the physical system attributable to present use of the land and water. To assist NRC in making these evaluations, the following sections describe the geologic and hydrologic characteristics of the areas where most of the future in-situ leach mining of uranium is expected to take place.

2.1 GEOLOGY OF POTENTIAL URANIUM LEACH MINING SITES

There is some degree of uranium mineralization in most Tertiary and older sedimentary rocks of the Western and Southwestern United States. However, the principal regions of potential uranium recovery by in-situ leach mining are the Wyoming Basins, the Colorado Plateau, and the Gulf Coastal Plain of Texas. The southern Black Hills and northeastern Colorado, within the Great Plains region, also contain sedimentary uranium deposits that may be amenable to in-situ leach mining (Figure 2.1 and Table 2.1). Details of the stratigraphy and mineralogy of these and other mining areas are given in Appendix A.

Leachable uranium deposits are found in sandstones that have been deposited in intermontane basins, along mountain fronts, and in near-shore marine and deltaic environments. Alternating periods of sluggish and swift streamflow, as well as changes in base level due to tectonic forces, have created a complex and heterogeneous sequence of sediments that may be greater than 6,600 ft (2,000 m) thick. These sediments are fine- to coarse-grained arkosic sands, with some conglomerates, siltstones, and claystones. Successive scouring, filling, and beveling of channel segments have resulted in the lenticular and cross-bedded characteristics of the deposits. The stream-channel deposits become fine-grained away from the source of sediments where they commonly grade into carbonaceous shales and lignites, deposited contemporaneously in swampy areas or lakes.[2]

Zones of uranium mineralization follow the general trend of drainage channels. However, individual ore bodies in sandstone lenses rarely exceed a few hundred yards in length; they are elongate and narrow, commonly a few tens of yards wide, and less than a few tens of feet thick. The geologic environment favoring the deposition of uranium ore is deficient in oxygen, has zones with less permeable siltstones and shales, and contains reducing agents such as carbonaceous material, hydrogen sulfide, or pyrite.[2] Figures 2.2 and 2.3 illustrate the occurrence of types of ore deposits and their relationships to sources of oxygenated ground water and changes in permeability.

2.1.1 Source and Deposition of Uranium

The uranium in sandstone-type deposits is thought to have been derived from either granite, which supplied the material to form the arkosic

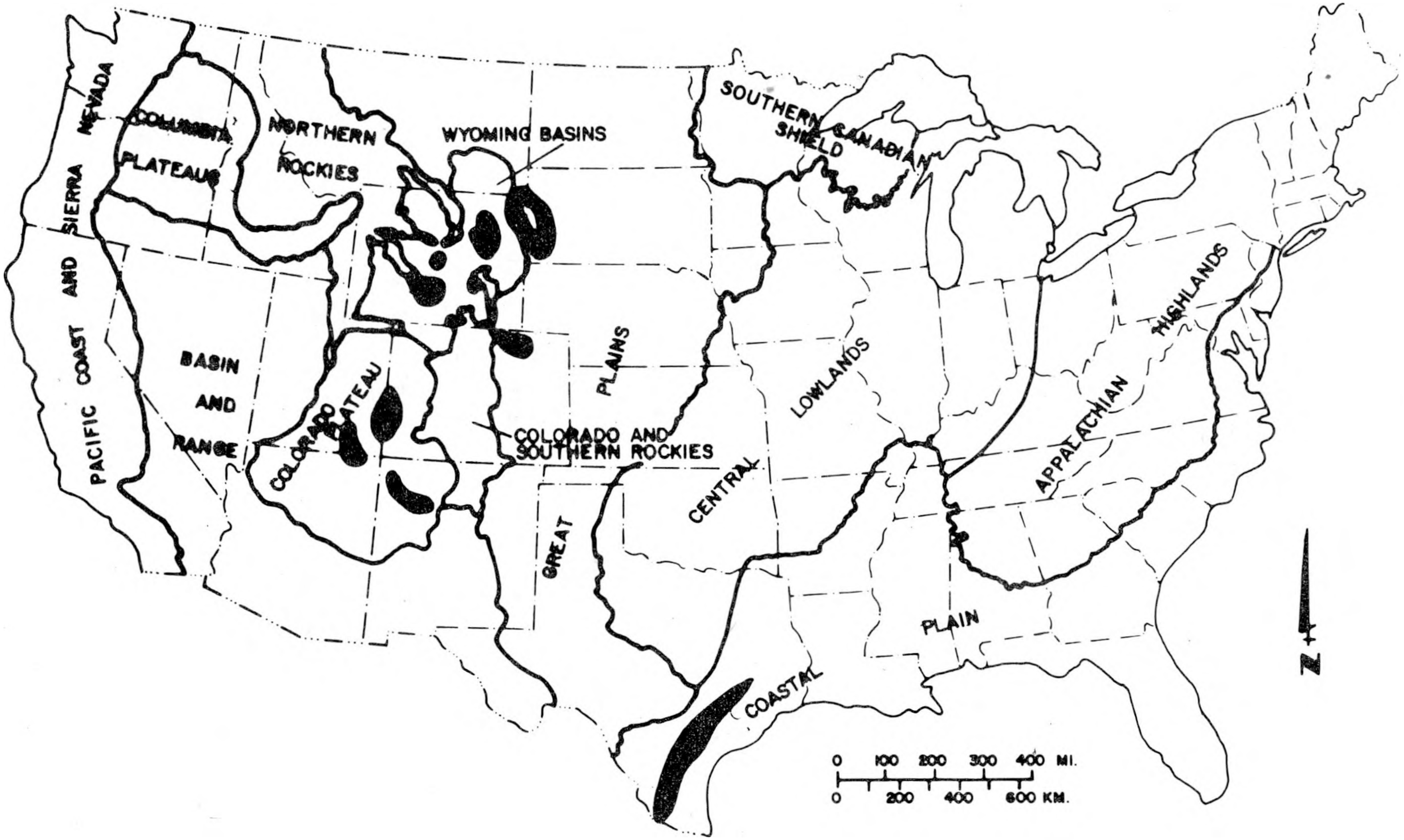


Figure 2.1. Map of the United States showing the major areas amenable to in-situ leach mining of uranium discussed in this report.[1]

TABLE 2.1
PRINCIPAL HOST ROCKS FOR POTENTIAL URANIUM PRODUCTION BY IN-SITU LEACH MINING IN THE WESTERN UNITED STATES

Region	Mining Area	Principal Ore-Bearing Formation	Age of Host Rock
Wyoming Basins	Shirley Basin	Wind River	Eocene
	Powder River Basin	Wasatch Ft. Union	Eocene Paleocene
	Wind River Basin (Gas Hills)	Wind River Wagon Bed	Eocene Eocene
	Great Divide Basin (Crooks Gap)	Battle Spring	Eocene
Colorado Plateau	Grants Mineral Belt, New Mexico	Morrison	Jurassic
	Monument Valley-White Canyon (S. Utah, S. Arizona)	Chinle	Triassic
	Uravan Mineral Belt (E. Utah, W. Colorado)	Morrison	Jurassic
Gulf Coastal Plain	Karnes District, Texas	Catahoula Tuff Whitesett	Miocene? Eocene
	Live Oak District, Texas	Catahoula Tuff Oakville Sandstone	Miocene? Miocene
Great Plains	Southern Black Hills, S. Dakota, Wyoming	Inyan Kara Group	Early Cretaceous
	Grover Area, NE Colorado	White River Group	Oligocene

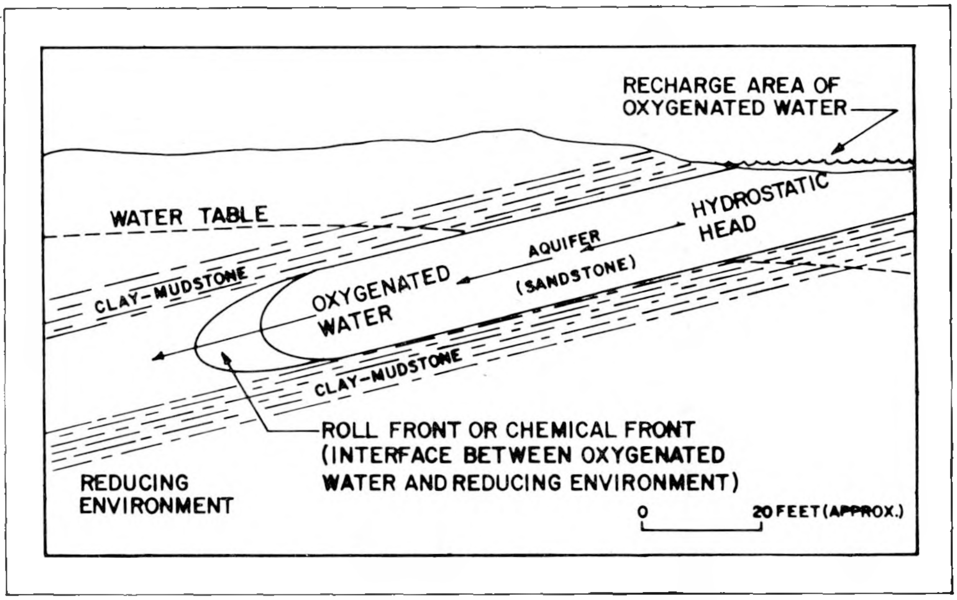


Figure 2.2. Position of uranium roll-front ore deposit relative to ground-water recharge and confining beds.[4]

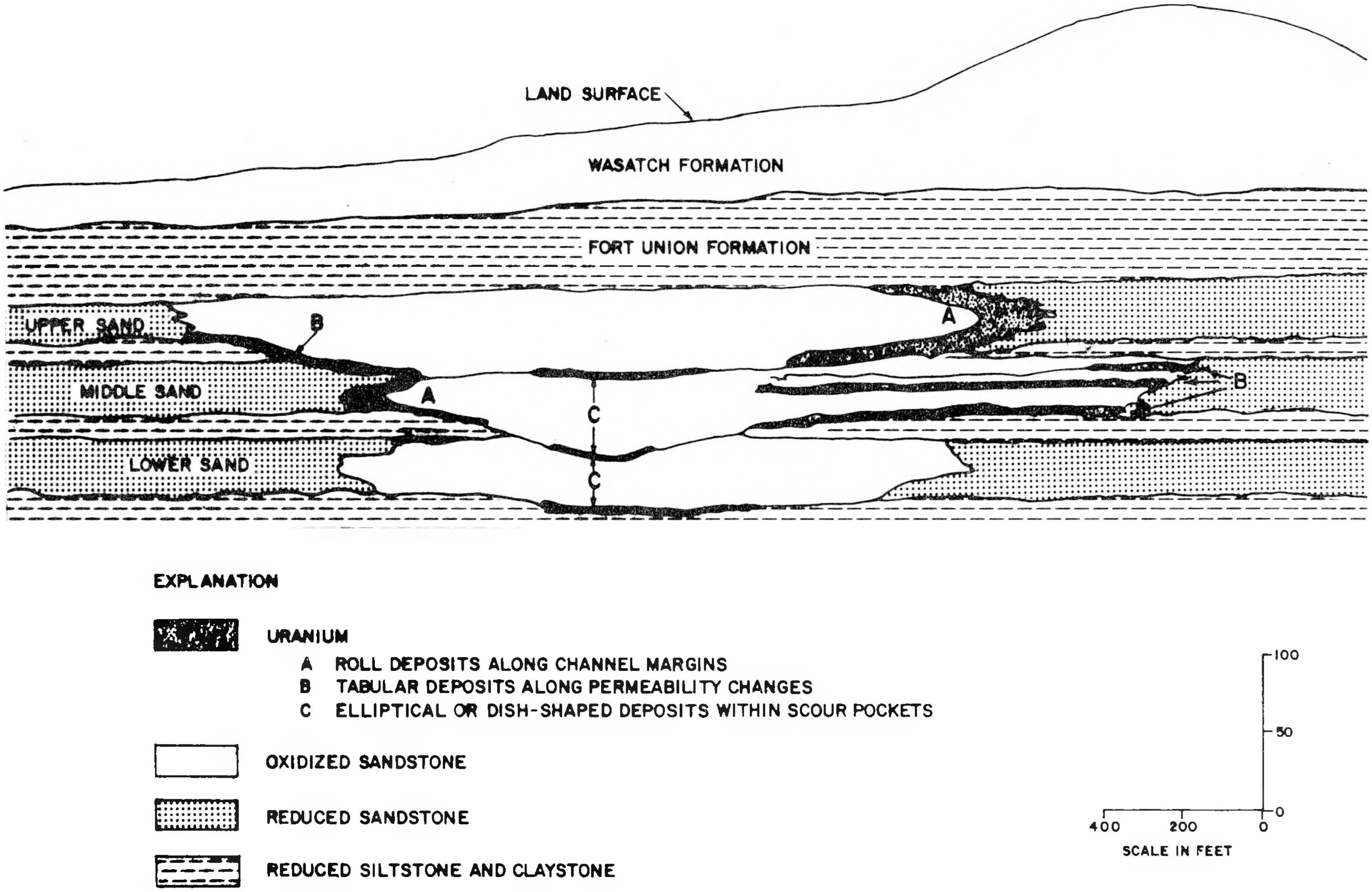


Figure 2.3. Uranium ore deposits in sandstone channels.[3]

sandstones, or from volcanic material that was deposited with, or later than, the sandstone, or perhaps from both.[5] Granitic bodies containing uranium are found in many of the mountains that supplied the sediment comprising the host sandstones. Oxygenated ground water percolating through these units oxidizes and mobilizes the uranium.

As the uranium-enriched ground water moves through the aquifer from the basin edge toward the basin center, it comes in contact with carbonaceous material and pyrite. During the period of active anaerobic decomposition of the organic material, the ground water may also encounter hydrogen sulfide and methane. None of these constituents is stable in the uranium-enriched oxidizing ground water and, therefore, will react to reduce the uranium to insoluble uraninite (UO_2). The dissolved oxygen is consumed, while hydrogen sulfide and sulfur from pyrite is oxidized to sulfate. Organic material and methane may be oxidized to carbon dioxide and water. The pH and Eh of the solutions decreases at this oxidation-reducted front. Further downgradient, the ground water is reduced, the pH is near neutral, and pyrite and organic material is found as the more stable phases for iron, sulfur, and carbon.

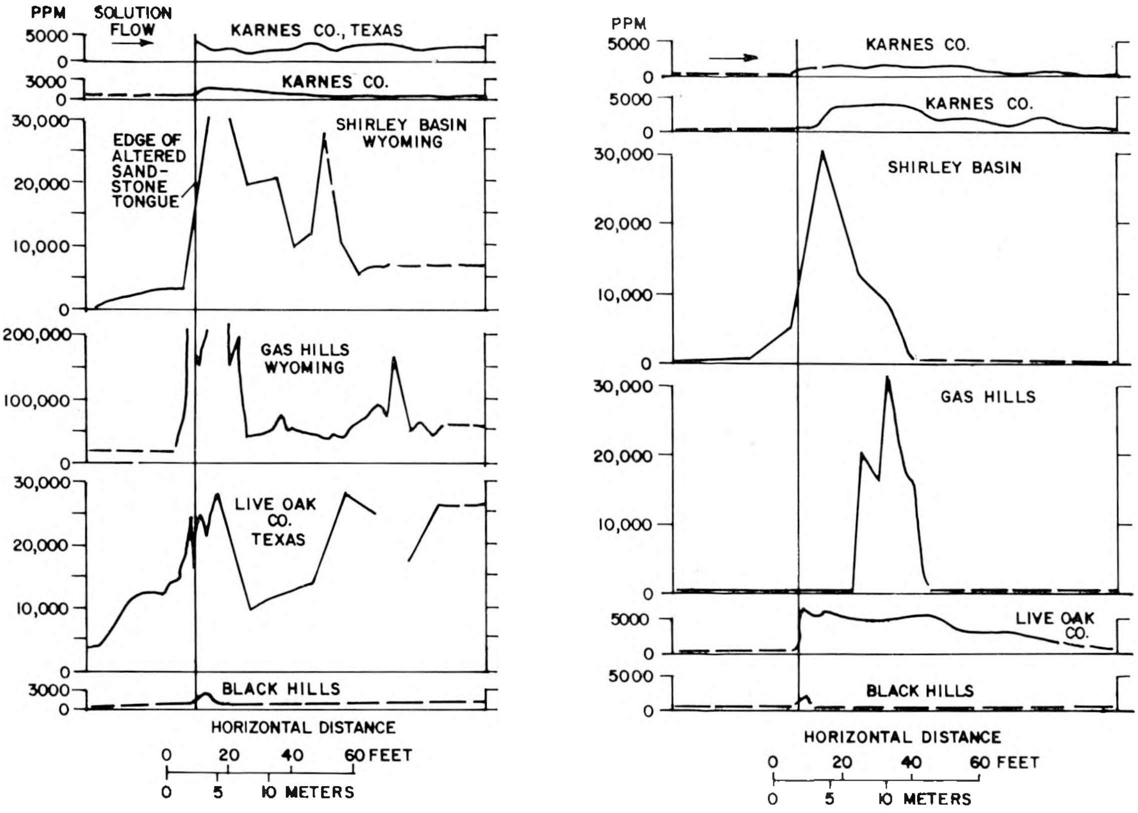
Freshly precipitated uranium along with uranium in the arkosic sandstone minerals is continually dissolved by oxygenated ground water and displaced further downgradient. Eventually, uranium of economically recoverable grade is deposited at the oxidation-reduction interface. The distribution of uranium and other elements in and around the ore deposits depends not only upon the oxidizing capacity of the ground water, but also upon the available reactive concentrations of precipitating agents.

2.1.2 Associated Minor and Trace Elements

Numerous other elements with similar chemistries are mobilized and precipitated under the same conditions as uranium; most importantly for this study, these include arsenic, selenium, vanadium, copper, and molybdenum. The most complete investigation of the distribution of these elements in and around uranium ore bodies was done in the Shirley Basin of Wyoming.[6,7] Although the core samples in that investigation were taken only at points about 30 ft (9 m) in front of the ore roll in the unoxidized portion of the aquifer and approximately 80 ft (24 m) behind the ore roll in the oxidized interior, certain trends in the distribution of the elements are obvious. Figures 2.4 and 2.5 present data from the Shirley Basin as well as other mining districts.

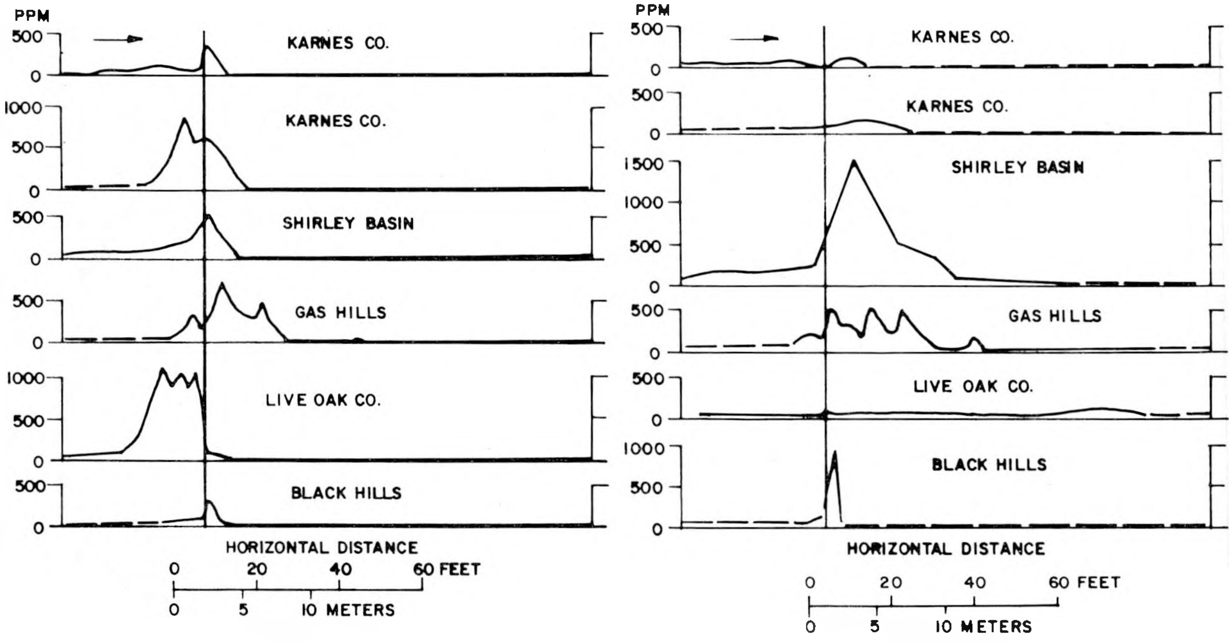
2.2 GROUND-WATER HYDROLOGY OF URANIUM LEACH MINING SITES

The sedimentary sequence in which the uranium-ore bodies are found may be several thousands of feet thick and may comprise one interconnected hydrologic unit (aquifer). Characteristically, this aquifer is made up of a number of water-bearing units separated by confining units. The water-bearing unit containing the ore body has been defined as the ore-zone aquifer for the purposes of this study. The confining materials separate the ore-zone aquifer (at least locally) from other water-bearing



PYRITE

URANIUM



SELENIUM

VANADIUM

Figure 2.4. Distribution of pyrite, uranium, selenium, and vanadium associated with uranium ore deposits in South Dakota, Texas, and Wyoming.[7]

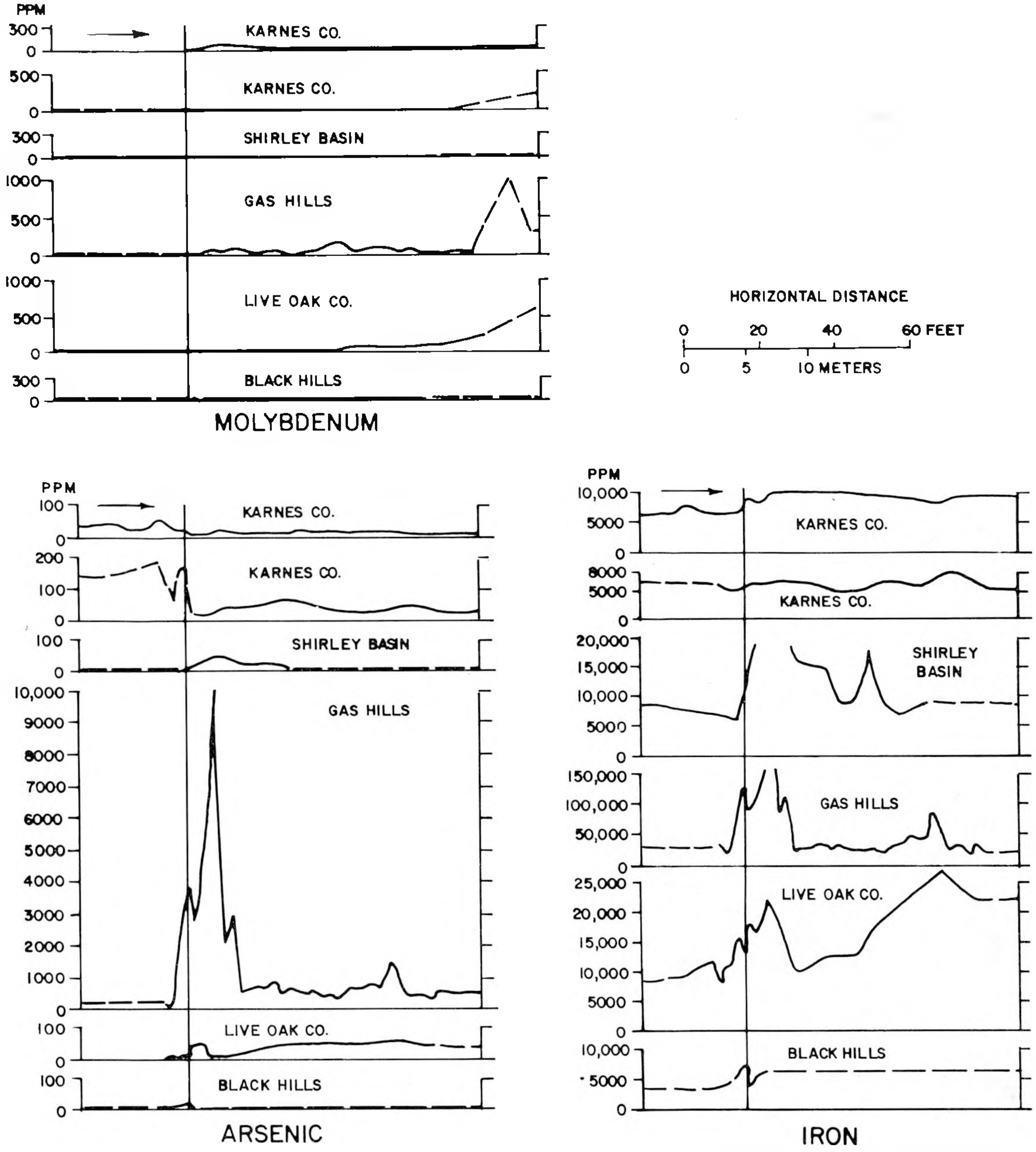


Figure 2.5. Distribution of molybdenum, arsenic, and iron associated with uranium ore deposits in South Dakota, Texas, and Wyoming.[7]

units above and below. In all cases, the aquifer zones are saturated with ground water moving in response to hydraulic forces.

The aquifer system is recharged by direct infiltration of rainfall or snow melt at the land surface. The recharge generally occurs in the outcrop areas and moves slowly downgradient to and through the ore body. The uppermost part of the aquifer system is under water-table conditions and the ore-zone aquifer is under confined conditions. Uranium deposits found in water-table aquifers cannot presently be mined by the in-situ leaching method.

2.2.1 Hydraulic Properties

The permeability of the typical ore-zone aquifer is generally less than 1,000 millidarcies (1 x 10^{-2} cm/sec). Individual wells completed in the ore-zone aquifer generally yield 5 to 10 gpm (0.3 to 0.6 l/s) which is adequate to meet domestic and livestock supply needs. Additionally, the ore-zone aquifer can produce enough water to support in-situ leach mining and even certain water-intensive restoration techniques without affecting the ground-water system's ability to meet other demands.

Depths below land surface to the ore-zone aquifer are between a few tens of feet and thousands of feet. Economic considerations determine which ore bodies will be mined; at present, only ore bodies less than about 500 ft (160 m) deep are being mined.

2.2.2 Water Quality

Throughout the uranium mining areas, the quality of the ground water is variable, depending on proximity to sources of recharge and to depth. Ground water at potential sites in Wyoming and the Colorado Plateau is of the calcium or sodium sulfate or bicarbonate type, with a total dissolved solids (TDS) concentration generally in the range of 160 to 1,250 milligrams per litre (mg/l). In Texas, however, the ground water is of the sodium bicarbonate and sodium chloride type, with a TDS concentration generally ranging from 1,250 to 3,000 mg/l. Higher or lower TDS levels are found locally. Trace and heavy metal concentrations generally are within accepted public health limits in all areas. Levels of radioactive parameters (radium-226, gross alpha, and gross beta), however, are commonly above recommended public health standards in water samples taken from water in contact with the ore body. Appendix B provides specific hydrologic and water-quality information for the uranium-mining areas.

2.3 LAND AND WATER USE IMPACTS

Ground water in the anticipated mining areas is currently used for residential supplies, stock water, and small municipal supplies. Some irrigation utilizing ground water is taking place in Texas and some coal mining operations are using ground water in Wyoming. The uranium deposits are generally in sparsely populated areas that are not heavily used for agriculture or ranching (Texas is an exception, although the local population cannot be considered dense even there). Water quality does not appear to preclude the use of ground water for these purposes, although the quality may be marginal in some parts of Texas.

Future conjunctive development of uranium, oil, coal, and oil shale in some uranium mining districts could have an extensive cumulative adverse impact on ground-water supplies. A complete water-management study would have to be undertaken to adequately define these impacts. The study should be undertaken by the state, Federal government, or some intergovernmental body. A detailed assessment of present uses and available, usable water supplies should be made. Future spatial and volumetric water demands should be predicted and evaluated against current needs and available supplies. (Appendix B contains an overview assessment of present water use and needs for each mining area).

2.4 POTENTIAL IMPACTS OF IN-SITU LEACH MINING

The water-quality effects that can result from in-situ leach mining include excursions of lixiviants during injection and natural migration of residual lixiviants and other mine-affected ground water after mining has ceased. The ideal lixiviant for in-situ use is one that will oxidize the uranium, complex it so as to maintain it in solution, and interact little with barren host rock. Unfortunately, no lixiviant is entirely inert to the other minerals commonly associated with sedimentary uranium deposits. Numerous chemical interactions are possible between a lixiviant and the uranium and associated secondary minerals; therefore, lixiviant agents and concentrations must be adapted to each ore body to assure maximum uranium recovery while minimizing undesirable secondary reactions.

Lixiviants for in-situ leach mining are salt solutions of ions such as sulfate, bicarbonate, carbonate, and ammonium known to form stable aqueous complexes with hexavalent uranium. An oxidant such as air, hydrogen peroxide, sodium chlorate, sodium hypochlorite, or potassium permanganate, is added to the lixiviant to effect the oxidation of uranium. The lixiviant solution may have any pH, although the mineralogy of most uranium deposits dictates the use of neutral or basic lixiviants such as bicarbonate and carbonate lixiviants.

The principal geochemical reactions among lixiviants, ore minerals, and host rock are discussed below; secondary reactions, including those involving the geochemistry of some trace metals and minor elements, are given in Appendix C.

2.4.1 <u>Principal Geochemical Reactions</u>

Interactions and reactions between lixiviant agents and minerals, which occur at the time of lixiviant injection and may continue well after solution mining operations have terminated, can be divided into four broad categories: (1) oxidation and reduction; (2) dissolution; (3) reprecipitation; and (4) adsorption and ion exchange.

2.4.1.1 Oxidation and Reduction

Oxidation ultimately controls the amount of uranium recovered by solution-mining methods. The tetravalent ore minerals, uraninite and coffinite, are insoluble under reducing conditions but will dissolve in the presence of a suitable oxidant. The oxidizing agent may be injected along with the lixiviant or generated internally through the actions of the lixiviant on associated non-uranium minerals. For example, when hydrogen peroxide is injected in the presence of the bicarbonate ion, the oxidation reaction can be depicted by equation 2.1:

$$UO_2 + H_2O_2 + 2HCO_3^- \rightarrow UO_2(CO_3)_2^{-2} + 2H_2O \qquad (2.1)$$

Any oxidant introduced with the lixiviant also may generate chemical species, such as ferric iron, which are capable of oxidizing tetravalent uranium. Oxidation of ferric iron may be the mechanism by which most of the uranium is actually oxidized. For example, chlorate ion oxidizes ferrous iron to ferric iron, which, subsequently oxidizes uranium according to equations 2.2 and 2.3:

$$6Fe^{+2} + ClO_3^- + 6H^+ \rightarrow 6Fe^{+3} + Cl^- + 3H_2O \qquad (2.2)$$

$$UO_2 + 2Fe^{+3} \rightarrow UO_2^{+2} + 2Fe^{+2} \qquad (2.3)$$

Once oxidized, the uranium is readily leached by sulfate, bicarbonate, or carbonate solutions.

2.4.1.2 Dissolution

During in-situ leach mining, other minerals are decomposed, with the extent of decomposition depending upon the chemical nature of the lixiviant and the minerals. In most instances, decomposition or dissolution of these minerals is undesirable, as it consumes lixiviants, introduces contaminants, and diminishes uranium recovery. Carbonate minerals are most susceptible to dissolution by the lixiviant solution; the extent depends on the pH of the lixiviant. For example:

$$CaCO_3 + 2H^+ \rightarrow Ca^{+2} + H_2O + CO_2 \qquad (2.4)$$

Mining with neutral or slightly basic lixiviants tends to minimize the dissolution of uranium-associated minerals. However, some alteration of carbonates and silicates is expected in localized zones. For example, ferrous iron minerals deposited in intimate contact with carbonates and silicates may undergo oxidation reactions that produce acid which, in turn, reacts with the same carbonates and silicates.

2.4.1.3 Reprecipitation

The mobility of many salt complexes placed into solution by the lixiviant is limited by reprecipitation and coprecipitation reactions. Reprecipitation of uranium may be detrimental to the in-situ leach mining operation by diminishing uranium recovery. Conversely, reprecipitation and coprecipitation of non-uranium elements may be beneficial by reducing the contaminants recovered along with uranium. For example, calcium ion can reprecipitate as gypsum or as secondary calcite. Hexavalent uranium may coprecipitate depending upon the concentration of dissolved uranium and upon the degree of lixiviant supersaturation with respect to calcite or gypsum. Oxidized uranium may also become fixed within the structures of slightly soluble vanadate and arsenate minerals that can form during the leaching process.

Uranium is especially susceptible to precipitation whenever the oxidizing potential of the solution transporting the element has been diminished. This may occur when the lixiviant migrates toward the border areas of the leach field where it comes in contact with unleached, reduced rock. Chemical reduction and subsequent reprecipitation of uranium, and other trace elements, is possible under these circumstances and may, in essence, reverse the leaching process.

2.4.1.4 Adsorption and Ion Exchange

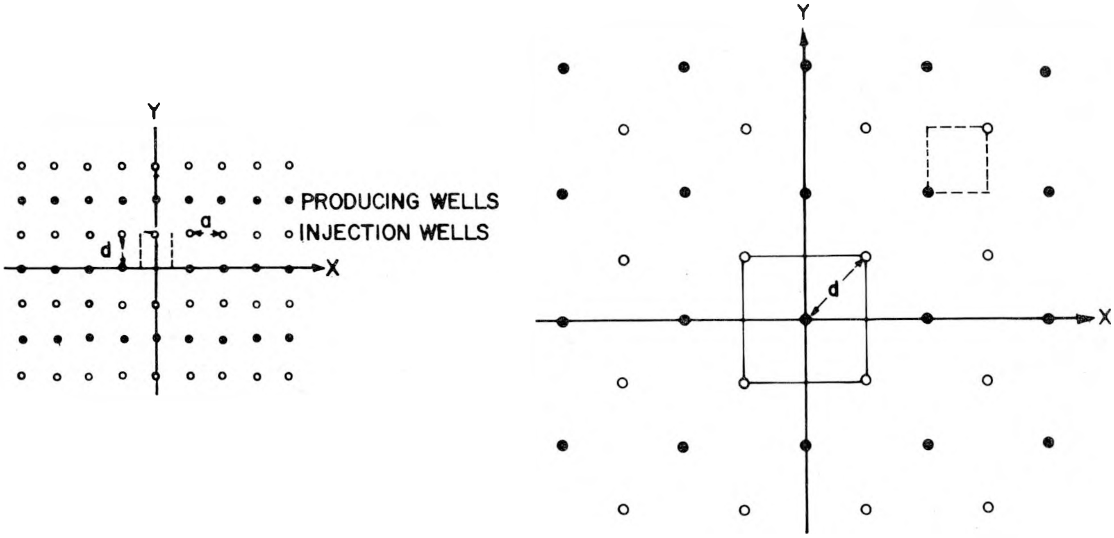
The principal mechanism for removing heavy metals from solution is the adsorption on colloidal precipitates of hydrous iron oxides. Ion exchange between lixiviant and clay material can also be anticipated. Montmorillonite clay, commonly present as matrix material, has a high capacity for ion exchange, which can occur either at the surface of individual clay platelets or within layers in the clay structure. Calcium and magnesium, for example, may be replaced with sodium from the lixiviant.

Montmorillonite also has a high cation exchange capacity for potassium and ammonium, whose ionic radii are similar. Ammonium fixation is confirmed in leach tests with ammonium bicarbonate lixiviants. Nearly twice as much ammonium has been found in clays invaded by ammonium lixiviant as existed prior to leaching operations.

2.4.2 Hydraulic Impacts of Well Injection

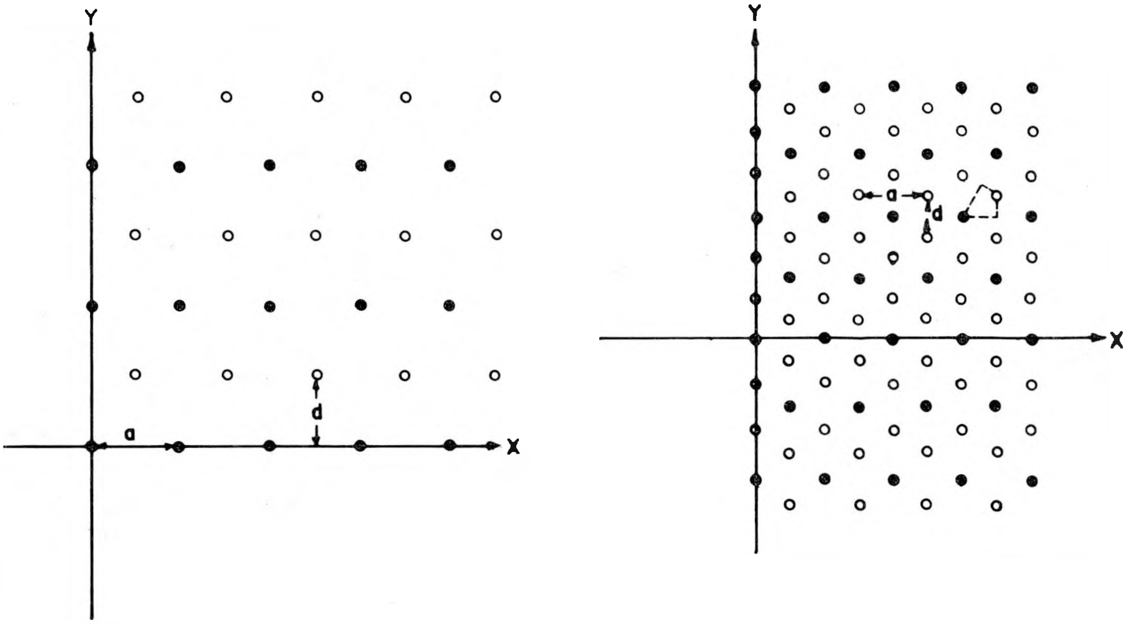
The spacing and arrangement of injection and production wells and differences in the rates of injection and production are the variables that can be manipulated to achieve optimum hydraulic and economic leaching-field design. The hydraulic response of an aquifer to fluid injection or production can be estimated if the hydraulic properties of the aquifer are known. The arrangement of wells is similar to that in networks used for secondary-recovery operations in oil fields, and can be classified as: (1) direct line drive, (2) staggered line drive, (3) five spot, and (4) seven spot (Figure 2.6).

The pressure distribution around a single well, for the steady-state case in which rates of flow are kept constant, is proportional to the volume of material injected or produced and inversely proportional to the thickness and permeability of the ore-zone aquifer. Calculations based on these factors will show how far beyond the edge of a well field



A. DIRECT LINE DRIVE

B. STAGGERED LINE DRIVE



C. 5-SPOT

D. 7-SPOT

Figure 2.6. Standard injection/production well arrangements for in-situ leach mining of uranium.

the pressure effects extend. Assuming the case of a direct-line-drive arrangement and assuming that the outer row of wells is used to inject lixiviant, the pressure effects are calculated to be of significance only within a few tens of feet of the well field. Even if the field consists of a large number of rows of wells, this condition is maintained if the net rates of injection and production remain equal for all wells, except for the outer row of production wells, which must be produced at 1.5 times the average flow rate for each well.

On the other hand, model studies show that even a slight excess of injection (or deficit of production) at one well, in a well field that is otherwise balanced, creates a pressure front that expands rapidly away from the well field. Fluid flow will respond to this imbalance so that the injected lixiviant will begin to flow out of the field. However, unless flow is along a pathway of anomalously high permeability, such as a fracture or a sand lens, the movement away from the field will be very slow.

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3. MONITORING PROGRAM

In this report, the term monitoring program is used to describe a comprehensive surveillance system, which includes not only the installation and operation of monitoring wells, but also the collection and evaluation of information concerning premining conditions, economic circumstances, and regulatory requirements. The criteria used in the following sections reflect this broad concept of surveillance.

3.1 CRITERIA AND METHODOLOGY FOR ESTABLISHING BASELINE WATER QUALITY

3.1.1 Data to be Supplied by the License Applicant

Prior to operation of the in-situ leach mining facility, the applicant should supply NRC with data on (1) geology, (2) hydrology, (3) land and water use impacts, (4) in-situ leach mining impacts, and (5) methods to comply with any applicable regulatory requirements. A list of the principal items to be addressed under each of these headings is given below.

A. Geology

Regional geologic structure and seismicity

Regional stratigraphy

Cross sections through the mining site depicting the location and trend of the ore zone and the confining beds

Isopach, contour, or structure maps of the mining site

B. Hydrology

Water levels (potentiometric levels) of the ore-zone aquifer and the aquifers above and below

Regional and local directions of ground-water flow

Total and effective porosity and permeability of the ore-zone aquifer

Transmissivity and storage coefficient of the ore-zone aquifer

Water quality of the ore-zone aquifer including the ore body and both upgradient and downgradient areas

Water quality of the aquifers above and below

Competence and extent of the confining beds

Surface-water flow rates through the property including seasonal variations

Surface-water quality

C. Land and Water Use Impacts

Water supplies - areally and by source

Other mining activities

Agricultural activities

Potential sources of pollution

Locations of unplugged exploration wells

D. Mining Influences

Type and quality of lixiviant

Volumes and pressures of injection/production

Well-field design

Recovery process plans

Methods of waste disposal

E. Regulatory Requirements

Well construction

Monitoring

Waste disposal

Restoration

Reclamation

Site Abandonment

In some mining areas, much of the background data may be compiled from an examination of geologic and ground-water reports, well logs, well records, pump-test results, and water-quality information available from the U.S. Geological Survey, State Geological Surveys, the Soil Conservation Service, State departments of Land Management or Resources Management, and Environmental Protection Agencies. An inventory of existing water-supply, oil, or exploration wells may have to be made to supplement the available records, particularly with regard to data on well depths, depths to water, fluctuations of water levels, and chemical quality.

Commonly, however, there are insufficient data in public files to meet all of the data requirements, and field studies, including exploration test drilling and installation of observation wells, may have to be undertaken to collect data on the specific ground-water hydrology of the mining site.

3.1.2 Methodology for Collecting Background Hydrologic and Water-Quality Data

Figure 3.1 presents a procedure for acquiring pre-mining data on site-specific hydrologic and water-quality characteristics for production scale operations. The system may be modified on a case-by-case basis to achieve individual needs. The information is developed through the installation of observation wells, virtually all of which may be used later on as production or injection wells or as excursion monitor wells.

3.1.2.1 Hydrologic Data Collection

Flow Regime

The basic information to be developed pertains to water levels existing prior to initiation of mining in the ore-zone aquifer and in the aquifers above and below, to determine horizontal and vertical flow directions in all three units. For this purpose, four three-well arrays, placed in triangular formation, plus one additional well, are used. Three of the arrays are installed to collect data on the ore-zone aquifer, one array being in the ore body, one in the reduced rock area, and one in the oxidized rock area. The fourth array is installed in the aquifer above the ore-zone aquifer. The single observation well should penetrate the aquifer below the ore-zone aquifer (Figure 3.2).

As few as three observation wells could be constructed into the ore-zone aquifer to develop a rudimentary potentiometric surface map of that aquifer. However, it is recommended that three such arrays be constructed to provide a better definition of ground-water movement to and through the ore body itself. Additional observation wells may be constructed into the aquifers above and below the ore-zone aquifer if there is reason to believe that extensive exploratory drilling has opened potential avenues for the excursion of fluids.

The direction of horizontal flow will be determined from a comparison of water-level readings taken in the completed wells; Figure 3.3 illustrates one method to accomplish this. Once the ground-water elevations are known, a map showing ground-water contours and flow directions can be prepared.

Vertical flow components can be determined by comparing water-level measurements for each of the three aquifers. The ground-water flow in the vertical direction is from the aquifer showing the highest water level (potentiometric level) into the unit showing the lowest water level.

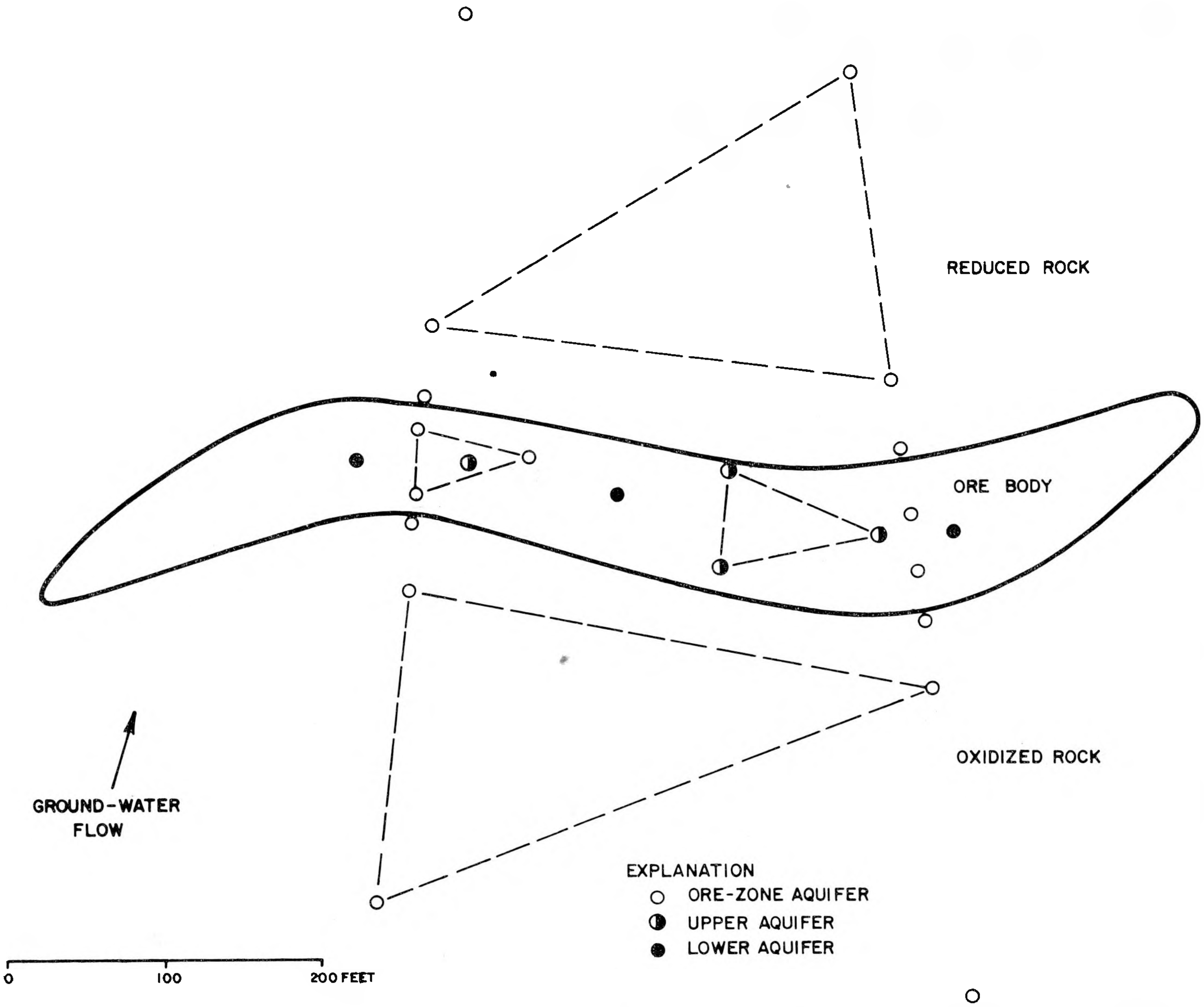

Figure 3.1. Location of observation wells used to collect pre-mining hydrogeologic and water-quality data at an in-situ leach mining site.

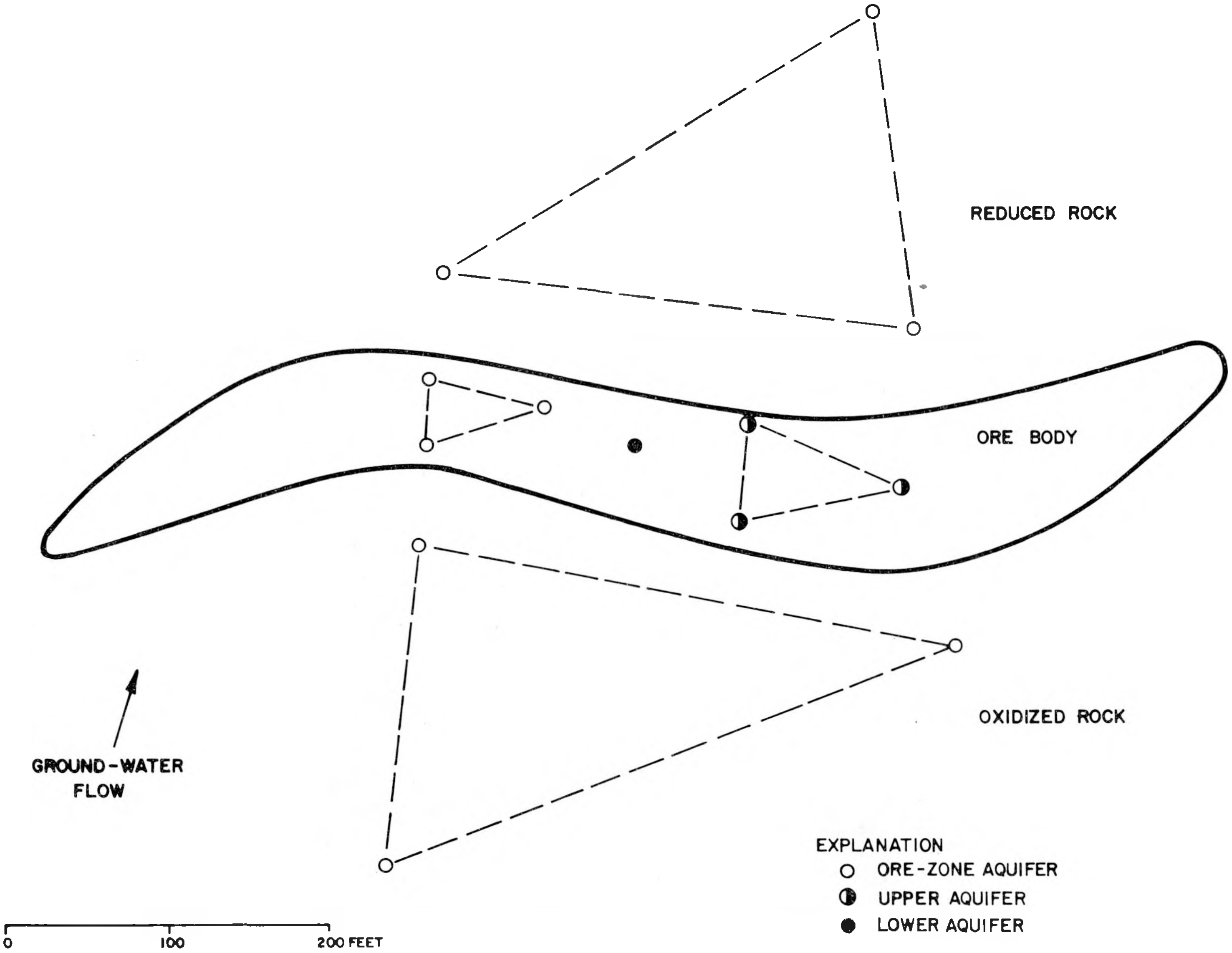

Figure 3.2. Location of observation wells used to collect pre-mining hydrogeologic data at an in-situ leach mining site.

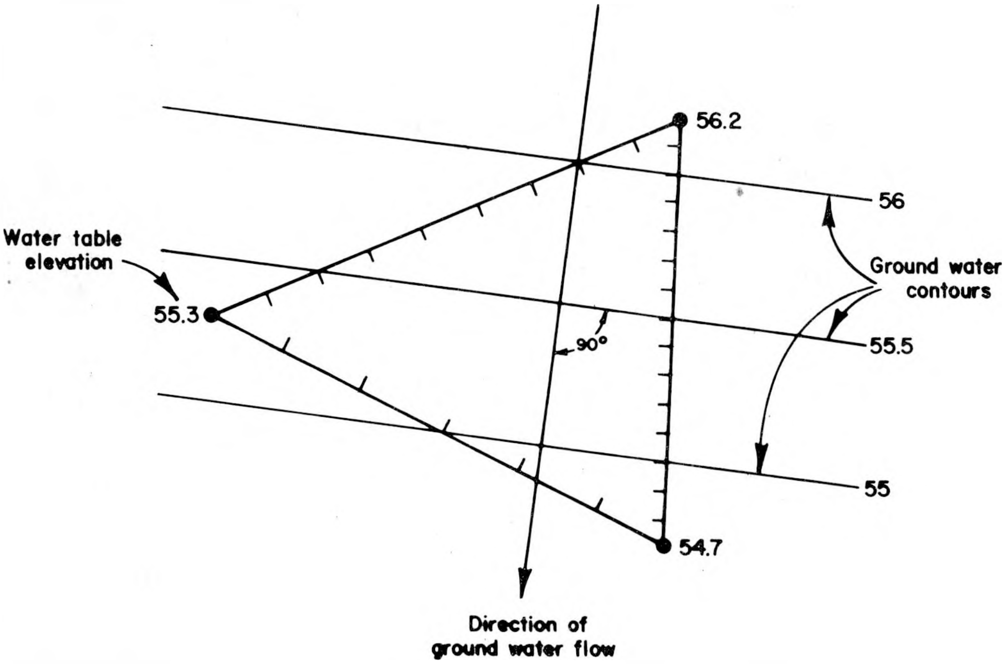

Figure 3.3. Graphic method to estimate ground-water contours and flow direction from water level readings in three wells.[1]

Water-level measurements in the 13 wells in the system should be made within a short period of time (preferably on the same day) to rule out water-level changes attributable to seasonal, daily, or barometric fluctuations. In most situations, pre-mining water-level measurements need be made only once, inasmuch as the natural ground-water flow pattern will not vary significantly over a short period of time, if at all. However, if pumping wells are located nearby, it would be desirable to repeat the measurements in the network, on perhaps a weekly or monthly basis, to ascertain whether radical shifts are taking place.

Hydraulic Properties

The observation wells installed to determine the flow regime of the ground-water system may also be used in an aquifer testing program (pump test). One of the wells installed in the ore body should be selected as the pumping well for the testing program. Results of the pump test will be used to determine (1) the capacity of the ore-zone aquifer to transmit water (transmissivity), (2) the storage coefficient of the ore-zone aquifer, (3) the permeability of the ore-zone aquifer, (4) the anisotropy of the ore-zone aquifer, and (5) the relative extent and capacity of the confining beds to transmit fluid.

The pumping well should be pumped for at least 24 hours at a constant rate at least equal to the bleed anticipated for the production scale leach operation. The water levels in all other wells should be observed and recorded during the pumping, either by means of continuous water-level recording instruments or by manual water-level measuring. Standard methods presented by Krauseman and De Ridder,[2] Lohman,[3] or Walton[4] and others may be used to determine the transmissivity, storage coefficient, anistropy, and permeability of the system.

The capacity of the confining bed to transmit fluid is defined by the response of observation wells in the aquifers above and below the ore-zone aquifer. Water-level change is not expected in these wells unless the confining bed has been artificially breached, has natural paths of higher permeability, or is not laterally extensive. The integrity of these confining beds is critical to the prevention of vertical excursions of lixiviant.

3.1.2.2 Baseline Water-Quality Data Collection

It is important to note that baseline water-quality, which is called the background water quality by many, refers to the natural water-quality conditions occurring in and around the uranium ore body prior to leach mining. Because NRC utilizes the information on baseline conditions to gauge aquifer contamination due to in-situ leach mining practices, it is necessary to develop a program to collect sufficient baseline information to cover any condition. The program outlined below for collection of baseline water-quality data is therefore particularly intensive, and NRC should continue to evaluate its usefulness as excursion and restoration programs are developed and modify the data-collection program accordingly.

Baseline water-quality levels must be determined not only for the common constituents of natural waters, but also for minor constituents, particularly trace and heavy metals, whose concentrations are likely to change as a result of chemical reactions initiated during leach mining. Although solubilities and theoretical equilibrium reactions under varying Eh and pH conditions can be determined for relatively simple compounds, it is not yet possible to adequately predict the effects of the mobilization, reprecipitation, and adsorption of trace metals in a complex ore body undergoing solution mining. Therefore, comprehensive chemical and radiochemical analyses of water samples obtained within the ore body and at locations away from the ore body should be made to determine pre-mining conditions. A list of water-quality parameters (Table 3.1) to be measured has been prepared, based on an evaluation of uranium-ore body mineralogy, EPA drinking water standards (Table 3.2), water-quality standards for agricultural uses (Table 3.3), and uranium leaching processes (lixiviants used).

An analysis of ore-zone aquifer mineralogy and the ground-water flow regime indicates that several different baseline water-quality conditions are present in different parts of the potential mining area. The major differences are in the: (1) oxidized rock areas, (2) the reduced rock areas, (3) the ore body, and (4) the transition zone immediately downgradient from the ore body (Figure 3.4). Data thus far supplied to NRC by mining companies do not reflect a recognition of these different water-quality zones.

For the purpose of this investigation, the water sampling system is designed to determine whether the inferred water-quality profile across the ore zone actually exists. This system may be modified to suit unique conditions. Figure 3.5 shows the 22 wells which will be used to collect baseline water-quality data. Two linear arrays consisting of eight wells each are completed in the ore-zone aquifer, and three wells each are installed in both the overlying and underlying aquifers. The ore-zone wells describe baseline water quality conditions within approximately 250 ft (76 m) on either side of the ore body. Although the two linear arrays will be adequate for most standard mining operations, it is suggested that there be one array for each 300 ft (100 m) of length of the mining well field. The wells used for sampling the other aquifers should be installed directly above and below the ore body, approximately every 100 ft (30 m) between the linear arrays.

For the determination of the baseline water quality conditions, it is suggested that two sets of samples be collected. The samples should be split and sent to different laboratories to varify the natural conditions. The sets of samples should be taken within a week or two of each other. Natural ground-water flow rates and recharge conditions suggest that additional sampling is not necessary as rapid or extensive quality variation would not be expected. If, however, mining is planned in an aquifer system that is essentially unconfined, seasonal water-quality changes could be expected and a more intensive sample collection program would be needed.

TABLE 3.1
BASELINE WATER-QUALITY PARAMETERS TO BE DETERMINED DURING PREMINING DATA COLLECTION

A. Trace and Minor Elements

Aluminum
Arsenic
Barium
Boron
Cadmium
Chromium
Cobalt
Copper
Fluoride
Iron
Lead
Manganese
Mercury
Molybdenum
Nickel
Radium 226
Selenium
Thorium 230
Uranium
Vanadium
Zinc

B. Common Constituents

Ammonium
Bicarbonate
Calcium
Carbonate
Chloride
Magnesium
Nitrate
Potassium
Sodium
Sulfate

C. Physical Parameters

Specific Conductivity[1]
Temperature[2]
pH[1]
Gross Alpha[3]
Gross Beta[3]
Appearance, color, odor[2]
Total Dissolved Solids[3]

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[1] Field and laboratory determination.

[2] Field only.

[3] Laboratory only.

TABLE 3.2
SELECTED EPA INTERIM PRIMARY AND PROPOSED SECONDARY DRINKING WATER STANDARDS[5,6)

Parameter	Maximum Level (mg/l) 1/
A. Interim Primary	
Arsenic	0.05
Barium	1.0
Cadmium	0.01
Chromium (VI)	0.05
Fluoride	1.4-2.4
Lead	0.05
Mercury	0.002
Nitrate (as N)	10
Selenium	0.01
Silver	0.05
Radium	5 pCi/l
Gross Alpha	15 pCi/l
Gross Beta	4 millirem/yr
Turbidity	1 TU
B. Secondary	
Chloride	250
Copper	1
Hydrogen Sulfide	0.05
Iron	0.3
Manganese	0.05
Sulfate	250
TDS	500
Zinc	5
Color	15 Color units
Corrosivity	Non-corrosive
Odor	3 Threshold odor number
pH	6.5-8.5

1/ Concentrations in milligrams per liter unless otherwise noted.

TABLE 3.3
EPA WATER-QUALITY CRITERIA FOR INDUSTRY AND IRRIGATION[7)]

Parameter	Irrigation (mg/l)[1/]	Industry (mg/l)
Alkalinity	-	40-500
Aluminum	1.0	0.01-5
Ammonia (as N)	-	0.1-0.7
Arsenic	1.0	-
Beryllium	0.5	-
Bicarbonate	-	48-600
Boron	0.75	-
Cadmium	0.005	-
Chloride	-	200-1,000
Chromium	5	-
Cobalt	0.2	-
Copper	0.2	0.01-0.5
Hardness (as $CaCO_3$)	-	100-850
Iron	-	0.01-1
Lead	5.0	-
Manganese	2.0	0.01-5
Magnesium	-	12-36
Molybdenum	0.005	-
Nickel	0.5	-
pH	-	5-10
Selenium	0.05	-
Silica	-	0.01-50
Sulfate	-	200-620
Total dissolved solids	5,000	1,000
Vanadium	10	-
Zinc	5	-

[1/] All constituents in mg/l except where otherwise noted.

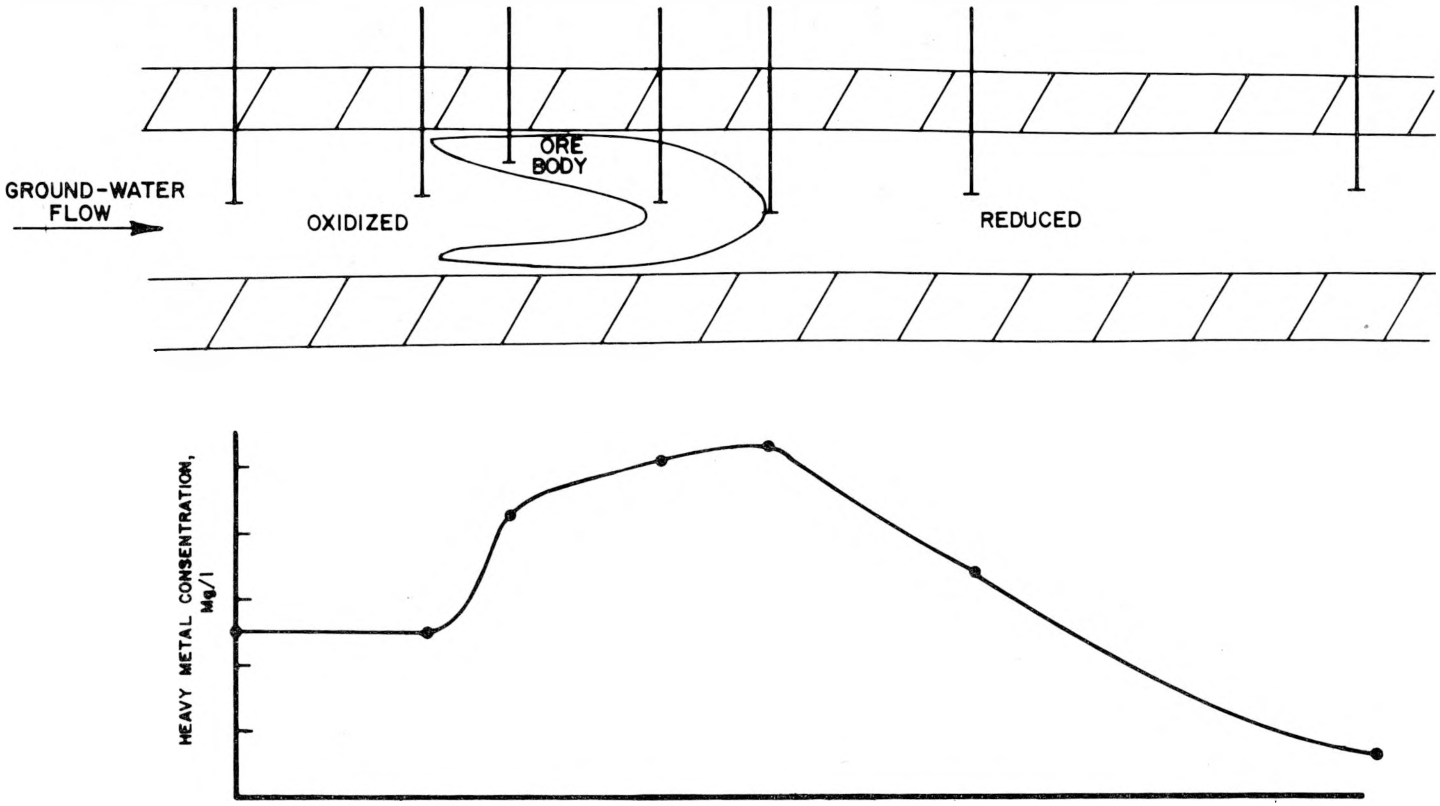

Figure 3.4. Cross section of an uranium-ore body showing the location of observation wells to collect water-quality samples, and the anticipated water-quality trend (for heavy metals) resulting from that data.

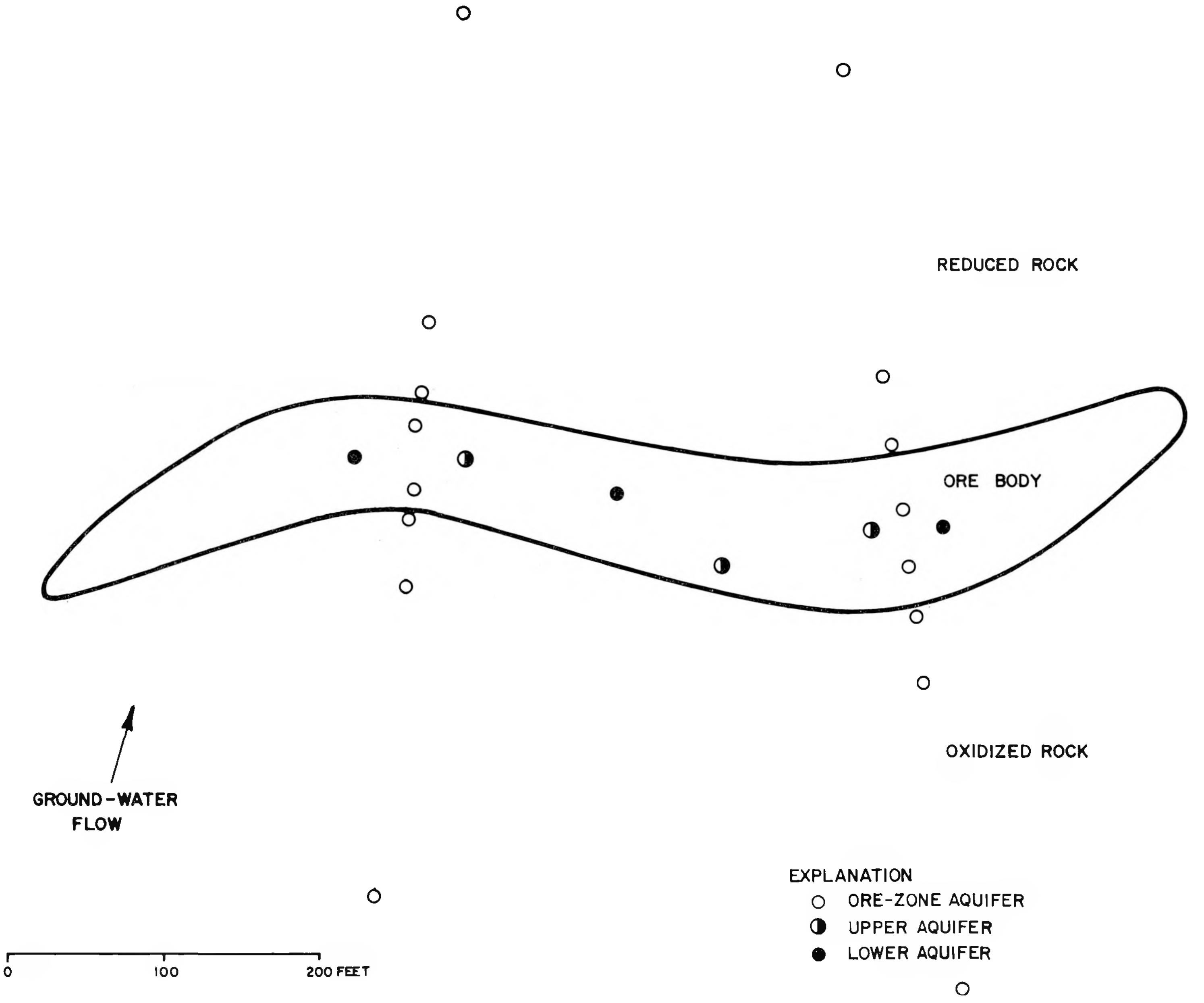

Figure 3.5. Location of observation wells used to collect pre-mining water-quality data at an in-situ leach mining site.

3.2 CRITERIA AND METHODOLOGY FOR MONITORING EXCURSIONS

3.2.1 The Excursion-Monitoring System

The excursion-monitoring system is designed to detect excursions of lixiviants into the ore-zone aquifer, outside the ore body itself, and into aquifers above and below the ore-zone aquifer. Where possible, the monitor wells installed to collect hydraulic and water-quality background data should be incorporated into the excursion-monitoring system.

The pre-mining aquifer test results and other data will be used to determine the method of monitoring the aquifers above and below the ore-zone aquifer. For example, if the aquifer test shows no evidence that an adjacent aquifer is susceptible to excursion from the ore-zone aquifer, the need to monitor the aquifers during mining is decreased. As a precaution, however, monitor wells should be constructed in whichever adjacent aquifer has a water level or potentiometric level that is lower than the water level in the ore-zone aquifer. If it is desired, monitor wells may also be constructed into any other water-bearing unit to provide an additional level of safety. At least three monitor wells should be used to monitor the non-ore-zone aquifer. These wells should be constructed above the ore body segment being mined.

If the pre-mining aquifer test shows a susceptibility to excursions between the ore zone and the aquifer above or below, no mining should take place until it is determined if the connection is natural or is the result of improper construction of wells. If the wells are not sealed opposite the confining beds, for example, the annular spaces around the wells may serve as direct pathways for the excursion of lixiviants. Such wells would of course have to be plugged or sealed to prevent such excursions. Because naturally leaky confining beds cannot be artificially sealed, the operation of the well field must be closely controlled to prevent vertical excursions.

To monitor excursions within the ore-zone aquifer, two tiers of monitor wells will be used. The wells are installed 50 ft (15 m) and 250 ft (76 m) outward from the outmost injection wells (Figure 3.6). The location of the monitor-well tiers corresponds to the locations used to collect pre-mining water-quality data; in fact, the pre-mining data collection wells should be used as excursion-monitor wells. In addition, the location of monitor wells has been selected to provide meaningful data for the water-level monitoring program outlined below. It is important also to note that the excursion-monitor well network is not greatly different than that being used or proposed by mining companies today.

3.2.2 Water-Level Monitoring

The procedure being followed at present to detect excursions of lixiviants is to collect water-quality samples from monitor wells located 200 to 400 ft (61 m to 122 m) from the well field. Generally, the samples are collected biweekly and analyzed for specific conductance, uranium,

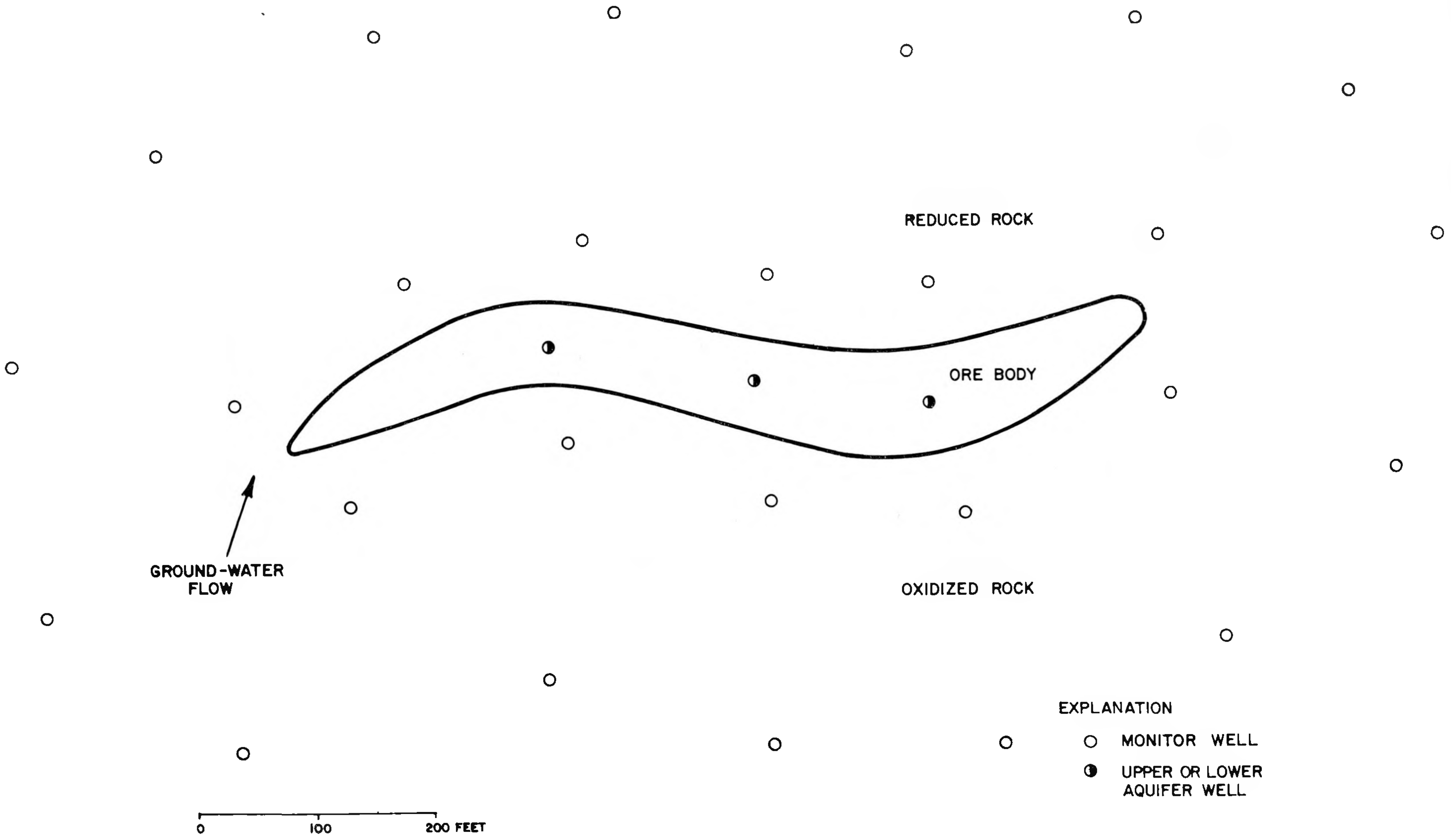

Figure 3.6. Location of wells in the excursion-monitor network at an in-situ leach mining site.

ammonia, and chloride or sulfate. However, the hydraulic properties of the ore-zone aquifer are such that the natural ground-water flow rate is very slow, and even though the addition of pressure provided by injection of lixiviants causes the flow rate to increase, it is not expected that the operational flow rate will exceed 1 ft (30 cm) per day. Thus, there is little likelihood of detecting water-quality changes in the widely spaced monitor wells unless a large volume of material has escaped over a long period of time.

On the other hand, pressure changes resulting from an imbalance in injection and withdrawal rates are transmitted instantaneously throughout the aquifer system and therefore should serve as a much more timely indicator of an excursion. Lixiviants will flow in response to the new hydraulic gradients developed, and if there is a complete reversal of gradient, the lixiviants will flow away from the well field as an excursion. The lixiviant will move a distance into the aquifer that is a function of the hydraulic properties of the aquifer and of the volume of excess fluid being put into the system during any increment of time.

Based on the foregoing, monitoring of water levels in a system of monitor wells should provide sufficient data to detect an excursion event immediately, long before any change in chemical quality could ever show up in samples from the monitor wells. Evidence to support this position has been documented at the Wyoming Minerals Corporation site in Bruni, Texas.[8]

All monitor wells in the ore-zone aquifer should be equipped with water-level recorders capable of easily recording water-level changes as small as 0.01 ft. When an evaluation of all water-level measurements shows that an outward hydraulic gradient has been established in part of the well field, it should be presumed that an excursion is taking place. Several days of continued reversed conditions (maybe 5 to 7 days) should be allowed before action is taken to assure that the problems are not the result of routine adjustments of the mining operation. To locate the cause of the excursion, water-level readings for the three wells surrounding the presumed excursion area should be analyzed (see Figure 3.3). Appropriate action, as described in Section 5, should be taken. It is important that someone knowledgable in hydrology be responsible for evaluation of the water-level data to confirm the excursion.

3.2.3 Water-Quality Monitoring

Water-quality monitoring will be used as a backup indicator to assure that the water-level monitoring program provides adequate detection and early warning of lateral excursions, and will be the only indicator used to monitor vertical excursions. Any program to monitor water quality should be based on a "fingerprint" of the excursion. Because relatively simple chemical compounds are used as lixiviants, ground-water degradation will be demonstrated by increased concentrations of the common cations and anions of the lixiviant. Determination of the electrical conductivity of the fluid in a monitor well, which is a measure of the TDS content (major common cations and anions), should provide an adequate fingerprint to monitor excursions.

Biweekly electrical conductivity readings are to be made in all wells in the excursion monitoring system, by lowering a conductivty probe into the monitor well to position the probe approximately one-third of the way opposite the length of the well screen or open hole above the bottom of the hole. The conductivity should be read at that depth and recorded. When the probe is retrieved, it should be rinsed with distilled water before being used in other wells.

Natural water quality normally will vary within rather narrow ranges, although there also may be instances where large natural changes in conductivity may be seen. It is therefore necessary to set criteria which will denote a possible excursion. Several possible alternatives exist to define excursions. Based on baseline conditions, excursion criteria can be set with respect to the average of the specific conductivity readings or with respect to the high naturally occurring value. Excursion would then be indicated if the criteria were exceeded by a pre-defined amount. If the mean condition is used, it may be logical to require a conductivity increase of at least one standard deviation; if the high naturally occurring value is used, a percent increase above this value might be set. Current practice in Texas considers an excursion to be indicated if the conductivity increases (1) 30 percent above the mean baseline condition within a short period of monitoring or (2) 15 percent above the mean baseline condition over a protracted monitoring period.

To differentiate between normal water-quality changes and excursion events, as may be indicated by conductivity readings, water samples should be collected and analyzed to determine the concentrations of the major cations and anions, including calcium, sodium, magnesium, potassium, chloride, sulfate, and carbonate/bicarbonate. Results should be plotted graphically on bar graphs, vectors, or Stiff diagrams and compared with pre-mining conditions (see Figure 5.1). Departures from background concentrations of the common ionic constituents will confirm the excursion event. Samples should be collected daily until the excursion is reversed.

Although it is current practice to monitor such water-quality parameters as uranium, arsenic, selenium, or ammonia, it is felt that these parameters are not good indicators for an excursion monitoring program. These materials are removed from solution in the ground water within a very short distance of the well field as a result of oxidation/reduction reactions, precipitation, or sorption and there is little reason to believe that they will persist in solution long enough to be detected in samples from distant monitor wells (See Section 5).

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4. DESIGN AND INSTALLATION OF THE MONITOR-WELL NETWORKS

4.1 MONITOR-WELL DESIGN

The monitor-well system, as described in the preceding section of this report, must be designed to function satisfactorily throughout the period of its use, employing materials and methods of construction which in themselves do not offer a possibility of contributing to erroneous measurements. Moreover, the system must be designed to conform with regulatory standards imposed by State or other Federal regulatory agencies.

4.1.1 Casing

Material normally used for monitor-well casing is either metal or plastic. The possibility that chemical reactions may take place between the casing and the mineral constituents in the water affects the choice of the casing material to be used in the monitor wells. For example, iron oxide in steel-cased wells will adsorb trace and heavy metals dissolved in the ground water, so that in the baseline water sampling program, which seeks to determine the concentration of trace metals, casing must be used that is inert to these metals, such as PVC or fiberglass. Use of PVC or fiberglass in wells over 500 ft (152 m) deep or where high pressure cementing techniques are used is not recommended because casing collapse can be expected.

The casing should have an inside diameter of 4 in (10.2 cm) or larger, to accommodate pumps of sufficient size to evacuate the casing to obtain water samples. Pumping by air lift, which requires smaller casing, is not recommended as some constituents to be analyzed are susceptible to aeration. The 4-in casing will also accommodate a continuous water-level recorder (3 in [7.6 cm] diameter float) and the conductivity probe.

4.1.2 Bottom Hole Completion

The method used to complete the monitor well is determined by the type of material penetrated and its susceptibility to collapse. Wells completed into indurated sands can be left as an open hole through the sampling horizon without fear of collapse; however, it is necessary to use some type of casing or screening in zones that are less stable. The screening material should be PVC or fiberglass. An artificial gravel pack should be placed around the screen to allow free water movement into the well while preventing sand from entering. Evaluation of the available geologic data will indicate the bottom-hole completion method to be used at any particular site.

4.1.3 Backfilling and Sealing

The annular space between the casing and the side of the borehole above the open portion of the well should be backfilled with a sealant to the ground surface. Proper backfilling isolates the screened formation against vertical migration of water from the surface or from other formations, and also provides support for the casing. Leakage caused by head differentials between formations in an improperly backfilled well may result in misleading water-level readings.

Cement grout should be used for the monitor wells. The grout should be placed by pressure cementing or tremie methods.

4.1.4 Developing Monitoring Wells

When the well is completed, it must be developed by pumping and/or surging until production of essentially sediment-free water is assured for the life of the well. One technique of surging involves the use of a surge block or plunger in the well to create a vacuum on the upstroke and positive pressure on the downstroke. A similar effect may be obtained by alternately turning a suction pump on and off or alternately increasing and decreasing the discharge. All fine-grained materials brought into the well during development should be removed.

4.1.5 Costs

Five wells meeting the basic design criteria discussed above are shown in Figures 4.1 through 4.5. The wells are completed to depths of 150 ft (45.5 m), 400 ft (121 m), and 1,500 ft (455 m), typical of the range of depths expected to be needed during a monitoring program. The 150-ft and 400-ft wells are constructed using PVC casing; the 1,500-ft well uses black steel casing. Construction methods will vary with each drilling contractor, but special care should be taken to assure proper completion.

Unit well costs, including those for the drilling of the hole, installing casing and screen, cementing, emplacing of gravel, and mobilization/demobilization of the drill rig and crew, are presented in Table 4.1. In addition, it will be necessary to conduct downhole testing to assure that the well has been completed in the proper zone for monitoring. Due to the lenticularity of the formations involved, this could be the most critical phase of the project. Table 4.2 presents the total construction cost for each of the five wells.

In addition, allowance must be made for the services of a geologist/hydrologist to assure proper completion of the wells. Other testing may be required such as coring or running of additional logs, which will increase the cost of each monitor well.

4.2 SAMPLING OF MONITOR WELLS

Stagnant fluid in the well casing must be evacuated prior to any sample collection to prevent contamination of the sample caused by mixing of fluids in the well. The well casing need not be evacuated to make conductivity readings because there is little probability that this activity will result in the mixing of bore-hole fluids. An accurate measurement of the static water level in the well should be made prior

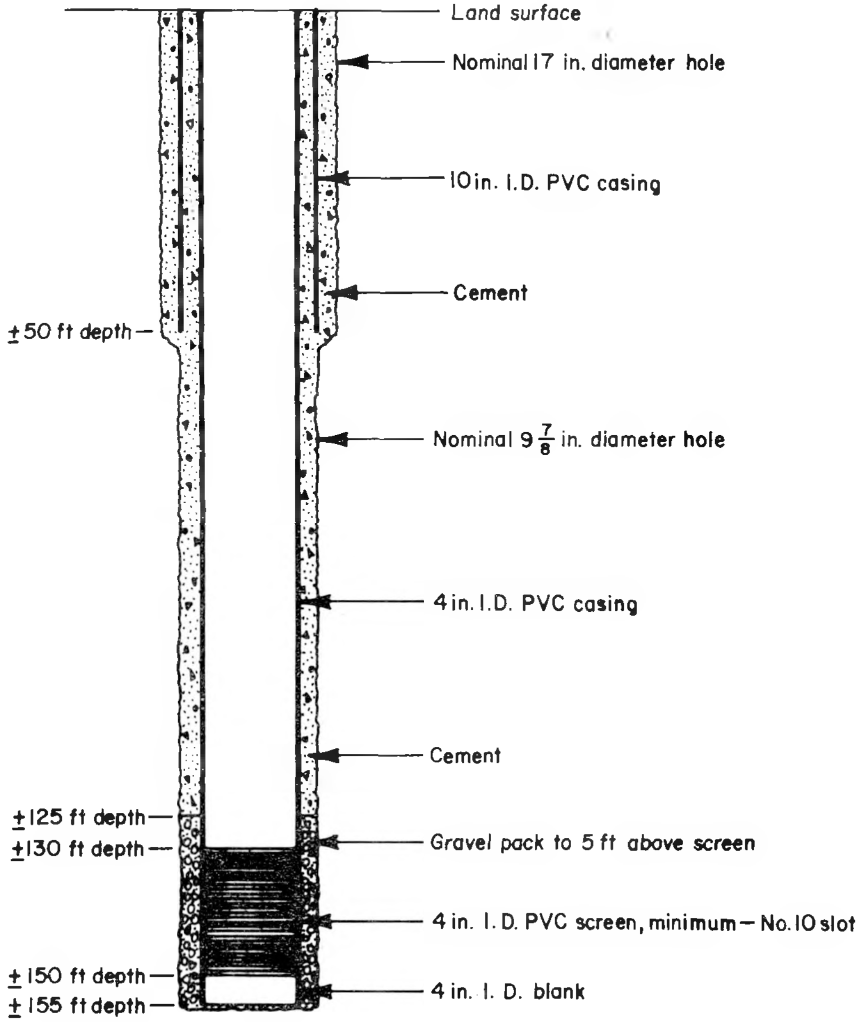

Figure 4.1. Diagram of 150-foot monitor well: screened completion.

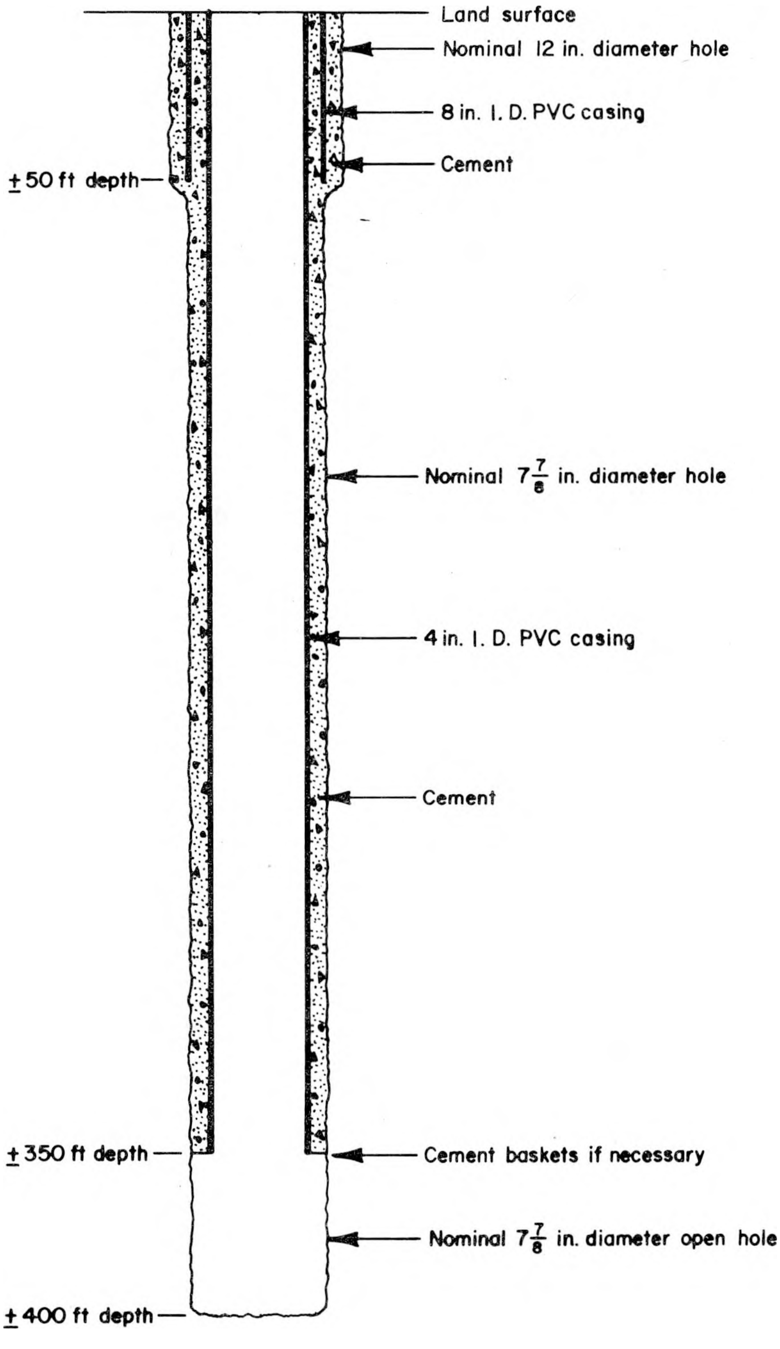

Figure 4.2. Diagram of 400-foot monitor well: open-hole completion.

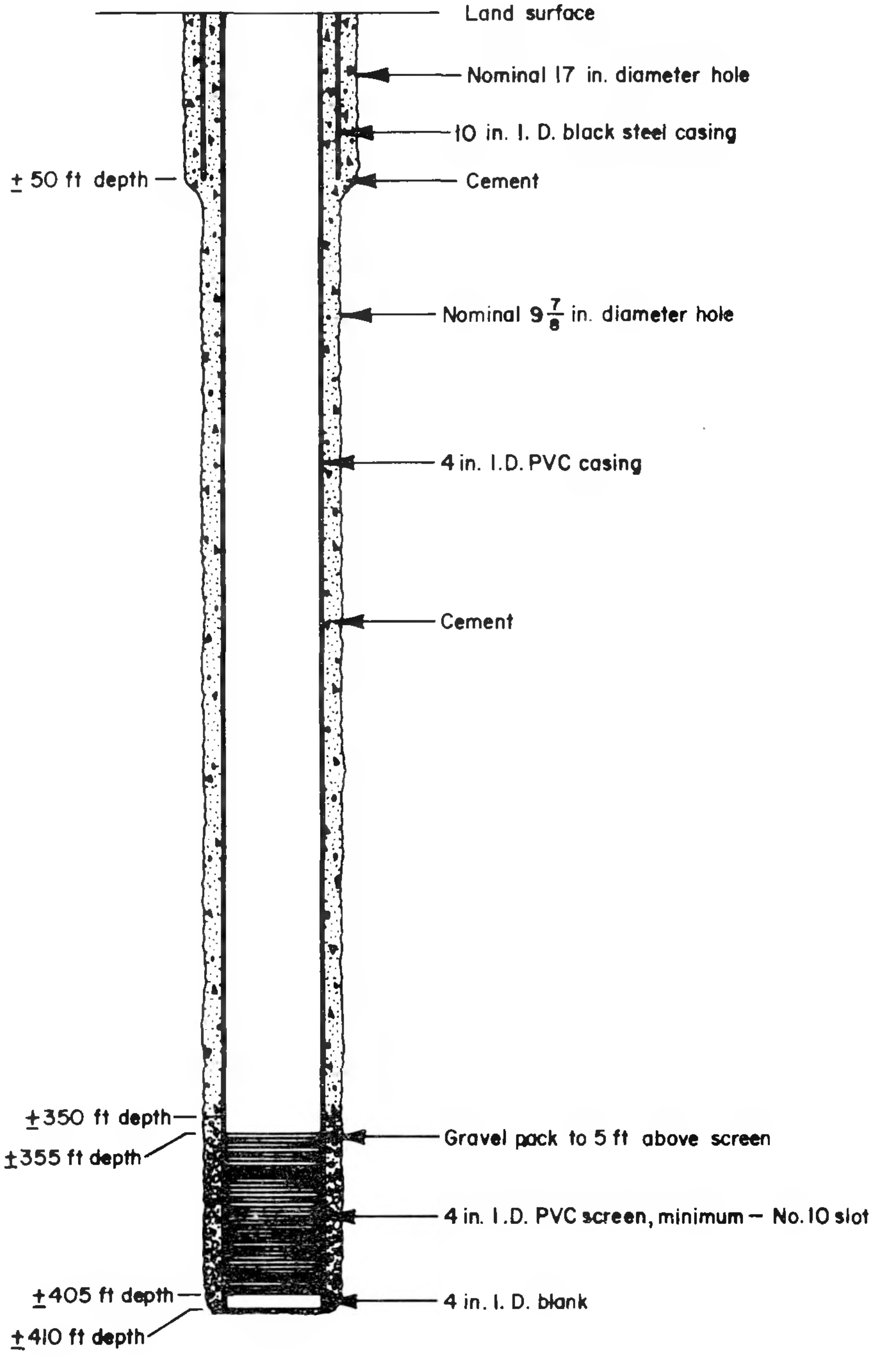

Figure 4.3. Diagram of 400-foot monitor well: screened completion.

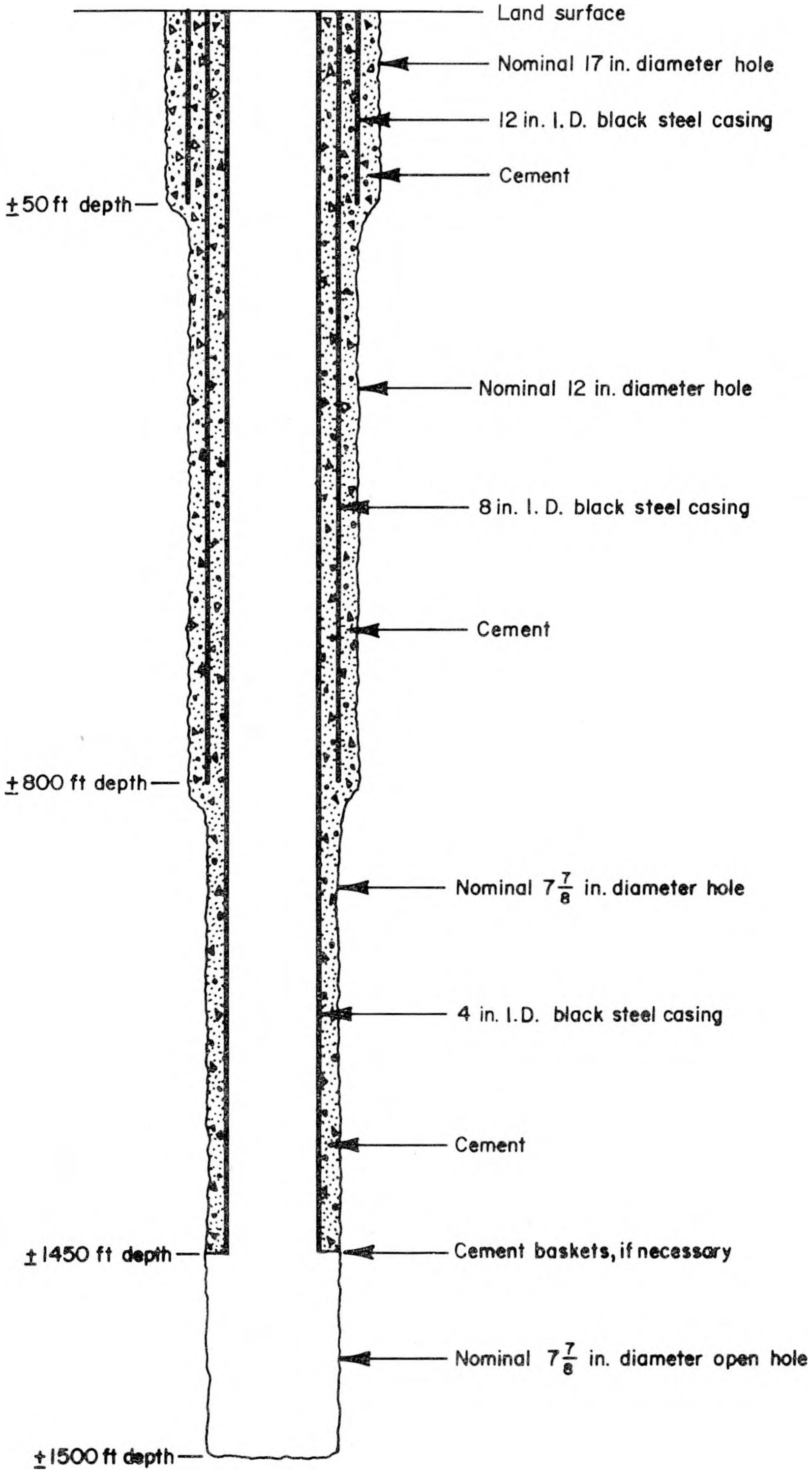

Figure 4.4. Diagram of a 1,500-foot monitor well: open-hole completion.

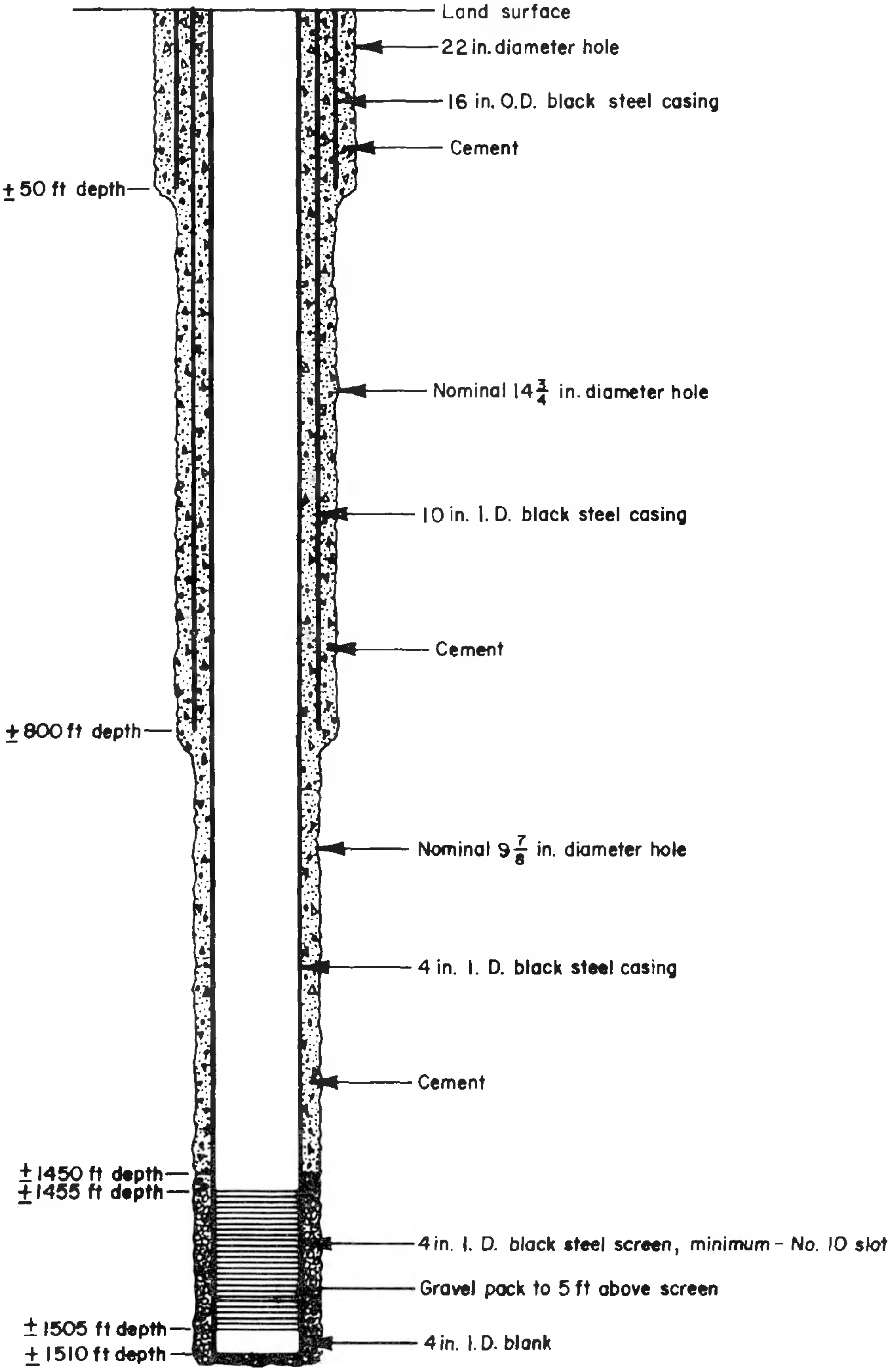

Figure 4.5. Diagram of a 1,500-foot monitor well: screened completion.

TABLE 4.1
UNIT COSTS: MONITOR WELL CONSTRUCTION
(1978 Dollars)

Cost Items	Unit Cost
Drilling	
22 in.	$ 36.00/ft
17 in. (diameter)	24.00/ft
14-3/4 in.	24.00/ft
12 in.	23.00/ft
9-7/8 in.	18.00/ft
7-7/8 in.	15.00/ft
Casing	
16 in.	22.00/ft
12 in. (diameter)	15.00/ft
10 in.	12.00/ft
8 in.	9.00/ft
4 in.	6.00/ft
Cement Baskets	180.00/unit
Screen (4 in. diameter)	43.00/ft
Cement	113.00/yd^3
Gravel	75.00/yd^3
Mobilization	1,200.00/hole
Logs (Resistivity and Gamma)	2,400.00/hole

TABLE 4.2
TOTAL COST OF IN-SITU LEACH MINING MONITOR WELLS

Cost Items	Depth of well in feet				
	Screened			Open Hole	
	155	400	1,500	400	1,500
Drilling	$ 3,990	$ 8,580	$48,180	$ 7,150	$42,100
Casing	1,410	2,760	19,560	2,550	16,680
Screen	860	2,150	2,150	-	-
Cement	373	798	4,565	460	3,170
Gravel	34	75	100	-	-
Cement Baskets	-	-	-	180	180
Subtotal:	$ 6,667	$14,363	$74,555	$10,340	$62,130
Mobilization	1,200	1,200	1,200	1,200	1,200
Logs	2,400	2,400	2,400	2,400	2,400
Total:	$10,267	$17,963	$78,155	$13,940	$65,730

to removal of water, in order to compute the volume of stagnant water to be evacuated. This volume of water should be pumped to waste prior to sampling. Dewatering may be accomplished by bailing or pumping.

4.2.1 Water Sample Withdrawal

Pumps or bailers may be used to collect water samples. Because of the low yields of the aquifers to be sampled and the large depth to water in the principal uranium-leaching areas, electric submersible pumps may prove to be the most practical sampling devices.

The monitoring program necessitates the use of portable pumping devices for well sampling because samples will not be collected frequently enough to justify the expense of equipping all wells with pumps. Particular care should be taken to clean the pump and the sampling equipment to prevent the possibility of getting erroneous readings due to water left over from prior sampling operations. The use of a self-priming pump can prevent such cross-contamination. If the well has a very low yield, the combined use of pumping and bailing equipment may be the only practical way to secure a water sample.

4.2.2 Sample Collection and Field Analysis

After evacuating the stagnant fluid from the casing and allowing the water level in the well to recover, a sample is collected and placed in an appropriate container for transport. Each container should be labeled prior to or immediately after collecting the sample. The label should include the site designation, monitoring well number, sampling date and time, any treatment applied (preservatives, filtration, etc.), and a list of the specific constituents to be included in the analysis.

Several other types of measurements should be made during sampling to provide useful data. Temperature measurements should be made as the water leaves the well. Specific conductance (related to total dissolved solids concentration) and pH can be determined easily with portable battery-operated instruments.

The pH of ground water frequently changes after the water sample contacts the atmosphere. Gas exchange between water and the atmosphere induces a change in oxidation-reduction (redox) potential that alters the water chemistry. Therefore, pH should be measured as soon as possible after the water sample is collected. The physical appearance, odor, and color of the water sample should be noted at the time of collection.

4.2.3 Settling and Filtration of Water Samples

Ions adsorbed on silt, clay, and organic particles suspended in water samples may go into solution if certain preservatives are added directly to the sample. In the chemical analysis, this can result in higher concentrations of these ions and not reflect the true water quality. Settling and filtration are the two primary field methods for reducing or eliminating suspended matter. The method(s) selected depends upon the particle size of the suspended matter and the specific analyses indicated for the sample.

Sand and silt-sized particles settle out fairly rapidly under the influence of gravity. Clay-sized particles, colloidal precipitates, and other smaller particles will remain suspended for much longer periods of time, in which case filtration in the field should include gravity filtration and vacuum filtration.

4.2.4 Preservation of Water Samples

Water samples should be analyzed as soon as possible to assure representative water-quality measurements. Because the laboratory may be far removed from the well location, sample preservation is important to insure that the chemical quality of the formation water remains unchanged until the sample can be analyzed. During transit of water samples, exposure to the atmosphere and changes in temperature can lead to changes in pH and subsequent alteration of the original ionic balance in solution.

Volatilization of organics, oxidation of heavy metals, and many other chemical as well as biological reactions can occur, which may ultimately affect the concentration of the constituents present at the time of analysis. Storage at low temperature (4°C) is perhaps the best way to preserve samples. Chemical preservatives for a given constituent should be chosen with regard to potential interference with other determinations that are to be made. Because interference occurs, as many as six or seven bottles, each treated with preservatives for various special groups of chemical constituents, may be necessary to contain a sufficient sample volume for a comprehensive analysis of water from one source. Table 4.3 provides information as to the specific preservation methods to be used for each of the parameters to be sampled.

EPA, USGS, and APHA standard methods for laboratory analysis[1,2,3] of all parameters to be evaluated are available for use and should be adhered to unless some alternative method has been approved by NRC. All have been shown to be highly reliable and legally acceptable.

4.2.5 Monitoring Costs

4.2.5.1 Water-Level Recorders

Depending on the size of the ore body to be monitored, several dozen recorders may be needed. Recorders are designed to meet individual conditions; consequently, prices are variable. Table 4.4 presents the unit cost of materials needed to custom fit a recorder. A recorder for a monitoring well with a depth to water of 100 ft (30 m) is estimated to cost approximately $836.

TABLE 4.3
SAMPLE SIZE AND PRESERVATION TECHNIQUES FOR STANDARD ANALYSIS[1,2,3)

Measurement	Vol. Req. (ml)	Container	Preservative	Holding Time[1/]
Ammonia	400	P,G[2/]	Cool, 4°C H_2SO_4 to pH<2	24 Hrs.[3/]
Arsenic	100	P,G	HNO_3 to pH<2	6 Mos.
Barium	200	G	HNO_3 to pH<2	6 Mos.
Boron	100	P,G[4/]	Cool, 4°C	7 Days
Cadmium	200	G	HNO_3 to pH<2	6 Mos.
Calcium	200	P,G	Filter on Site, HNO_3 to pH<2	6 Mos.
Carbonate/Bicarbonate Alkalinity	100	P,G	Cool, 4°C	24 Hrs.
Chloride	50	P,G	None Required	7 Days
Chromium	200	G	Cool, 4°C	3 Days
Copper	200	G	HNO_3 to pH<2	6 Mos.
Fluoride	300	P,G	Cool, 4°C	7 Days
Gross Alpha and Gross Beta	100	P,G	None Required	7 Days
Iron	200	P,G	Filter on Site, HNO_3 to pH<2	6 Mos.
Lead	200	P,G	HNO_3 to pH<2	6 Mos.
Magnesium	200	G	Filter on Site, HNO_3 to pH<2	6 Mos.
Manganese	200	P,G	Cool, 4°C	24 Hrs.
Mercury	100	P,G	Filter HNO_3 to pH<2	38 Days (G) 13 Days (Hard P)

TABLE 4.3 (Continued)

Measurement	Vol. Req. (ml)	Container	Preservative	Holding Time[1]
Radium-226	200	P,G	None Required	7 Days
Selenium	50	P,G	HNO_3 to pH<2	6 Mos.
Silica	50	P only	Cool, 4°C	7 Days
Silver	200	P,G	HNO_3 to pH<2	6 Mos.
Sodium	200	P	HNO_3 to pH<2	6 Mos.
Specific Conductance	100	P,G	Cool, 4°C	24 Hrs.[5]
Sulfate	50	P,G	Cool, 4°C	7 Days
Total Dissolved Solids	100	P,G	Cool, 4°C	7 Days
Temperature	1,000	P,G	Determine on Site	No Holding
Uranium	200	P,G	None Required	7 Days
Vanadium	200	P,G	HNO_3 to pH<2	6 Mos.
Zinc	200	P,G	HNO_3 to pH<2	6 Mos.

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[1] It has been shown that samples properly preserved may be held for extended periods beyond the recommended holding time.

[2] Plastic or glass.

[3] Mercuric chloride may be used as an alternate preservative at a concentration of 40 mg/l, especially if a longer holding time is required. However, the use of mercuric chloride is discouraged whenever possible.

[4] Use boron free glass.

[5] If the sample is stabilized by cooling, it should be warmed to 25°C for reading, or temperature correction made and results reported at 25°C.

TABLE 4.4
UNIT COSTS: WATER-LEVEL RECORDER
(1978 Dollars)

Cost Item	Cost/Unit
Basic Recorder[1/]	$315
Clock (30-day battery driven)	200
Float Pulley (10 in. circumference)	19
Float (3 in. circumference)	21
Float Cable (200 ft)	120
Gears (1:1)	26
Charts (Box of 54)	10
Recorder Shelter	125
Total	$836

[1/] Stevens Type F-11 Recorder.

4.2.5.2 Water-Quality Analysis

Table 4.5 provides a range of costs for different sets of water-quality analyses that may be made during the course of the monitoring program. The costs shown in this table are based on a single sample analysis only and do not include collection or transportation charges. Discounts of as much as 50 percent may be given for multiple analyses. Comprehensive analyses will only be necessary for the wells used in the pre-mining data collection program (22 wells total) unless NRC determines that additional such data are needed during other phases of the in-situ uranium leaching operation.

During well field operation, a specific-conductivity meter will be used. The meter will have to be equipped with a windlass device to raise and lower the conductivity probe. The price of this specially designed conductivity meter is estimated to be $931 (including the meter @ $413, the probe @ $43, the cable @ $400 (400 ft), and the windlass @ $75).

TABLE 4.5
COST OF WATER QUALITY ANALYSES
(1978 Dollars)

Major Inorganic Chemicals

- Iron
- Magnesium
- Chloride
- Sulfate
- Carbonate
- Bicarbonate
- Sodium
- Calcium
- Potassium
- pH
- Electrical Conductivity

Group Rate: $53.50 to $107.00

Comprehensive Analysis

- Uranium
- Vanadium
- Copper
- Selenium
- Molybdenum
- Arsenic
- Radium 226
- Lead
- Iron
- Manganese
- Chromium
- Nickel
- Cobalt
- Cadmium
- Mercury
- Zinc
- Barium
- Fluoride
- Boron
- Magnesium
- Chloride
- Sulfate
- Carbonate
- Bicarbonate
- Nitrate
- Ammonia
- Sodium
- Calcium
- Potassium
- Silica
- Gross Alpha
- Gross Beta
- Total Dissolved Solids
- pH
- Electrical Conductivity

Group Rate: $206.00 to $447.00

Radiochemical

- Gross Alpha
- Gross Beta
- Radium 226
- Uranium

Group Rate: $41.00 to $94.00

REFERENCES

1. U.S. Environmental Protection Agency. Methods for Chemical Analysis of Water and Wastes. EPA-625/6-74-003.

2. U.S. Geological Survey. Techniques of Water-Resource Investigations of the United States Geological Survey. Book 1, Chapter D2, Book 5, Chapter A1, and Book 5, Chapter A5, 1976, 1970, and 1977.

3. American Public Health Association. Standard Methods for the Examination of Water and Wastewater. 13th Edition, 1971.

5. METHODS APPLICABLE TO EXCURSION CONTROL

5.1 LATERAL EXCURSION

Lateral excursions in the ore-zone aquifer will occur only when the hydraulic gradient is directed away from the well field. If flow away from the well field is relatively uniform, it should take a considerable period of time for an excursion to reach monitor wells that now are usually placed 200 to 400 ft (61 m to 122 m) from the well field. Geologic conditions favoring unusually rapid excursions are:

1. The presence of a zone of high permeability relative to the sandstone as a whole that would allow perferred movement along a small portion of the sandstone.

2. The presence of fractures along which preferred movement could occur.

3. Completion of an injection well or wells in a sandstone unit that extends only a short distance away from the well field and is thus not penetrated by a production well.

The present practice of using water-quality data only as the indicator of excursion events is probably the reason why significant lateral excursions have been able to develop undetected in some field operations.

The monitoring program developed for this study (Section 3) recommends water-level or hydraulic monitoring as the preferred indicator to provide early detection of developing excursion. Even though a well field may be pumped at a net inflow rate, the flow pattern associated with any one well is generally unknown. Also, metering devices are not accurate enough to maintain a total leach field production rate that is reported to be 1 to 2 percent above the total leach field injection rate.

If the system is properly monitored, it should be possible to reverse an excursion of lixiviant in a short period of time without causing environmental problems. If an excursion is verified, action should be taken to adjust the well-field operation to restore the desired inward hydraulic gradient. The principal corrective actions are: over-production, reordering the pumping balance of the well field, or reducing or stopping injection. These methods may be applied locally to a few wells within a cell, to the entire cell, to several cells, or to the entire well field as the situation dictates.

If the lateral excursion is extensive, corrective measures are similar to those used for restoration (Section 6). The only significant difference between correction of excursions and restoration is that the main body of a lateral excursion may not have wells centered within or close to it. Injection into a well that is within the body of the excursion, but outside of any production wells, could drive the contaminated water away from the well field rather than towards it, making it difficult to recover the contaminated water by pumping of the well field.

An excellent example from Texas of the development and correction of a lateral excursion shows that the excursion to three monitor wells was caused by an injection-production imbalance.[1] Excess injection in parts of the mining area established a hydraulic gradient away from the well field that led to the movement of well-field water to adjacent monitor wells. The behavior could be directly related to rises in water levels in the monitor wells. It is probable that, had action been taken to restore the injection-production balance when water levels in the monitor wells began to rise, the excursion would not have reached the monitor wells. Background water quality was apparently restored successfully at the affected monitor wells when the hydraulic system was rebalanced (Figure 5.1).

Extensive water sampling during the excursion provided an excellent opportunity to study the pattern of water-quality change that accompanied the excursion (Table 5.1). The best indicator of the excursion was an increase in total dissolved solids attributable to large changes in calcium, magnesium, sodium, chloride, and sulfate. In spite of the fact that ammonium bicarbonate was being injected and uranium mobilized, none of these three parameters was found to be an indicator of the excursion, probably because the ammonium was adsorbed, the bicarbonate consumed, and the uranium reprecipitated before reaching the monitor well.

The water-quality results also indicate that the surrounding ground water was impaired only as a result of the increase in total dissolved solids. Such an increase may or may not affect the usability of the water. No hazardous or toxic material was detected in concentrations that would impair use of the water as a drinking-water supply.

5.2 VERTICAL EXCURSION

A vertical excursion takes place when leach field fluids move into aquifers above or below the ore-zone aquifer, as a result of:

1. Vertical leakage upward around the casing of an improperly cemented operating or monitoring well or through the casing and cement of a damaged well.
2. Vertical leakage upward and/or downward through improperly plugged exploration boreholes.
3. Vertical leakage upward and/or downward through semi-permeable confining beds.

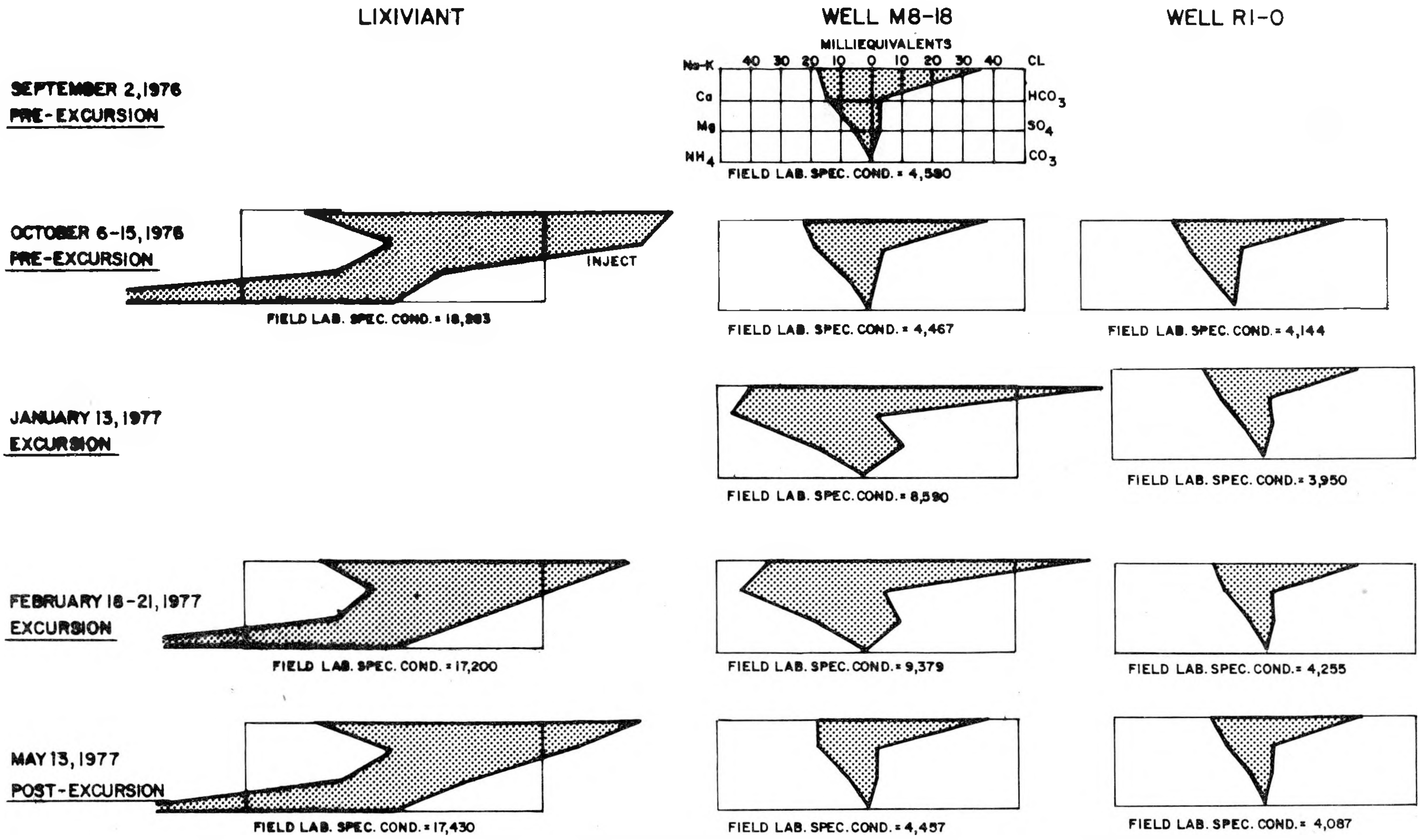

Figure 5.1. Graphic plot (Stiff Diagram) of a lateral excursion confirmed by water-quality readings. Included are plots for the lixiviant, the affected monitor well, and an unaffected well.[1]

TABLE 5.1

APPARENT CHANGE OF SELECTED WATER-QUALITY PARAMETERS RESULTING FROM A CONFIRMED EXCURSION[1)]

Parameter	Apparent Change
Specific Conductance	Large Increase
Calcium	Large Increase
Magnesium	Moderate to Large Increase
Sodium	Moderate Increase
Chloride	Large Increase
Sulfate	Large Increase
Potassium	Small Increase
Boron	Moderate to Large Increase
Manganese	Large Increase
Radium	Inconsistent Laboratory Results
Bicarbonate	Very Small Increase
Fluoride	No Measurable Change
Ammonia	No Measurable Change
Arsenic	Inconsistent Laboratory Results
Barium	Inconsistent Laboratory Results
Cadmium	No Measurable Change
Chromium	No Measurable Change
Copper	No Measurable Change
Iron	Inconsistent Laboratory Results
Mercury	No Measurable Change
Lead	Inconsistent Laboratory Results
Molybdenum	No Measurable Change
Nickel	No Measurable Change
Selenium	No Measurable Change
Silver	No Measurable Change
Uranium	No Measurable Change
Vanadium	No Measurable Change
Zinc	No Measurable Change
Nitrate	No Measurable Change

4. Vertical leakage upward and/or downward along natural fractures in confining beds.

5. Vertical leakage upward along induced hydraulic fractures.

Monitoring for vertical excursions is best achieved by pumping from a well in an adjacent aquifer so that the water-level cone of depression around the well extends to the boundaries of the field. With such monitoring, any significant vertical leakage of well-field water will be drawn to the monitor well where it will be detected by a water-quality change.

Determining the precise source and the path of a vertical excursion may be difficult, in that the monitor well can only detect a change in chemical quality and not the direction from the monitor well to the point where the excursion is taking place. At best, it is only possible to conclude that the leakage is the result of two or three possible causes. For example, it is seldom possible to distinguish, unequivocally, between leakage from an injection well and leakage through an improperly plugged exploration hole.

If the source of vertical excursion can be determined, several elimination or control actions can be used (Table 5.2). After the source of vertical excursion has been eliminated or controlled, action can be taken to remove or immobilize the contaminants introduced during the excursion. Methods available are the same as those discussed for restoration. The difficulty in the case of vertical excursions is that the wells needed for pumping or pumping and injection in order to control the excursion are not in place in the affected aquifer and would have to be constructed, unless one or more of the monitor wells could be converted to that use.

TABLE 5.2
POTENTIAL ACTIONS TO CONTROL VERTICAL EXCURSIONS

Source	Action
When source of vertical excursion can be determined:	
Improperly cemented casing	Remedial cementing
A well whose casing has failed	Plug and abandon
Semi-permeable or naturally fractured confining beds	Reduce operational pressures so that little or no outward hydraulic gradient exists across the confining beds
Artifically fractured confining beds	Keep injection pressures below fracture pressure
When source of vertical excursion cannot be determined:	
	Maintaining injection pressures below the natural pressures in the vertically adjacent aquifers
	Abandonment of the field or that portion of the field in which the vertical excursion has developed

REFERENCES

1. Guyton, W.F. and Associates. M8-13 Excursion, Bruni Mine Site, June, 1977.

6. METHODS OF AQUIFER RESTORATION

As used here, restoration means the reduction of the concentrations of dissolved minerals, within the leaching field and in adjacent affected portions of the aquifer, to an acceptable level, based on regulatory considerations. Several techniques are being used or have been proposed to achieve restoration. Thus far, however, efforts have been limited to pilot-scale projects. Experience and consideration of geochemical and geological principles indicate that restoration of all elements and parameters to baseline levels will be very difficult, if not impossible. However, restoration based on water use, appears to be possible.

6.1 GEOCHEMISTRY OF AQUIFER RESTORATION

In-situ leach mining takes place in an environment of complex mineralogy. All of the common trace elements associated with the ore body are susceptible to solubilization, which is likely to occur as a result of oxidation, complexation, or replacement reactions under favorable chemical conditions. The major elements, such as sodium, calcium, magnesium, and iron can be put into solution by common dissolution or replacement reactions or ion-exchange reactions brought about by direct contact of the host rock minerals with injected lixiviant agents, or by contact with chemical agents formed within the ore body during leaching.

The mobility of an element in the in-situ mining environment is defined in terms of the tendency for lixiviant waters to transport significant concentrations of the element over some distance. The usual mode of transport is as stable, soluble ions or ionic complexes. Mobility will depend upon: (1) the pH of the lixiviant, (2) the type of complexing agent introduced by the leaching solution, and (3) the efficiency of the natural geochemical traps capable of purging minor and trace amounts of deleterious elements from the lixiviant.

The extent of aquifer contamination may be controlled by selecting lixiviants that are effective on uranium but that minimize the dissolution of associated trace elements. As a general rule, more trace elements will be mobilized by acid lixiviants than by base lixiviants.

Lixiviants are prepared with salts known to form stable aqueous complexes with uranium, however, some will also stabilize unwanted trace elements. For example, ammonium bicarbonate/carbonate lixiviants form stable aqueous amine complexes with environmentally sensitive arsenic, copper, zinc, cadmium, and mercury. Such complexation may retard the effectiveness of natural geochemical mechanisms that purge a lixiviant of these contaminating trace elements. A similar problem may arise with the oxidant used. Chlorites and chlorates, for example, introduce chloride ion which complexes readily with heavy metals.

Natural geochemical traps are likely to restrict the mobility of contaminating elements. Reprecipitation and ion-exchange mechanisms tend to immobilize carbonate, sulfate, ammonium, iron, manganese, uranium, and vanadium, whereas adsorption is most effective with the common heavy metal trace elements. These mechanisms can purge ground water of significant amounts of contaminating ions.

Once solution mining has started, the mined aquifer will remain in an oxidizing state until reducing conditions are re-established. The mere termination of lixiviant injection may have negligible short-term effects. Migration of contaminated waters outside the immediate mining-affected area will bring the dissolved metal complexes into contact with reduced and less altered rock where reduction and precipitation of dissolved chemical species are likely to occur. The transition metals susceptible to reduction reactions will be purged from solution in preference to the stable alkali, alkaline earths, and halogens. It is important to note that these reactions are analogous to reactions responsible for the deposition of ore and associated minerals described elsewhere in this report. Indeed, redeposition has been observed where uranium-bearing lixiviants have come into contact with reduced sandstones on the periphery of a producing well field.

Table 6.1 lists the common elements susceptible to mobilization by both mildly acid and alkaline lixiviants during in-situ leach mining and cites the mechanisms likely to limit their mobility. Four mechanisms are included for purposes of comparision: (1) reprecipitation reactions as a result of solubility consideration, (2) ion exchange with common clays, (3) adsorption onto hydrous iron and manganese oxides, and (4) chemical reduction by means such as contact of solution with more reducing strata. The table is not intended to be absolute; reactions that are questionable or effective only under very specific conditions were purposely omitted.

6.2 EVALUATION OF RESTORATION TECHNIQUES

Techniques of leach field restoration that have been attempted or proposed are: (1) pumping of selected leach field wells; (2) pumping of selected leach field wells in combination with injection into other selected wells of natural ground water, recirculated treated leach field water, or one of the above types of water with chemicals added; and (3) natural restoration. In evaluating these techniques, it must be realized that, as previously mentioned, the only existing experience with leach field restoration is at the pilot project level. Some problems with extrapolating pilot-scale restoration results to production-scale operations therefore exist. First, the geologic and geochemical framework of the pilot-scale operations may be different. For example, a pilot-scale project might be entirely within and surrounded by an ore body, whereas the production-scale operation would be expected to extend to the limits of the ore body. Second, a pilot-scale operation, because of its small size (typically only a single five-spot array of wells), would not be expected to encounter the stratigraphic variations that will commonly be found over the area of a production-scale operation.

TABLE 6.1
NATURAL MECHANISMS LIMITING MOBILITY OF ELEMENTS IN MILDLY ACID AND ALKALINE LIXIVIANTS

Mechanism	Elements Immobilized
Mildly Acid Lixiviants	
Reprecipitation	S(SO_4^{-2}), Mo, Se, As, V, Ba, Ra
Ion Exchange	Na, Ca, Mg, N(NH_4^{+}), U, V
Adsorption	S(SO_4^{-2}), Mn, Mo, Se, As
Reduction	S(SO_4^{-2}), U, Fe, Mo, Se, As, Cu, Pb, Zn, Cd, Hg
Mildly Alkaline Lixiviants	
Reprecipitation	Ca, Mg, C(CO_3^{-2}), S(SO_4^{-2}), U, Fe, Mn, Se, As, V, Cu, Pb, Ba, F, Ra
Ion Exchange	Na, Ca, Mg, N(NH_4^{+}), U, V, Cu, Pb, Zn, Hg
Adsorption	S(SO_4^{-2}), U, Mn, V, Cu, Pb, Zn, Ba, Cd, Hg
Reduction	S(SO_4^{-2}), U, Fe, Mo, Se, As, Cu, Pb, Zn, Cd, Hg

6.2.1 Pumping of Selected Leach Field Wells

The initial concept of leach field restoration, as developed in Texas, involves only the pumping of selected leach field wells after cessation of lixiviant injection. The pumping is intended to draw uncontaminated ground water from outside the leaching field to displace the injected lixiviant and the constituents mobilized by it. Under ideal conditions, it is believed that ground water from outside the leaching field will completely displace the lixiviant, thus producing a water-quality condition that is the same as average baseline quality.

The best data examined for restoration by pumping alone are those obtained by the Exxon Company at the Highland Uranium Mine.[1] The pilot project involved a single injection well surrounded by six producing wells (Figure 6.1) and a single ring of six monitor wells. The ore bearing sandstone at the site averages 23 feet in thickness and has a porosity of 29 percent.[1] Based on this thickness and porosity, the pore volume within the ring of production wells is about 1.27 million gal (4,800 m^3) and within the ring of monitor wells is about 3.53 million gal (13,350 m^3). Because excursion beyond the ring of production wells did occur during mining, it can only be concluded that the aquifer volume affected by mining was greater than 1.27 million gal, but less than 3.53 million gal.

During mining of the pilot project, 11.55 million gal (43,890 m^3) of lixiviant ($NaHCO_3$ and O_2) were injected and 10.29 million gal (39,100 m^3) were withdrawn, leaving 1.26 million gal (4,770 m^3) in place when injection ceased on November 4, 1974. After injection of lixiviant ceased, pumping of the six production wells continued and pumping of the injection well began. Aggregate production from the seven wells averaged about 21,000 gpd (80 m^3/day).

It is not known what the uranium concentration was in the produced pregnant lixiviant during well-field operation, but it would be expected to be in the hundreds of mg/l, in contrast to the baseline uranium values which were less than 1 mg/l. By October 26, 1977, after production of about 22.7 million gal of water (Table 6.2 and Figure 6.2), the uranium concentration in water produced from the former injection well was 61 mg/l and concentrations were from 9 to 33 mg/l in the production wells. Figure 6.2 shows an irregular, but clear, tendency toward reduction in uranium concentration in the water produced from the injection well until late 1977, although uranium levels at that time were still more than 100 times the original average baseline value of 0.2 mg/l (Table 6.3).

The restoration of other parameters including carbonate, bicarbonate, radium-226, thorium-230, arsenic, and selenium was evaluated. Inspection of available data, without a rigorous statistical analysis, shows that both carbonate and bicarbonate levels remained very high in water samples from the injection well until April 1977, when the levels of both declined rapidly, with the bicarbonate level reaching baseline (Tables 6.4 and 6.5). Radium-226 was originally high (120 pCi/l) and has remained in

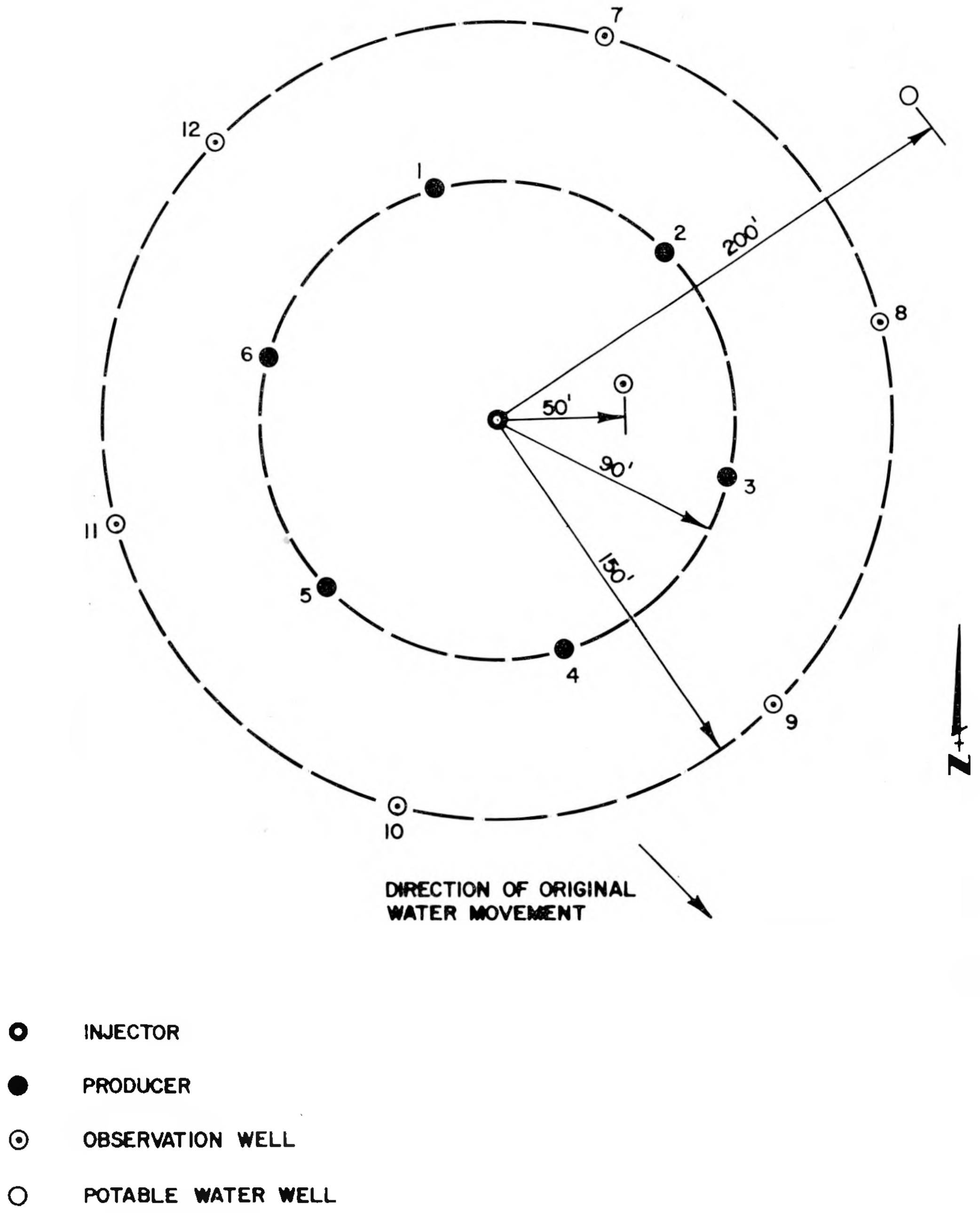

Figure 6.1. Well configuration of Exxon's Highland in-situ leach mining pilot project.[1]

TABLE 6.2
URANIUM CONCENTRATION DURING RESTORATION, HIGHLAND SOLUTION MINE PILOT1)

Date	Observed Uranium Concentrations Milligrams Per Liter By Well						
	1	2	3	4	5	6	INJ.
08/19/76	34	72	9	14	57	60	157
09/25/76	-[1]	62	6	12	-	58	165
10/11/76	-	49	5	9	-	-	111
10/19/76	-	62	10	15	-	46	145
10/29/76	8	54	13	16	-	50	133
11/04/76	7	52	6	13	-	46	131
11/15/76	6	42	11	15	-	42	126
11/24/76	19	60	13	14	14	48	134
12/03/76	16	42	11	12	31	41	135
12/07/76	24	44	7	11	37	39	128
12/20/76	20	54	10	11	45	42	139
01/13/77	12	-	13	-	47	48	129
01/30/77	27	-	6	-	60	49	112
02/14/77	27	-	6	-	60	49	103
03/01/77	27	33	10	-	61	54	121
03/12/77	31	38	21	-	21	42	54
03/25/77	18	37	50	-	24	19	89
04/21/77	31	47	24	-	59	-	94
04/26/77	17	37	5	-	42	31	73
05/21/77	36	55	28	-	69	-	110
06/23/77	11	31	5	-	42	39	68
07/21/77	10	32	-	-	32	31	54
08/04/77	9	31	1	-	28	-	54
09/25/77	3	31	3	-	-	31	57
10/26/77	14	26	9	-	-	33	61

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[1] Dash indicates well not producing, and no sample was taken on that date.

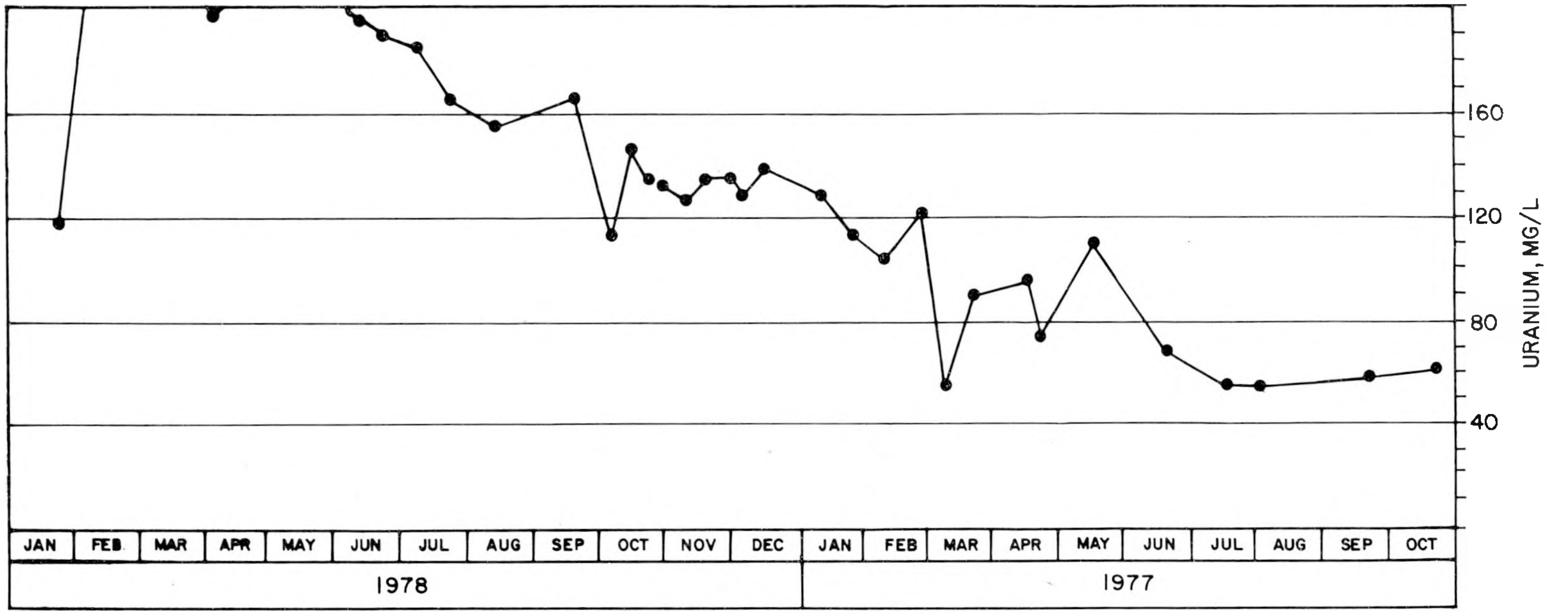

Figure 6.2. Uranium concentrations in the produced fluid during restoration by the "pumping" method, Exxon's Highland Pilot Project.[2]

TABLE 6.3
ORE-ZONE BASELINE WATER QUALITY,1/
HIGHLAND SOLUTION MINE PILOT1)

Parameter	Value
Sodium	161 ppm
Calcium	77 ppm
Magnesium	13 ppm
Chloride	27 ppm
Sulfate	119 ppm
Bicarbonate	237 ppm
Selenium	<0.5 ppm
Uranium	212 ppb
Radium 226	1.2×10^{-7} uCi/ml
Thorium 230	8.6×10^{-8} uCi/ml

1/ Average of 3 samples taken from 3 production wells in original pilot area during May 1970.

TABLE 6.4
CARBONATE CONCENTRATIONS DURING RESTORATION, HIGHLAND SOLUTION MINE PILOT1)

	Observed Carbonate Concentration Milligrams Per Liter By Well						
Date	1	2	3	4	5	6	INJ.
08/19/76	51	181	0	42	51	173	554
09/25/76	-	163	0	23	-	209	650
10/11/76	-	147	2	-	-	-	505
10/29/76	0	165	0	11	-	143	569
11/04/76	-	174	34	33	-	152	535
11/24/76	11	161	0	11	0	97	550
12/07/76	48	145	16	48	11	0	469
12/20/76	24	167	24	24	24	71	547
01/30/77	70	-	11	-	34	139	550
02/14/77	47	-	0	-	6	104	485
02/27/77	0	258	11	-	47	-	469
03/06/77	50	71	0	-	14	50	264
02/25/77	20	22	0	-	0	7	242
04/21/77	30	60	0	-	10	40	20
04/26/77	0	86	0	-	21	29	21

TABLE 6.5

BICARBONATE CONCENTRATIONS DURING RESTORATION, HIGHLAND SOLUTION MINE PILOT[1)]

	Observed Bicarbonate Concentration Milligrams Per Liter By Well						
Date	1	2	3	4	5	6	INJ.
08/19/76	512	849	157	353	506	792	1,503
09/25/76	-	495	142	355	-	520	1,511
10/11/76	-	619	255	-	-	-	1,233
10/29/76	236	418	259	351	-	489	1,275
11/04/76	165	472	178	311	-	495	1,145
12/07/76	220	477	145	187	207	477	1,224
12/20/76	387	676	290	338	436	556	1,718
01/30/77	311	-	228	-	456	519	1,494
02/14/77	328	-	234	-	517	434	774
02/27/77	332	519	199	-	519	477	1,286
03/06/77	181	226	113	-	266	226	447
03/25/77	147	194	68	-	158	136	520
04/21/77	119	201	174	-	174	146	137
04/26/77	90	271	102	-	254	226	243

the range of 50 to 100 pCi/l during the restoration phase (Tables 6.6). There does not seem to have been a clear trend toward reduction in the level of arsenic during the restoration period, but selenium levels appear to have decreased during restoration (Table 6.7).

It can be concluded that pumping for the purpose of drawing in natural ground water does produce a trend of water-quality improvement, but it can be very time consuming, and perhaps impossible, to bring the levels of all elements of concern back to within the original baseline range. Furthermore, the volume of water pumped to produce significant improvement in quality was large, and handling of such volumes of water would be a major waste-disposal problem during a full-scale project.

Pilot leaching projects using an alkaline leach, with the exception of the Exxon test, have used ammonium bicarbonate in the lixiviant. The use of ammonium has caused a special restoration problem. Figure 6.3 shows the results obtained by Wyoming Mineral Corporation during restoration by pumping alone at that company's Irigaray site.[3,4] The pumping or "ground-water sweep" test was a single-well test, and, thus, particularly unrepresentative of a production-scale effort. However, the inability of pumping alone to lower the ammonium level is typical of other such test data that have been examined. The total dissolved solids were restored to below baseline, but many of the individual parameters, in addition to ammonium, remained at many times the initial values measured in the 517-well area (Table 6.8).

The three principal reasons why pumping alone is only partly successful, as evidenced by available data, are:

(1) Sandstone bodies of the type in which uranium leaching is being practiced are naturally inhomogeneous and commonly include preferred paths of fluid flow. During restoration by pumping, it is expected that inflowing ground water will readily sweep contaminated water from the areas through which flow is preferentially channelled, but will bypass contaminated water in other areas. As restoration continues, water that was originally bypassed will be slowly removed.

(2) Some ions, of which ammonia is an extreme example, adsorb to minerals (particularly clays) in the aquifer. During leaching, these minerals are present in the water in relatively high concentrations. During restoration, as the amounts in solution decrease, the ions begin to desorb. The desorption process can be very slow, resulting in the presence of the desorbing ion for a long period of time.

(3) Prior to mining, water in contact with minerals in and around the uranium ore body is expected to have reached some state of chemical equilibrium with the minerals. During leaching, the existing chemical equilibrium will be disturbed and it may be difficult, if not impossible, to reestablish it.

TABLE 6.6
RADIUM AND THORIUM CONCENTRATIONS DURING RESTORATION, HIGHLAND SOLUTION MINE PILOT[1)]

Date	Radium 226 (μCi/ml x 10^{-8})	Thorium 230 (μCi/ml x 10^{-7})
05/01/70[1/]	12.0	0.86
07/04/72	9.2	39.5
09/04/72	1.1	21.0
01/19/73	21.4	68.1
05/10/74	110.0	1040.0
08/05/74	-	42.0
11/12/74	40.0	280.0
02/04/75	8.8	67.0
05/02/75	4.4	1.6
08/08/75	12.5	0.5
09/03/75	6.8	1.2
10/02/75	10.0	0.3
11/03/75	14.0	3.6
12/01/75	9.0	4.3
01/05/76	8.2	20.4
02/03/76	12.2	3.4
03/01/76	8.2	0.3
04/05/76	5.2	0.1
05/03/76	7.9	1.3
06/04/76	8.6	0.9
07/02/76	5.9	0.7
08/02/76	6.4	0.9
09/01/76	5.6	1.0
10/13/76	7.3	1.4
11/09/76	7.7	2.1
12/01/76	5.6	1.0
01/03/77	7.4	.7
02/01/77	7.6	1.2
03/04/77	9.2	1.4

[1/] Average of 3 samples taken prior to solution mining operations.

TABLE 6.7
ARSENIC AND SELENIUM CONCENTRATIONS DURING RESTORATION, HIGHLAND SOLUTION MINE PILOT[1]

Date	Arsenic (mg/l)	Selenium (mg/l)
May 1970[1]	-	<0.5
09/03/75	0.36	0.17
01/05/76	0.38	0.14
02/03/76	0.37	0.17
04/05/76	0.33	0.16
05/03/76	0.36	0.17
06/04/76	0.44	0.21
07/02/76	0.31	0.14
08/02/76	0.28	0.08
09/01/76	0.40	0.13
12/01/76	0.09	0.05
01/03/77	0.23	0.10
02/01/77	0.32	0.08
03/04/77	0.21	0.08

[1] Sample taken in pilot area prior to initiating solution mining test.

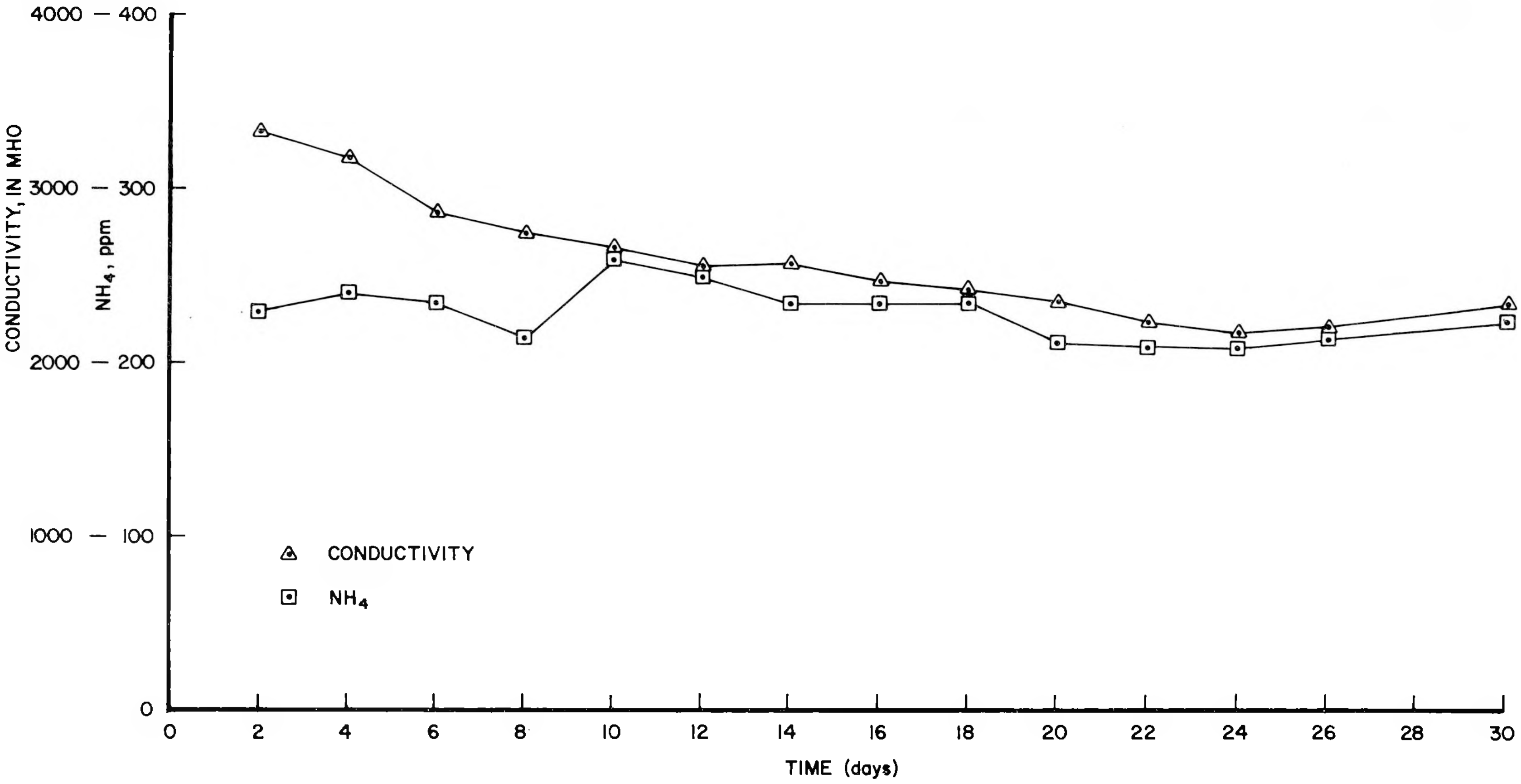

Figure 6.3. Ammonia concentrations and specific conductivity in the produced fluid during restoration by the "ground-water sweep" method, Wyoming Mineral's Irigaray Pilot Project.[3]

TABLE 6.8
WATER-QUALITY CHANGES RESULTING FROM GROUND-WATER SWEEP, IRIGARAY 5I7-3 PILOT[3]

	Initial (ppm)[1]	Final (ppm)	5I7 Baseline[2] (ppm)
NH_4	180	123	< 1.0
As	.033	.017	< .0025
Ba	.09	.03	.12
B	8.3	0.26	.16
Cd	0.30	< .002	< .005
Ca	58.5	13.5	---
CO_3	4.2	4.7	---
Cl	531	229.9	10.75
Cr	< .002	.004	.0135
Cond (μmhos)	3.30 x 10^3	1.95 x 10^3	---
Cu	.215	.041	.019
F	2.75	4.10	---
$CaCO_3$	616	445	232
Fe	2.15	.65	---
Pb	.32	0.58	.0035
Mg	19.5	5.4	---
Mn	.784	.150	.12
Hg	.0002	< .0002	.0028
Mo	< .02	.42	---
Ni	1.79	< .20	.018
NO_3	4.92	1.24	---
NO_2	2.76	0.151	---
pH	7.94	8.14	---
K	8.14	2.9	---
Se	1.02	.339	.013
Si	5.3	3.3	---
Ag	< .002	< .002	< .005
Na	308	210.8	---
SO_4	270	233	---
TDS	1,302	712	793
V	< .05	.21	---
U_3O_8	18	12.3	.098
Zn	.218	.02	.003
Ra-226 (pCi/l)	478 ± 9	105 ± 10	26.8 ± 5.2
Gross Alpha "	12,317 ± 288	5,412 ± 177	168 ± 11
Gross Beta "	5,374 ± 115	2,052 ± 85	164 ± 19
Th 230 "	640 ± 21	1.5 ± 0.9	---

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[1] Values in ppm, except pH and as otherwise noted.

[2] Original 5I7 baseline values were determined on a single sample analysis and did not include all parameters of interest.

6.2.2 Pumping in Combination With Injection

Restoration could be expedited by simultaneously pumping selected wells and injecting water that has been tailored by pretreatment and/or chemical addition into other wells. Pumping would draw out the injected lixiviant and mobilized ions, while injection would drive the contaminated water toward the pumping wells.

6.2.2.1 Injection of Natural Ground Water

Injection of natural ground water is perceived to have no advantages over pumping alone. Pumping alone draws in natural ground water without the added cost and technical difficulty of injection. In fact, if the injected water were to contain oxygen, it would be expected to have a negative effect by sustaining the mobilization of uranium and other oxidizable elements. For example, 1 mg/l of dissolved oxygen is capable of oxidizing 17.5 mg/l of U_3O_8.

6.2.2.2 Injection of Treated Leach Field Water

One of the major problems associated with restoration by pumping alone is the disposal of the contaminated water brought to the surface (Section 7) Treatment of pumped water, for reduction of some or all of the contaminants, and reinjection of the treated water to the well field reduces the volume of contaminated water that must be disposed. A variety of partial or complete treatment methods are available. For example, partial treatment might consist of uranium stripping and precipitation of radium-226. Complete treatment by one of the deionization methods, such as reverse osmosis, may be utilized where partial or selective treatment is precluded.

Wyoming Mineral Corporation is the only company known to have experimented with injection of treated well-field water. At its Irigaray, Wyoming site, water produced from the well field was run through a reverse-osmosis unit and reinjected during the "clean water recycle" test. The effectiveness of the reverse-osmosis treatment of produced well-field water is shown in Table 6.9. It is estimated that the concentrate containing the contaminants comprised only 20 percent of the volume of water treated, thus eliminating 80 percent of the water that would otherwise have to be disposed.[3,4] Obviously, injection of the treated water will achieve a considerable reduction in the average levels of dissolved constituents by dilution.

As discussed above, injection of treated water would be expected to introduce oxygen into the ground-water system that will cause continued oxidation and mobilization of uranium and other metals, unless some form of deaeration is used prior to injection.

6.2.2.3 Injection of Water Containing Added Chemicals

An alternative restoration technique is the injection of water containing appropriate chemicals to remove uranium and trace metals from solution.

TABLE 6.9
EFFECTIVENESS OF REVERSE OSMOSIS IN WYOMING MINERALS IRIGARAY PROJECT 3)

Constituent	Concentration of constituent in mg/l[1] Before reverse osmosis	 After reverse osmosis	Percent Reduction
U_3O_8	43	< 1	> 97.6
CO_3	8	< 4	> 50.0
Cl	686.8	26	96.2
SO_4	641.8	4.3	99.3
Na	434	10.7	97.5
Ca	71.5	2.2	96.9
Mg	23.3	< 1.0	> 95.7
NH_4	54.3	2.7	95.0
pH	4.7	4.9	--
Conductivity	3,237.3 μmhos	149 μmhos	--

[1] Constituents in mg/l except pH and conductivity.

The most effective chemical would reduce oxidized elements, and combine with them to form insoluble compounds. Sulfides, such as hydrogen sulfide or sodium sulfide, appear suitable because of their assumed chemical effectiveness, environmental compatibility, and relatively low cost. Readjustment of the reduction potential of the ground-water system is expected to have only a minor effect on the major cations and anions (Na, Ca, Mg, SO_4, HCO_3, CO_3, Cl). The injection of reducing agents is not known to have been applied in the field.

The injection of a solution to promote rapid ammonium ion desorption has been suggested. The affinity of cations to adsorb to minerals generally increases with increasing valence and concentration. Therefore, it is expected that adsorbed ammonium ions can be displaced from clay minerals by high concentrations of multivalent ions. Bivalent calcium and magnesium ions appear to be good candidates because of their affinity to adsorb and their common occurrence in nature.

Wyoming Minerals performed a test at the Irigaray site in which a solution high in calcium, sodium, and/or magnesium was injected to desorb ammonium (Figure 6.4).[3,4] As expected, the concentration of ammonium in the recovered solution increased during injection of the ion-bearing solution from about 65 mg/l to over 200 mg/l, reflecting the increased desorption of ammonium. The concentration then decreased as the ammonium was depleted. After recovery of about 450,000 gal (1,710 m^3) of fluid, injection of water treated by reverse-osmosis was begun to remove the injected saline solution. After recovery of an additional 550,000 gal (2,090 m^3) of fluid, the ammonium level was about 35 mg/l as compared with the value of 65 mg/l before the test began. It is concluded that additional reduction in well-field ammonium values can be achieved by injection of a saline solution, but that the test failed by a considerable margin to achieve complete ammonium removal.

6.2.3 Natural Restoration

Thus far, state and Federal regulatory agencies have made pumping or a combination of pumping and injection the required means of leaching field restoration. No study has yet been made to determine what the result would be if reliance were placed upon the natural capacity of the ore-bearing stratum and uncontaminated ground water to restore or partially restore the affected area.

The concept of natural ground-water quality restoration may have particular merit in uranium leaching. It is believed that, under the proper circumstances, most of the objectionable elements that have been introduced or mobilized during leaching will be removed by reprecipitation, ion exchange, adsorption, or reduction, as discussed earlier in the introduction to the section.

Problems associated with the concept of natural restoration include the difficulty of predicting (1) the time and distance required for the contaminant removal processes to be effective, (2) the degree of

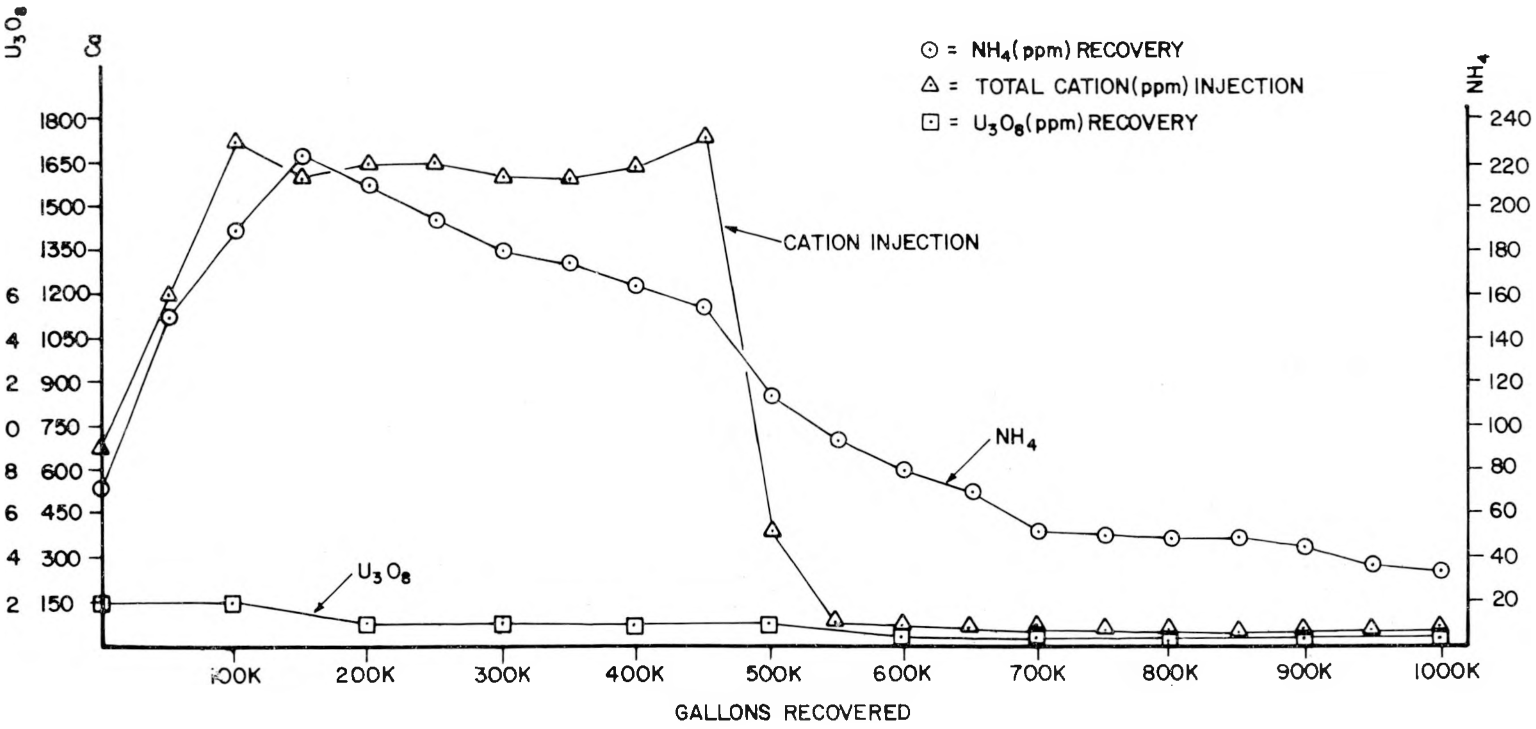

Figure 6.4. Ammonia changes in well-field fluid quality during restoration using injection of a cation solution.[3]

contaminant removal that will be achieved, and (3) the ultimate fate of some elements or ions, e.g., chloride and ammonia.

6.3 ENVIRONMENTAL IMPACTS OF RESTORATION TECHNIQUES

The uranium leaching process mobilizes varying amounts of natural uranium, thorium, arsenic, selenium, and other metals that are found in and adjacent to uranium ore bodies. In addition, leaching agents containing such chemicals as ammonia, carbonate/bicarbonate, sodium, sulfate, and chloride are added to the ground-water system.

It has been shown, in pilot restoration projects, that most of the introduced and mobilized chemicals can be significantly removed by mechanical and chemical restoration methods. It is believed that natural geochemical mechanisms, either alone or after mechanical restoration, are capable of causing significant water-quality improvement but prediction of the effectiveness of natural restoration is not now possible.

Mechanical restoration methods are time consuming, expensive, and, for geological and geochemical reasons, perhaps even incapable of returning every ion and parameter to its original baseline level. Additionally, mechanical restoration by ground-water pumping, the method most widely favored today, results in large volumes of waste water that must be handled. This may present environmental problems which are discussed in Section 7. Treatment and reinjection of pumped water produces a smaller volume of waste water, but the contaminants still must be handled at the surface in a concentrated liquid and/or solid form. In-situ restoration by chemical injection may have an advantage because no wastes are brought to the surface. This process, however, has only been proposed thus far.

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7. WASTE GENERATION AND DISPOSAL

Wastes are generated during uranium recovery and aquifer restoration, though the quality and quantity of the wastes are variable. In general, the process wastes have a low volume but a high dissolved solids content, whereas the restoration wastes are high volume and low solids. Appendix D and Section 6 discuss the process methods and restoration methods in detail.

Because most wastes will be either liquids or slurries, the following methods for disposing of wastes associated with in-situ leach mining have been evaluated: (1) disposal wells, (2) lined evaporation ponds or tailings ponds, and (3) liquid/solid separation with use of the residual water for such purposes as irrigation. Additionally, direct surface-water discharge was evaluated as a potential waste-disposal method, however, current EPA effluent guidelines prohibit the discharge to streams of any material from uranium mills.[1]

Several assumptions were made concerning the waste streams prior to making the assessment. The waste from a typical uranium recovery process (Figure 7.1) will be a liquid or a slurry of suspended solids produced at a rate of 27.9 ac-ft/yr (34.4 hm^3) [30 gpm (1.9 l/s)] or more. Table 7.1 presents a crude estimate of the chemical quality of this fluid (no complete chemical analyses are available from the industry). The restoration waste stream will be the fluid produced by the ground-water sweep restoration method. This method results in the handling of very large volumes of waste. The waste is produced at 1,300 ac-ft (1,600 hm^3) or more per year (800 gpm [50.4 l/s]) and has a chemical composition similar to that shown in Table 7.2. The quality of the recovered water will improve with time for any one area of restoration, but because two or more areas may be under restoration concurrently, only the poorer quality waste has been shown.

7.1 DISPOSAL WELLS

For a subsurface disposal system to be environmentally acceptable, it is necessary to locate a porous, permeable formation of wide areal extent at sufficient depth to ensure retention of the injected fluids. A low permeability zone should separate the injection horizon from horizons containing potable ground water and/or mineral reserves to prevent vertical migration of the wastes or displaced formation brines into these "usable" strata.[2] The disposal zone should contain water with a TDS quality poorer than 10,000 mg/l.

7.1.1 Regulatory Feasibility

All States in which in-situ leach mining may take place have a regulatory position that allows the use of disposal wells. The requirements to operate such wells differ considerably, although in general, extensive preliminary data collection and engineering safeguards are necessary. Disposal wells of any type are operating only in Texas and New Mexico.

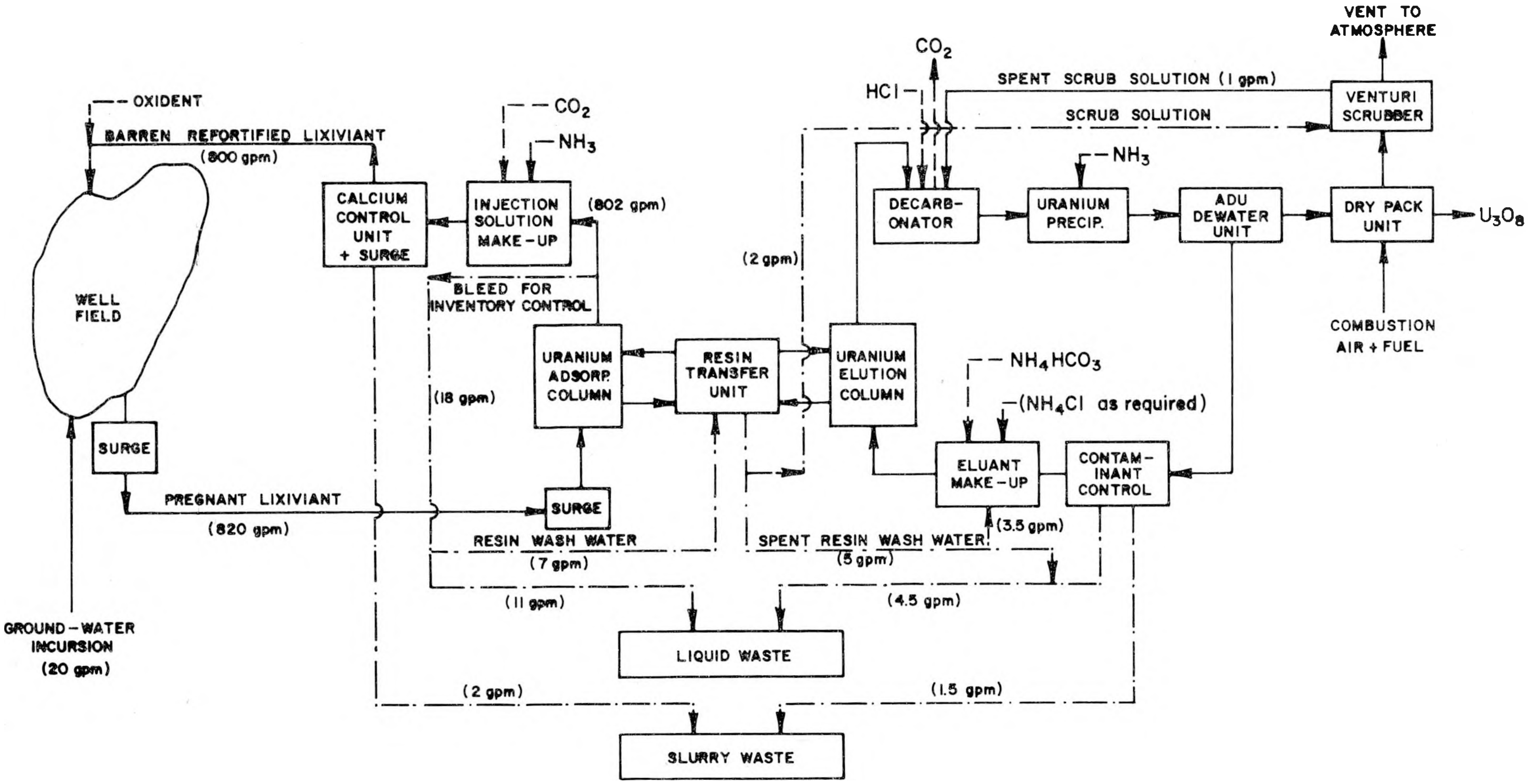

Figure 7.1. Schematic diagram of an uranium processing facility showing the waste streams.

TABLE 7.1
URANIUM PROCESS WASTE PRODUCTS

Waste Generating Process	Waste Volume Produced (yr)		Composition	
	Liquid (ac-ft)	Solid (tons)	TDS	Material
Calcium Control	3.1	800	3,000 (0.4-0.9 Ci)	Calcium Uranium Radium 226
Over-Produced Lixiviant	17.9	-	-	Ammonia Chloride Carbonate Metals
Resin Wash	2.3	-	-	Chloride Ammonia Metals
Yellowcake Processing	4.6	800	15,000[1]	Barium Ammonia Carbonate Chloride Sulfate Metals Uranium

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[1] Over-produced lixiviant, resin wash, yellowcake process combined effluent quality.

TABLE 7.2
QUALITY OF WATER PRODUCED DURING "GROUND-WATER SWEEP" RESTORATION

Parameter	Quality (mg/l)[1]
Ammonia	235
Arsenic	.021
Barium	.069
Bicarbonate	805
Boron	.283
Cadmium	.014
Chromium	.002
Chloride	524
Copper	.220
Lead	.110
Manganese	.97
Mercury	.0002
Nickel	.218
Selenium	1.75
Silver	0.15
Total Dissolved Solids	1,324
Uranium (U_3O_8)	24.4
Zinc	0.22
Gross Alpha	22,815 ± 296 pCi/l
Gross Beta	21,043 ± 441 pCi/l
Radium 226	371 ± 5.6 pCi/l

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[1] Constituents in mg/l unless otherwise noted.

Uranium wastes are routinely disposed via wells in Texas. One well to dispose of mill waste is operational in New Mexico.

Currently, EPA is preparing regulations applicable to disposal wells, under the mandate given to that agency by the Safe Drinking Water Act (PL 93-523). These EPA Underground Injection Control Regulations prescribe minimum Federal standards which are to be administered by the States.[3] Only Colorado, New Mexico, Texas, and Wyoming will be required to comply with the EPA program in the near future. The proposed regulations do not appear to represent a great change from requirements already in use in those States.

7.1.2 Well Design and Cost

Figure 7.2 is a schematic diagram of a disposal well, designed in a manner consistent with existing or proposed requirements for this type of well. The specific design criteria will differ but certain requirements will have to be met in all cases. The major factor in design and construction is the protection of potable water supplies and minerals of economic value in the rock through which the well is drilled. Casing strings are set and cemented into the borehole and usually, an injection tube is used to conduct the injected waste to the disposal formation.

The well should be designed to handle the largest volume of fluid potentially available for injection; in this case the combined flow rate of 830 gpm 52.4 l/s. Assuming that the disposal well will be constructed to a depth of approximately 4,000 ft (1,212 m) and will have a final diameter of 8 in. (20 cm), it is estimated that the well will cost between $500,000 and $750,000. This cost includes construction and testing. Not included is the cost for hydrologic field supervision, planning, pre-mining data collection, or other administrative costs.

7.1.3 Disposal-Well Practicability

Although disposal wells are currently in use in Texas for in-situ leach mining operations, it is unlikely that such wells can be used to any great extent in Wyoming, Utah, or South Dakota. The fluvial basins of Wyoming, for example, are made up of sedimentary materials that are of low permeability, and even though the sediments are areally extensive, the permeable zones are lenticular in nature. Moreover, the quality of the ground water through the entire sequence of sediments in the Wyoming basins is generally good. In most basins, for example, the Madison Limestone, whose base is at a depth of ± 10,000 ft (± 3,000 m), contains usable water. Injection above such depths would be precluded in order to protect this water.

In South Dakota, though a thick sequence of carbonates, sandstones, and siltstones containing saline ground water underlies the uranium mining districts, the permeability of these rock units is very low, thus raising serious doubts about their usefulness as an injection zone. Similar conditions also are believed to exist in southeastern Utah.

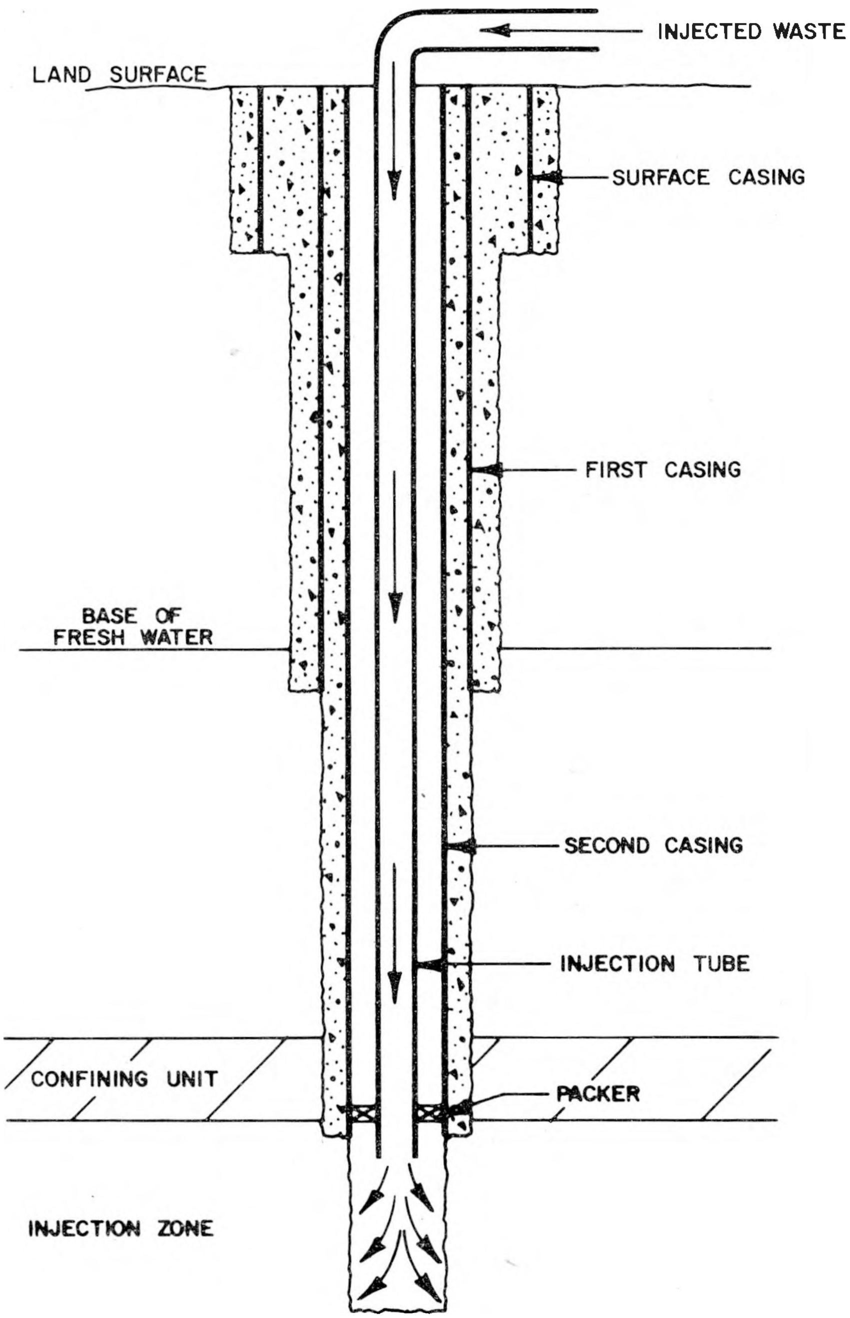

Figure 7.2. Diagram of a disposal well to handle in-situ leach mining wastes.

7.2 EVAPORATION PONDS

Evaporation ponds are designed to separate the dissolved and suspended solids from a waste liquid by means of solar evaporation. Pure water is removed from the pond, leaving behind the solid constituents. If unlined, part of the water held in the impoundment may seep to the water table presenting a threat to the potability of the near surface ground water.

7.2.1 Regulatory Feasibility

Both Texas and New Mexico have extensive guidelines for construction and operation of evaporation ponds. Both States generally require that the pond be constructed in natural earth materials which have very low water-transmitting characteristics. Where this is not possible, man-made synthetic liners or emplaced clay liners should be used.[4] In some instances, double liners may be required. Wyoming and Colorado both call for such construction methods, although the regulatory requirements are not as specific. Utah and South Dakota apparently have no detailed programs relating to impoundments.

At the Federal level, EPA is preparing regulations regarding disposal and treatment of hazardous wastes in impoundments, pursuant to the Resource Conservation and Recovery Act (PL 94-580). The requirements will be similar to those in the States outlined above. The program is to be State-administered, based on minimum Federal requirements. NRC has required the lining of ponds for many years.

7.2.2 Pond Design and Cost

The evaporation pond should be lined with a material that is inert to the chemical conditions to be encountered to assure its durability and integrity. It must be compatible with the regional climatic conditions and care must be given to avoid overflowing of contaminants to the land surface. Several liners were evaluated including bentonite clay, asphalt, and polymeric membranes such as polyvinyl chloride (PVC), Hypalon, 3110, ethylene propylene diene monomer (EPDM), and chlorinated and polyethylene (CPE). Bentonite and asphalt appear to be less safe than the plastic membranes, because they are subject to drying and cracking. The asphalt also will be subject to extensive frost action during the winter.

When installing polymeric membranes, the soil underlying the membrane must be cleared of rocks, debris, and sharp objects and it should be smoothed and compacted. As movement caused by wind lift (Venturi effect) or wave action can cause the seams on some liners to break, they may be weighted by a soil cover, sand filled bags, or old tires. If the liner has poor resistance to weather, a soil cover should be used to protect it from ozone attack and weathering.

Table 7.3 lists the uninstalled unit cost of various polymeric membrane liners. The total cost of installing a lined pond depends on the type of liner material, its thickness, and the site-preparation and finishing operations required.

TABLE 7.3
UNIT COSTS: POLYMERIC LINING MATERIALS
(1978 Dollars)

Lining Material	Thickness (mil)	Reinforced	Unreinforced	Deliver Cost Uninstalled ($/ft^2)
PVC	30		✓	.23
CPE	30		✓	.26
	30	✓		.40
EPDM	30		✓	.42
	30	✓		.52
HYPALON	30		✓	.32
	30	✓		.45
3110	20		✓	.24½
	20		✓	.27

The size of a lined pond is determined by comparing the yearly waste inflow with the net evaporation rate (evaporation minus precipitation) for the site (Figure 7.3). The pond design must include sufficient freeboard (extra depth) to prevent overtopping the impoundment as a result of unusually heavy precipitation or wind-induced waves.

Table 7.4 lists the cost for two ponds of different sizes, located in an area where the net evaporation rate is 38 in./yr (96 cm/yr). One pond covers 15 ac (6 ha) and handles only waste from the uranium precipitation process at an estimated flow rate of 30 gpm (1.9 l/s). The other pond covers 400 ac (160 ha) and is designed to handle restoration waste from a ground-water sweep operation at an estimated flow of 800 gpm (50.4 l/s).

The assumptions used to arrive at the cost are: (1) all costs are in early 1978 dollars; (2) ponds are constructed of 8-foot berms with 2:1 slopes, from material obtained near or on the site (no importation costs for fill material); (3) the liner is reinforced on slopes and unreinforced on the bottom of the ponds and is installed at unit costs of \$.045/ft^2 (\$4.90/m^2) and \$0.41/ft^2 (\$4.47/m^2) for the 15-ac (6-ha) and 400-ac (160-ha) size ponds, respectively. Land prices are not included in the figures for total pond cost.

7.2.3 Evaporation Pond Practicability

Lined evaporation ponds can be used successfully in all uranium mining areas covered by this study. Problems may arise, however, when ponds are used in conjunction with certain water-intensive restoration methods (ground-water sweep). As indicated above, several hundreds of acres of pond(s) may be needed to handle the waste fluid. The liner cannot be installed as one sheet in these large ponds thus providing a high potential of weak, leaky seams. Additionally, the large ponds are difficult to monitor with respect to ground water. As it may take years for contaminated fluid to move from the center of the pond to any monitor well located on the periphery, large volumes of water will be contaminated before it is detected. Smaller ponds may be used successfuly, however, to handle process wastes, as short term storage prior to well disposal, and to evaporate reverse osmosis wastes.

As much as 230 ton (209 tonne) or more of solids may be precipitated from the restoration pond and 1,320 ton (1,200 tonne) from the uranium process pond each year. These wastes will contain up to 1 Ci of Ra-226 plus uranium, arsenic, selenium, and ammonia, as well as chloride, calcium, sodium, etc. Ultimately, this waste must be disposed of at an NRC-approved disposal site. When the pond is no longer needed, the liner and any other materials must also be disposed of at an NCR-approved disposal site.

7.3 LIQUID/SOLID SEPARATION

In no case could wastes from uranium leaching processes be released to the surface environment without removal of the detrimental solid constituents by such methods as ion exchange, precipitation, or reverse

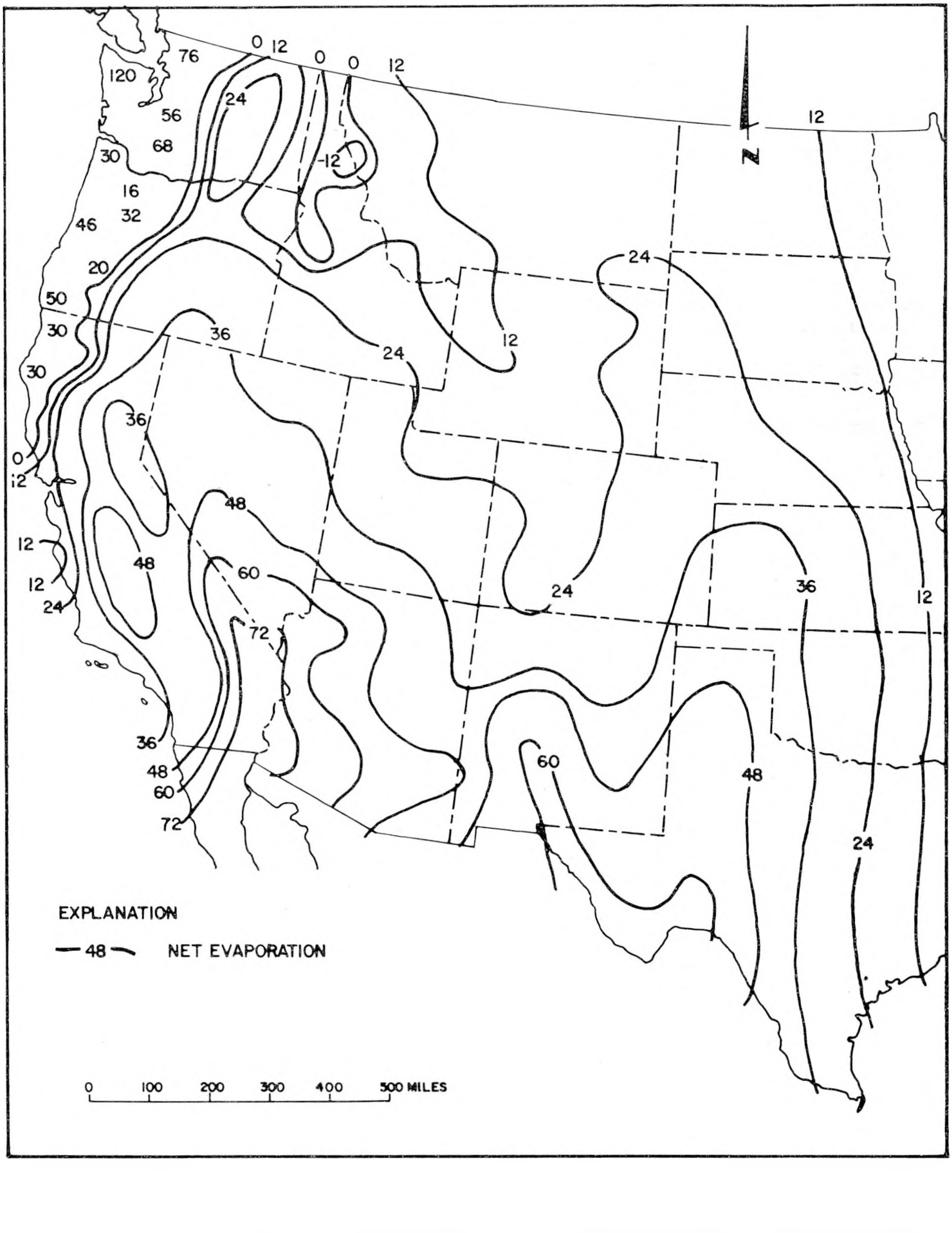

Figure 7.3. Map of the Western United States showing net evaporation (evaporation - precipitation).

TABLE 7.4

CONSTRUCTION COSTS OF EVAPORATION PONDS
(1978 Dollars)

	Waste Pond (15 acres)	Restoration Pond (400 acres)	Unit Cost
Unlined pond	27,391	86,824	$\$1.30/yd^3$
Compaction and smoothing of pond bottom	875	10,500	.24/ac
Hand dress side slopes	1,929	9,963	$.30/yd^2$
Anchor ditches	808	4,174	.25/linear ft
Installed linear cost	<u>325,891</u>	<u>7,290,000</u>	<u>1/</u>
Total cost of construction:	356,894	7,401,461	

1/ Unit cost of liner for 15-acre pond is $\$0.45/ft^2$, unit cost for 400-acre pond is $\$0.41/ft^2$.

osmosis. The waste resulting from the uranium processing is already concentrated to the point that further treatment is impractical. Restoration waste fluid produced by the ground-water sweep method, however, is of a generally good quality, except for the radioactive parameters and some metals, which must be removed prior to release for such purposes as irrigation. Restoration wastes produced during some more complex methods may not be ammenable to further treatment.

Reverse-osmosis treatment produces two liquid streams. The treated product is of good quality and has a volume of approximately 80 percent of the original 800 gpm (50.4 l/s) input; approximately 640 gpm (40.3 l/s) of usable water could be produced, with a quality expected to be within acceptable NRC, EPA, or State standards for agricultural use. The second liquid stream [160 gpm (10.1 l/s)] is a concentrated waste containing approximately 95 percent of the total solids from the treated waste. Disposal of the waste, which will have a volume of 258 ac-ft (318 hm^3) per year, is of primary environmental concern. Methods available for disposal of this water are evaporation ponds or disposal wells.

7.3.1 Regulatory Feasibility

There are no State or Federal regulatory programs that are directly applicable to this situation, although NRC guidelines limit the offsite release of these types of wastes if the radium-226 level is more than 5 pCi/l. Public opinion may prevent the use of water which contained radioactive material prior to treatment.

7.3.2 Cost

The cost of reverse-osmosis equipment is generally proportional to the volume and the solids content of the fluid to be treated. A capital investment cost of approximately $1.7 million can be assumed for a facility that would handle 1 mgd (3,800 m^3/day) and the operating cost for that facility would be approximately $1.25 per 1,000 gal ($0.33/m^3), for an overall yearly cost to the site operator of more than $500,000.

7.3.3 Practicability of Liquid/Solid Separation

Liquid/solid separation is possible at any location where in-situ leach mining may take place. The primary obstacle to its use is disposal of the treated fluid. It has been suggested that the treated fluid be reinjected as a restoration technique. Section 6 evaluates the feasibility of this restoration approach.

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Appendix A

STRATIGRAPHY AND ORE MINERALOGY OF SELECTED URANIUM-MINING AREAS

A.1 GAS HILLS, WYOMING

A.1.1 Stratigraphy

Approximately one-third of the Gas Hills Uranium District is located in the area known as the Puddle Springs quadrangle, which has been investigated in detail with regard to stratigraphy. The formations defined in the Puddle Springs study are probably representative of those in the entire district. The stratigraphy of the pre-Tertiary rocks is not relevant to the geochemistry of the uranium deposits and is not discussed further. The geologic formations that are exposed at land surface or that have been logged in drill holes in the area of the Puddle Springs quadrangle are listed in Table A.1.[1]

A.1.1.1 Wind River Formation

The Wind River Formation, of early Eocene age, was deposited on a pre-Tertiary erosion surface and is thus of varied thickness throughout the Gas Hills Uranium District. The formation has been divided into three members: the Lower Fine Grained Member, the Puddle Springs Arkose Member, and the Upper Transition Zone. A cross section through the Wind River Basin, including the area of the uranium deposits, is shown in Figure A.1.

The Lower Fine Grained Member consists of grayish-green siltstone, light-grey very fine to fine grained quartzose sandstone, and olive to greyish-green claystone. Some thin and discontinuous conglomerate beds are found locally near the base of the member. Thin carbonaceous shales and lignite beds are also found within the unit. The thickness of the Lower Fine Grained Member is about 150 ft (45 m) in pre-Tertiary valleys; elsewhere the member is thinner or it may be absent, as in the south where it laps on the Sweetwater Uplift.

The Puddle Springs Arkose Member is the host rock for most of the uranium mineralization in the Gas Hills district. It is the thickest of the three members of the formation and consists primarily of massive, very coarse to coarse-grained conglomeratic, arkosic sandstone. Beds of siltstone and claystone, as well as a few thin beds of carbonaceous shale and siltstone, are also present. Near the surface, the arkose is primarily yellowish-grey in color, but below or near the water table, where it has not been oxidized, it is mainly green or bluish-grey.

The original thickness of the Puddle Springs Member was probably about 400 to 800 ft (120 to 240 m); the member thins to the south, as does the Lower Fine Grained Member, and its thickness is highly variable due to variations in the pre-existing relief and later erosion.

TABLE A.1
STRATIGRAPHY OF THE PUDDLE SPRINGS QUADRANGLE, WYOMING1)

System	Series		Stratigraphic unit			Approximate thickness (feet)	Occurrence in quadrangle
Quaternary	Recent		alluvium			68+	Exposed at surface
	Pleistocene		pediment gravels			15	
Tertiary	Eocene	middle and upper	Wagon Bed Formation			400	
			Wind River Formation	upper transition zone (120 ft)		[1]825	
		lower		Puddle Springs Arkose Member (575 ft)[1]			
					Muskrat Conglomerate Bed		
					Dry Coyote Conglomerate Bed		
				lower fine-grained member (0-130 ft)			
Cretaceous	Upper		Cody Shale			5.000	
			Frontier Formation			730	
	Lower		Mowry Shale			300	
			Thermopolis Shale			275	Penetrated by drill
			Cloverly Formation			95	
Jurassic	Upper		Morrison Formation			230	
			Sundance Formation	"Upper Sundance"		250	
				"Lower Sundance"			
	Lower		Nugget Sandstone			245	
Triassic	Upper		Chugwater Formation	Popo Agie Member (350-400 ft)		1.045	
				Alcova Limestone Member (12 ft)			
	Lower			Red Reak Member (650-750 ft)			
			Dinwoody Formation			65	
Permian			Phosphoria Formation			300-335	
Pennsylvanian			Tensleep Sandstone			275(?)	Possibly present
			Amsden Formation			190(?)	
Mississippian			Madison Limestone			385(?)	
Cambrian	Upper		Gallatin Limestone			<100(?)	
	Middle		Gros Ventre Formation			400(?)	
			Flathead Sandstone			245(?)	
Precambrian			granite, gneiss, schist, and similar rocks				

[1] Composite thickness; maximum thickness of the formation in any one locality is about 600 ft and, of the Puddle Springs Arkose Member, about 500 ft.

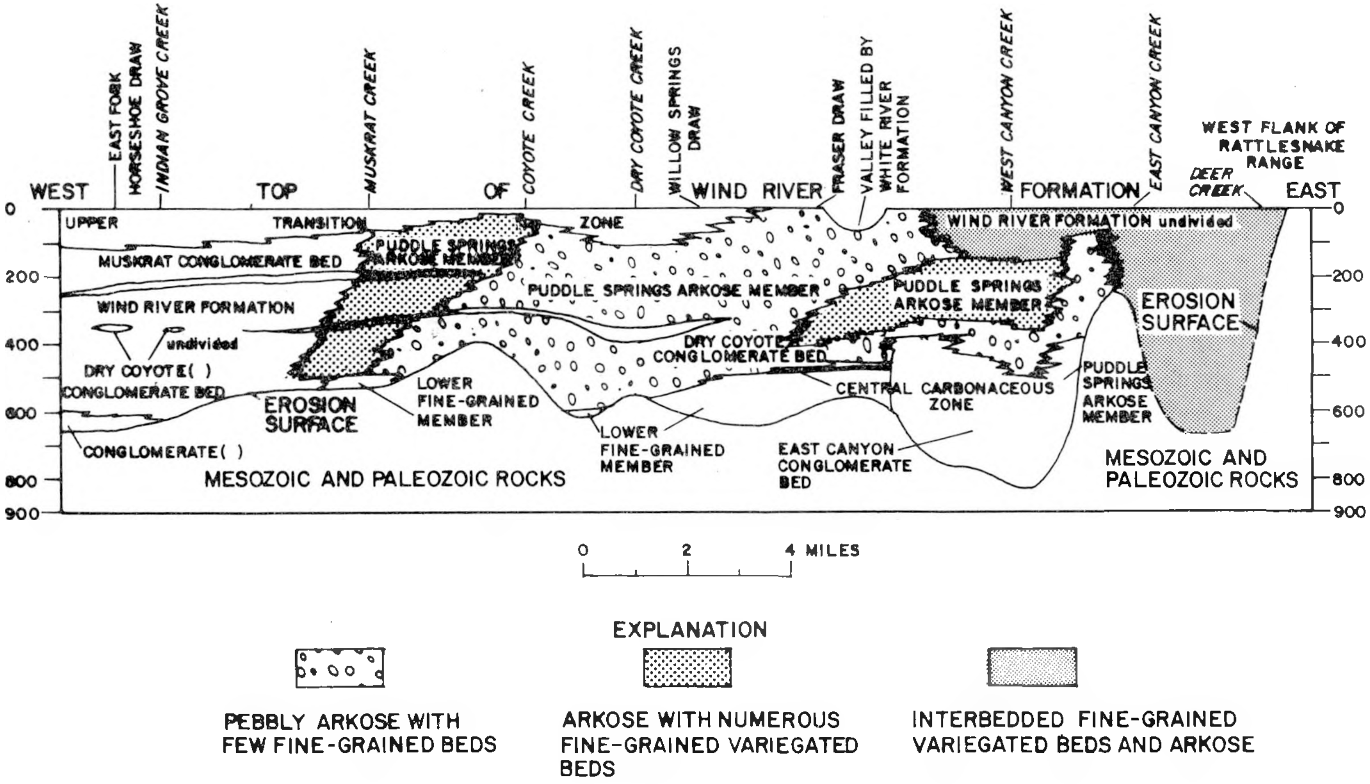


Figure A.1. Stratigraphic cross section of the Wind River Basin showing lithologic units and facies changes.[3]

Two granite-cobble and boulder conglomerate beds of the Puddle Springs Arkose Member are mappable in the Gas Hills district. The lower bed, termed the Dry Coyote Conglomerate Bed, is generally between 10 and 30 ft (3 and 9 m) thick, but it is known to be as thick as 53 ft (16 m) in the southern part of the district. The bed lies approximately 320 ft (97 m) above the base of the Puddle Springs Member in the northern part of the basin, but to the south it lies directly on the pre-Tertiary erosion surface.[1]

The Dry Coyote Bed consists mainly of cobbles and boulders of Precambrian granite, as much as 3 ft (1 m) in diameter, in a coarse arkosic sand matrix. Carbonaceous material is common in the upper part or directly overlies the conglomerate in places. Uranium minerals are common in the sand matrix and as coatings on pebbles and cobbles in the conglomerate.

The Muskrat Conglomerate Bed lies between 90 and 120 ft (27 and 36 m) above the Dry Coyote Bed and is usually about 20 ft (6 m) thick. This boulder conglomerate is sheetlike in areal extent. It contains boulders up to 2 ft (0.6 m) in diameter, of Precambrian granite and metamorphic rocks. The matrix of this conglomerate is commonly argillaceous. The beds above and below the Muskrat Conglomerate, as well as the matrix of the unit, are finer grained than those associated with the Dry Coyote Bed. No uranium minerals are associated with the Muskrat Conglomerate.

Carbonaceous beds, which are associated with uranium mineralization, occur primarily in the central portion of the Wind River Basin, above the Dry Coyote Conglomerate Bed. Carbonized wood and lenses and fragments of carbonaceous shale are found in arkosic sandstone as much as 200 ft (61 m) above the Dry Coyote Conglomerate in some portions of the mining district, and thin stringers and fragments of carbonaceous material are scattered throughout the lower 200 ft (61 m) of the Puddle Springs Arkose Member in other parts of the district.

The upper 150 ft (45 m) of the Wind River Formation consists of interbedded arkosic sandstones and tuffaceous and bentonitic mudstones. The arkose is similar to the Puddle Springs Arkose and the mudstones are similar to the overlying Wagon Bed Formation. Calcareous cement in the Upper Transition Zone is absent and the color of the rocks is generally yellow-grey to grey.

Most beds of the Puddle Spring Arkose Member are poorly consolidated. Cementing materials, where they are found, consist of clay, calcium carbonate, gypsum, goethite, limonite, jarosite, pyrite, marcasite, black manganese oxides, and silica.

A.1.1.2 Wagon Bed Formation

The Wagon Bed Formation of Middle and Late Eocene age is about 400 ft (121 m) thick and consists of bentonitic, tuffaceous, and arkosic mudstone, sandstone, and conglomerate. The arkosic material decreases upward in the sequence as the volcanic material increases. The rock is generally yellow-grey to light green.

A.1.2 Ore Deposits

The ore deposits in the Gas Hills District occur at or near the water table within the Puddle Springs Arkose member of the Wind River Formation.[1] Unoxidized portions of the ore bodies contain coffinite and uraninite as the main ore minerals in association with pyrite, calcite, and gypsum. In the oxidized zone the principal ore minerals are meta-autunite, phosphuranylite, and uranophane.

A.1.3 Minor and Trace Element Distribution

The distribution of several minor and trace elements in the Gas Hills District is shown in Figure A.2.[2] The elements considered are those which were found to be affected by the oxidation-reduction chemistry of roll-front uranium deposits in the Shirley Basin, Wyoming[3] (see following sections).

A.2 SHIRLEY BASIN, WYOMING

A.2.1 Stratigraphy

Igneous, metamorphic, and sedimentary rocks represented in the Shirley Basin area range in age from Precambrian to Quaternary. The igneous and metamorphic rocks, as well as Paleozoic sedimentary rocks, are exposed mainly in the Laramie Mountains. Tertiary sedimentary rocks are widespread at the surface in the basin and are the host rocks for the uranium mineralization. The Wind River Formation of early Eocene age, containing the uranium deposits, was deposited in a basin-like depression in rocks of Paleozoic and Mesozoic age. Table A.2 summarizes the stratigraphy of the area.[3]

The coarse clastic material at the base of the Wind River Formation consists of Precambrian granite boulders and smaller fragments of quartzite, chert, sandstone, limestone, etc., derived from the Paleozoic and Mesozoic rocks that flanked the mountain ranges during early Eocene time. The conglomerate, interbedded with thin silt beds, contains little or no cement. The conglomerate is between 5 and 15 ft (1.5 and 45 m) thick and is overlain by 100 to 200 ft (30 and 60 m) of sandstone and some interbedded conglomerate. In some places, considerable siltstone is present in this lower interval. The upper 100 to 200 ft (30 to 60 m) of the Wind River Formation contains considerable clayey, greenish-grey siltstone, generally in beds 5 to 20 ft (1.5 to 6 m) thick, intercalated with sandstone. The sandstone lenses and beds contain the area's uranium deposits.

The total thickness of the Wind River Formation west of the mining area is 425 ft (129 m). The formation thins to the north and to the east to a minimum thickness of about 15 ft (4.5 m). The regional dip of the Tertiary beds is 1 or 2° to the north.

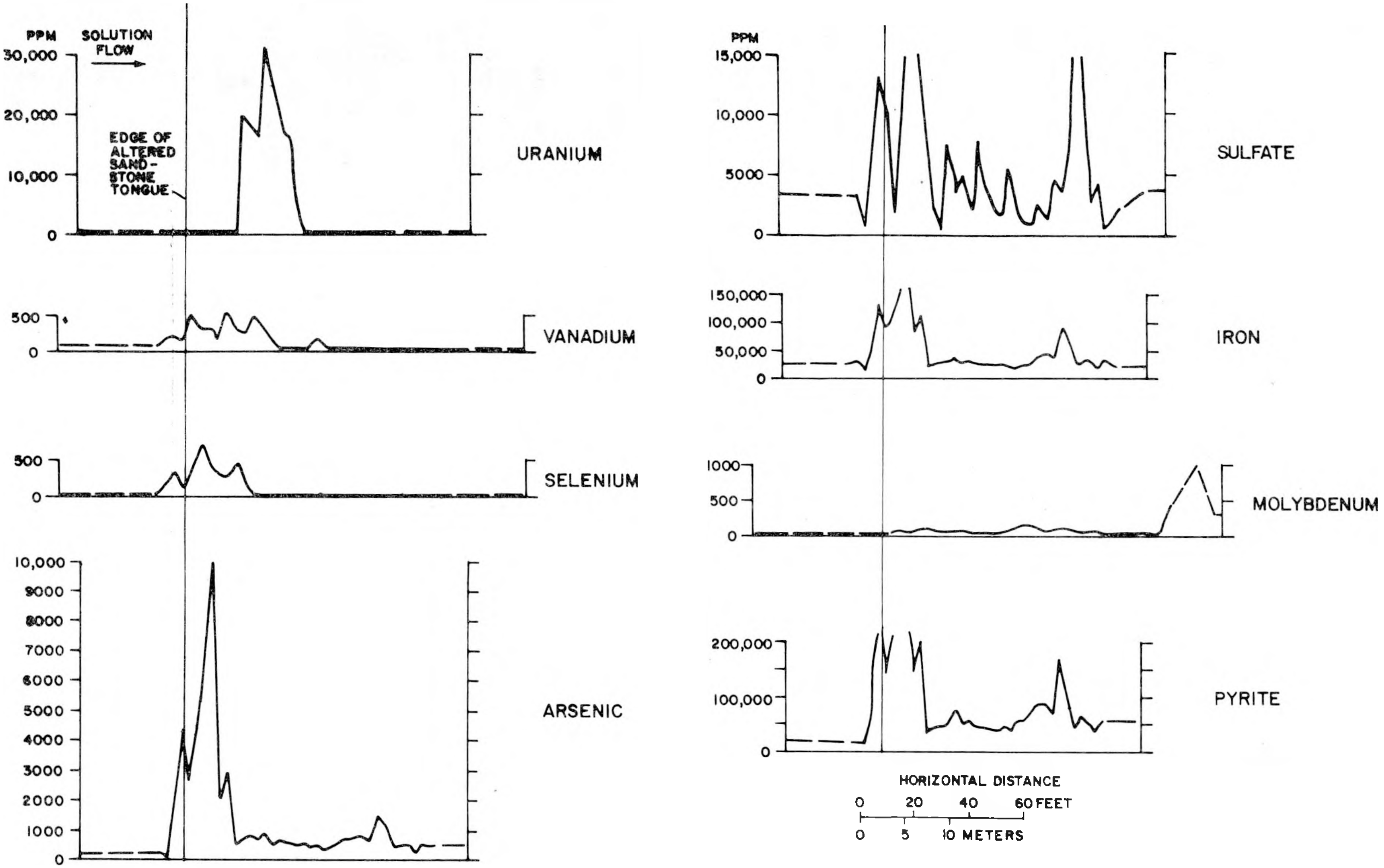


Figure A.2. Distribution of trace elements associated with ore deposits in Gas Hills, Wyoming.[2]

TABLE A.2
STRATIGRAPHIC UNITS IN THE SHIRLEY BASIN AREA, WYOMING[3)]

Geologic time unit				Rock unit	Approximate thickness (ft)	Description
Cenozoic	Quaternary	Holocene		Stream alluvium and terrace gravel	0–50	Surficial deposits of silt, sand, and gravel; in some areas includes terrace gravel.
		Pleistocene				
	Tertiary	Miocene		Arikaree Formation	180	Tuffaceous siltstone, sandstone, conglomerate, and fresh-water limestone of fluvial and lacustrine origin.
		Oligocene		White River Formation	750	Upper member — tuffaceous siltstone and conglomerate; fluvial and lacustrine. Lower member — tuffaceous siltstone and claystone; predominantly fluvial and lacustrine.
		Eocene	Late and middle	Wagon Bed Formation	150	Tuffaceous siltstone, sandstone, conglomerate, and limestone; fluvial and lacustrine.
			Early	Wind River Formation	500	Silty claystone, siltstone, arkosic sandstone, and conglomerate; fluvial.
Mesozoic	Cretaceous			Steele Shale	2,000	Thin-bedded carbonaceous shale, lenticular sandstones near top.
				Niobrara Formation	900	Thin-bedded carbonaceous shale, in part calcareous.
				Frontier Formation	860	Thin-bedded carbonaceous shale and sandstone; Wall Creek Sandstone Member at top.
				Mowry Shale	110	Thin-bedded siliceous shale; contains fish scales.
				Thermopolis Shale	185	Thin-bedded carbonaceous shale; Muddy Sandstone Member near base.
				Cloverly Formation	200	Sandstone, moderately cemented, even-bedded to crossbedded; carbonaceous shale in middle.
	Jurassic			Morrison Formation	200	Variegated waxy mudstone and siltstone; sandstone near base; limestone concretions.
				Sundance Formation	240	Thin-bedded and fissile shale, sandstone, and sandy limestone.
	Triassic			Jelm Formation	125	Shale and ledge-forming sandstone; red to buff.
				Alcova Limestone	20	Crinkly limestone and limy sandstone.
				Red Peak Formation	580	Siltstone and shale, red; sparse sandstone.
Paleozoic	Permian			Goose Egg Formation	400	Siltstone and sandstone, red; interbedded limestone.
	Pennsylvanian			Casper Formation	650	Dolomitic limestone and sandstone; overlain by crossbedded sandstone and quartzite.
	Mississippian			Madison Limestone	150	Dolomitic limestone; cherty near top; conglomerate and sandstone at base.
Precambrian				Granitic and metamorphic rocks and mafic dikes.		

A.2.2 Ore Deposits

The main ore bodies in the Shirley Basin occur in a belt extending northwest-southeast for about 6 mi (9.6 km) through the central part of the basin. The ore occurs as roll-type deposits in chemically favorable sandstone beds of the Wind River Formation, at the interface between large tabular bodies of altered and unaltered sandstone. The two principal altered sandstone units are separated by 50 to 75 ft (15 to 23 m) of unaltered siltstone, lignitic siltstone, and silty claystone. The upper sandstone unit is locally separated into two sands by 30 to 40 ft (7 to 12 m) of sandy siltstone. The upper sands range in thickness from a few feet (meters) at the western edge to about 70 ft (21 m) near the center of the basin. The lower sandstone ore horizon is in a single sandstone unit that overlies the pre-Tertiary erosion surface. This unit is about 35 ft (11 m) thick as exposed in the Petrotomics pit.[3]

Individual ore bodies in the Shirley Basin are not extensive. Dimensions of the larger known ore bodies are up to 200 ft (61 m) wide, 30 ft (1 m) thick, and a few hundred to a few thousand feet long (parallel to the altered tongue edge). Such an ore body may contain several hundred thousand tons of ore with an average grade of between 0.1 and 0.7 percent U_3O_8.

A.2.3 Ore Mineralogy

The main epigenetic minerals found in the uranium deposits of the Shirley Basin are pyrite, marcasite, uraninite, ferroselite, native selenium, hematite, and calcite. Because the ores are unoxidized, no secondary uranium minerals are found.

Uraninite is the only ore mineral identified in the ore bodies of the Shirley Basin, but it is possible that small amounts of coffinite also are present. The uraninite coats grains of the host sandstone, fills interstices between grains, and in some places fills fractures in grains. In many cases, the uraninite coats pyrite-marcasite, which itself coats sand grains.

A.3 POWDER RIVER BASIN

The location of the Powder River Basin is shown on the index map of Wyoming in Figure A.3. The basin is in a north-south aligned syncline in which the Tertiary fluvial deposits have been laid down. In the southern part of the basin, the source of the sediments was from the south, and the sediments dip from 1° to 3° northward.

Three stratigraphic units of Tertiary age are recognized in the Powder River Basin. The Fort Union Formation, which is the host for the uranium deposits, thickens from a featheredge on the southern margin of the basin to 3,300 ft (1,000 m) in the central portion of the basin. The unit overlies the Cretaceous Lance Formation and is, in turn, overlain unconformably by the Eocene Wasatch Formation. The Fort Union Formation

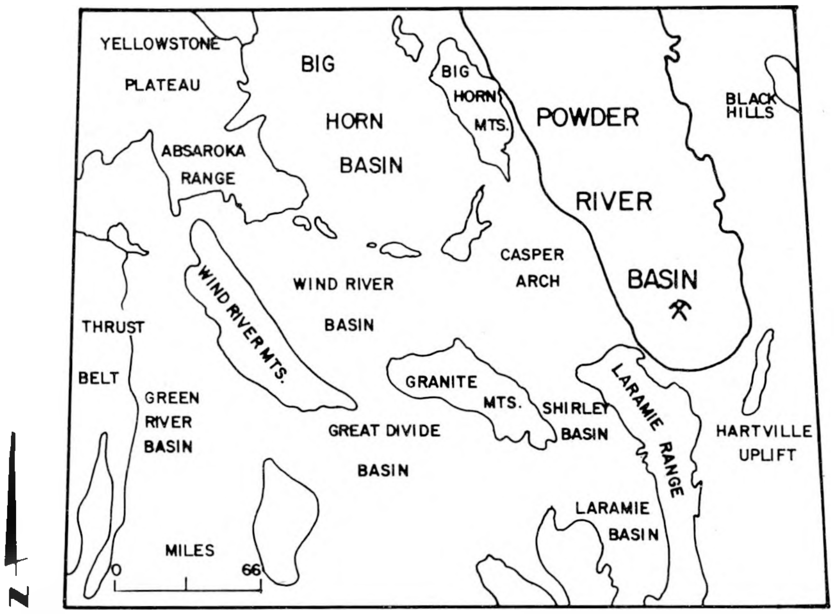


Figure A.3. Index map showing the location of the Powder River Basin, Wyoming.

is composed of interbedded fine- to coarse-grained sandstone, siltstone, claystone, lignite, and coal. The materials which make up the formation in the southern part of the basin were derived from Mesozoic and Paleozoic sedimentary rocks, from Precambrian crystalline rocks of the Laramie Range and the Granite Mountains, and from volcanic debris from the Absaroka volcanic center near Yellowstone.

The portion of the Fort Union Formation which is the host for the uranium ores is locally referred to as the Highland Sandstone. This sandstone is relatively consistent laterally and underlies a large area in the southern portion of the basin.[4]

The Highland sandstones are arkosic, loosely consolidated, and contain substantial organic debris and tuffaceous material. The sandstones are located in the upper part of the Fort Union Formation, as illustrated on the east-west cross section in Figure A.4.

Individual sandstones that contain the uranium deposits are tongue-like extensions off the edge of the central Highland sandstone unit, which is located approximately 3.8 mi (6 km) from the area of the ore deposits and attains a maximum thickness of 165 ft (50 m). The massive sandstone unit consists of discontinuous sands separated vertically by siltstones, claystones, and lignites; laterally, the sandstones exhibit facies changes into carbonaceous claystone and lignites.[4]

A.3.1. Ore Deposits

The detrital minerals that are found in the host Highland Sand units in the Powder River Basin are crystalline quartz, feldspar, and chert and rock fragments. Uranium occurs predominantly as coffinite with lesser amounts of uraninite. The coffinite occurs as thin sooty layers generally less than 10 microns in thickness and as irregular botryoidal masses. Other authigenic minerals in the sandstones are: hematite, goethite, pyrite, calcite, selenium, and sulfides of lead, zinc, nickel, cobalt, and manganese oxides.

Pyrite is found widely distributed in the unoxidized sandstones in the Powder River Basin and is more highly concentrated in the ore or in mineralized zones than in the protore; its distribution is similar to that in the Shirley Basin and in the Gas Hills district. Pyrite has been virtually totally destroyed in the oxidized and altered sandstones where hematite is the most common alteration product and goethite is the alteration product adjacent to the reaction front. The protore pyrite is thought to have been formed by the reaction of iron with H_2S generated during diagenesis by sulfate-reducing bacteria which probably existed in the anaerobic, organic muds.

Calcite occurs as a cement in thin seams mainly along the tops and bottoms of the host sandstone units. The altered sandstones updip of the uranium deposits are virtually barren of calcite.[4]

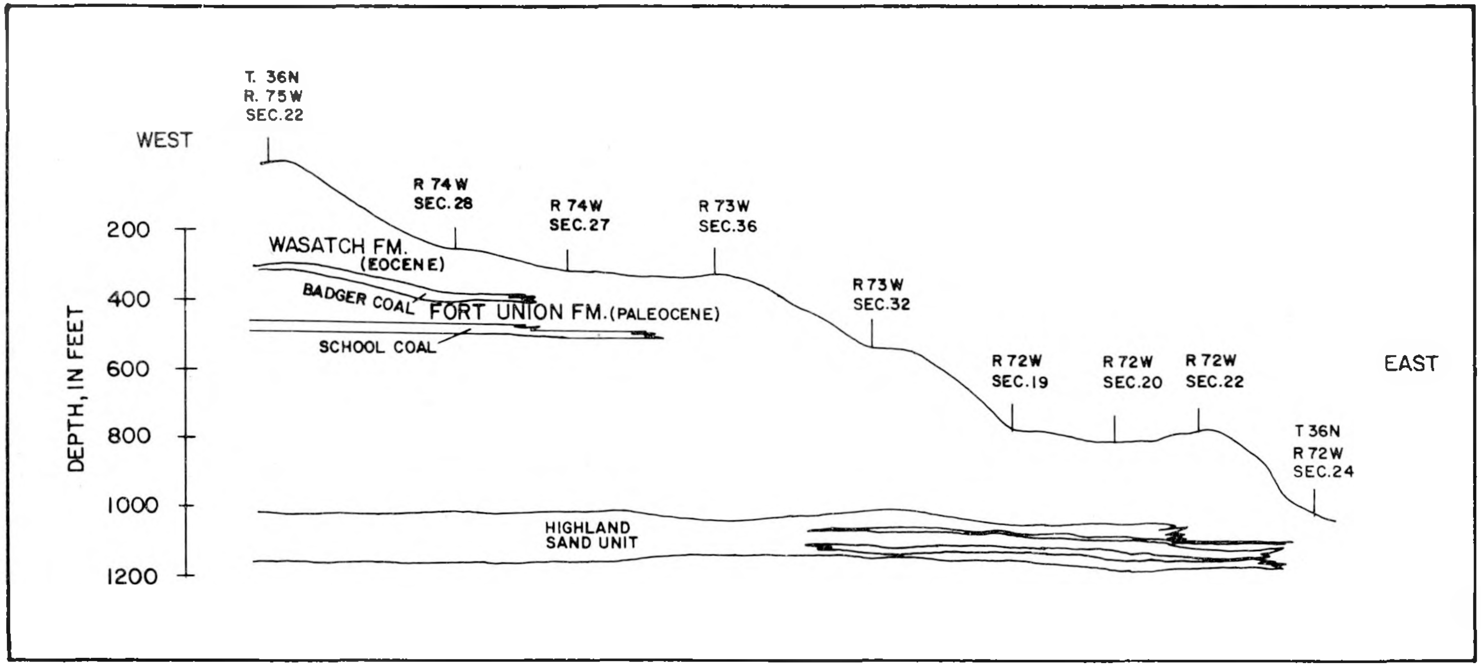


Figure A.4. Stratigraphic cross section showing the uranium-bearing units of the Fort Union Formation, Powder River Basin, Wyoming.[4]

A.3.2 Minor and Trace Element Distribution

Many trace metals commonly associated with uranium in sandstones of other areas are not found in the Powder River Basin in significant quantities. Selenium is not common and its distribution is irregular. Vanadium is sometimes found with uranium but often is not found at all. Molybdenum is not present and lead, zinc, manganese, nickel, and cobalt are present erratically and only in minute amounts.

A.4 MONUMENT VALLEY-WHITE CANYON DISTRICT

A.4.1 Stratigraphy

About 5,000 ft (1,515 m) of Permian and Triassic sediments were deposited in the Monument Valley-White Canyon area of southeast Utah and northern Arizona. The formations and their thickness and general character are shown on Figure A.5.[5]

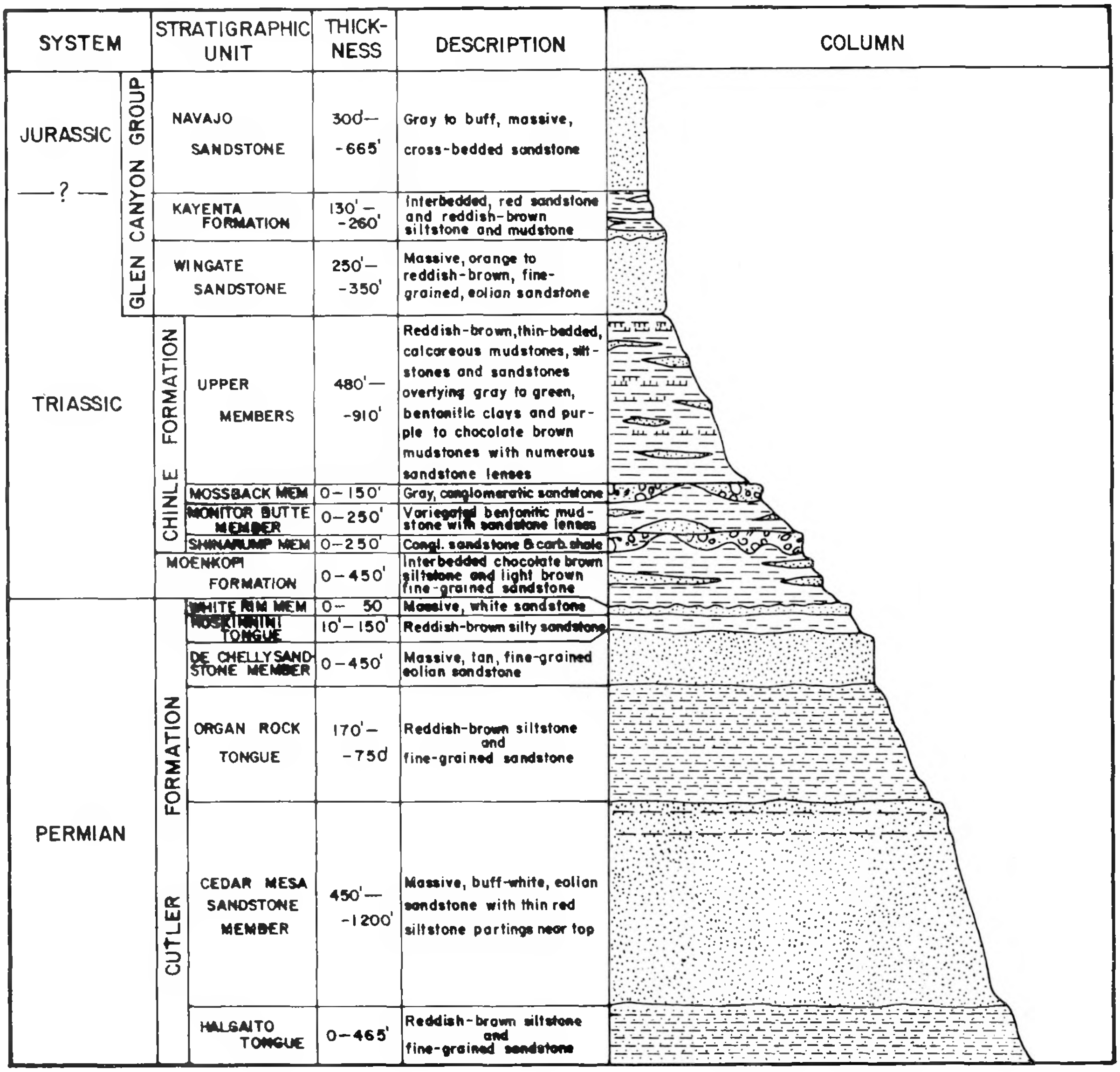
The important uranium deposits in the district are restricted to the Shinarump member of the Chinle Formation. This formation lies unconformably upon the Moenkopi Formation and consists of sediments deposited in stream channels and floodplains. Lenticular beds of sandstone, conglomerate, siltstone, and mudstone are typical. Carbonized and silicified wood fragments are common and calcite is the principal cementing material. The thickness of the Shinarump is variable from about 10 ft to 250 ft (3 to 76 m) because of erosion.

The Monitor Butte Member consists of a thin and discontinuous basal sandstone unit overlain by a thick mudstone. The Monitor Butte Member is thickest in northern Arizona where it is approximately 250 ft (76 m) thick. It thins northward to a feather edge as a result of erosion which preceded deposition of the Moss Back Member.

The Moss Back Member is only present in the northeastern portion of the Colorado Plateau where it is the host for uranium deposits, principally in the Lisbon Valley area. This member is composed of sandstone, siltstone, mudstone, and some conglomerate sandstone. The Moss Back Member ranges from a feather edge in the south to 150 ft (45 m) thick to the north.

The upper members of the Chinle Formation consist of about 500 to 1,000 ft (152 to 304 m) of varicolored mudstone and siltstone with minor sandstones.

The uranium deposits of the Monument Valley-White Canyon area are generally restricted to the carbonaceous sandstone and conglomerate beds at the base of the Shinarump Member of the Chinle Formation. In cross section, they are sometimes lens-like or pod-like, but more often have the typical roll-front configuration. The lengths of the ore bodies range from a few feet to thousands of feet and their thicknesses range from a few inches to 10 or 15 ft.[6]



SYSTEM	STRATIGRAPHIC UNIT		THICKNESS	DESCRIPTION
JURASSIC	GLEN CANYON GROUP	NAVAJO SANDSTONE	300'— -665'	Gray to buff, massive, cross-bedded sandstone
—?—		KAYENTA FORMATION	130'— -260'	Interbedded, red sandstone and reddish-brown siltstone and mudstone
TRIASSIC		WINGATE SANDSTONE	250'— -350'	Massive, orange to reddish-brown, fine-grained, eolian sandstone
	CHINLE FORMATION	UPPER MEMBERS	480'— -910'	Reddish-brown, thin-bedded, calcareous mudstones, siltstones and sandstones overlying gray to green, bentonitic clays and purple to chocolate brown mudstones with numerous sandstone lenses
		MOSSBACK MEM	0–150'	Gray, conglomeratic sandstone
		MONITOR BUTTE MEMBER	0–250'	Variegated bentonitic mudstone with sandstone lenses
		SHINARUMP MEM	0–250'	Congl. sandstone & carb. shale
	MOENKOPI FORMATION		0–450'	Interbedded chocolate brown siltstone and light brown fine-grained sandstone
PERMIAN	CUTLER FORMATION	WHITE RIM MEM	0– 50	Massive, white sandstone
		HOSKININNI TONGUE	10'–150'	Reddish-brown silty sandstone
		DE CHELLY SANDSTONE MEMBER	0–450'	Massive, tan, fine-grained eolian sandstone
		ORGAN ROCK TONGUE	170'— -750'	Reddish-brown siltstone and fine-grained sandstone
		CEDAR MESA SANDSTONE MEMBER	450'— -1200'	Massive, buff-white, eolian sandstone with thin red siltstone partings near top
		HALGAITO TONGUE	0–465'	Reddish-brown siltstone and fine-grained sandstone

Figure A.5. Stratigraphy of the Monument Valley - White Canyon area, Arizona and Utah.[5]

A.4.2 Ore Deposits

In the unoxidized portions of the ores in the Monument Valley-White Canyon district, uraninite and coffinite are the main uranium minerals. Vanadium minerals in this unoxidized ore are commonly montroseite, corvusite, doloresite, and vanadium hydromica. Sulfides of iron, copper, and lead are also present.

Calcium carbonate is present as the cementing material in most of the mineralized sandstone units. In the Monument Valley mines, calcium carbonate ranges from 1.4 to 10.3 percent; in the White Canyon mines it ranges from 1.3 to 8 percent.

The vanadium and copper content of the ores in this district is relatively high, and for many years the mines in the area were a principal source of vanadium. As much as 1.2 percent V_2O_5 and 2.5 percent copper have been determined in ore assays. In general, the vanadium content of ore in Monument Valley decreases from east to west and the copper content increases in the same direction.[5]

A.5 URAVAN DISTRICT

A.5.1 Stratigraphy

The Morrison Formation is the host rock for most of the uranium deposits in the Uravan district (Figure A.6) and is divided into two members: the Salt Wash Member and the Brushy Basin Member. The Salt Wash Member has an average thickness of about 250 ft (76 m) and consists of three prominent sandstones separated by layers of mudstones and thin sandstones lenses. The sandstone units are remarkably similar throughout the district, consisting of fine to medium grained quartz sand with minor amounts of feldspar, chert, and heavy minerals. Clay minerals occur as films coating sand grains and as lenses of claystone and mudstone. Iron occurs as limonite in the light brown portions of the sandstone and as pyrite and marcasite in unoxidized portions of the unit. Cementing materials in the sandstones consist of silica, calcite, dolomite, and gypsum. Carbonaceous material occurs in certain portions of the ore-bearing sandstone, representing coalified remains of vegetal matter.

The Brushy Basin Member ranges from 400 to 500 ft (121 to 151 m) in thickness and consists of variegated mudstone, with lenses of siltstone, sandstones, and conglomerates, principally in the lower portion.

The ore deposits of the Uravan Mineral Belt are relatively small tabular or podlike bodies, commonly elongate in the direction of the long axis of sandstone channels. Typical roll-front deposits are a few feet wide, 5 to 10 ft (1.5 to 3 m) thick, and several hundred feet (meters) long. Individual ore bodies commonly contain about 3,000 ton (2730 tonne) of ore.[7]

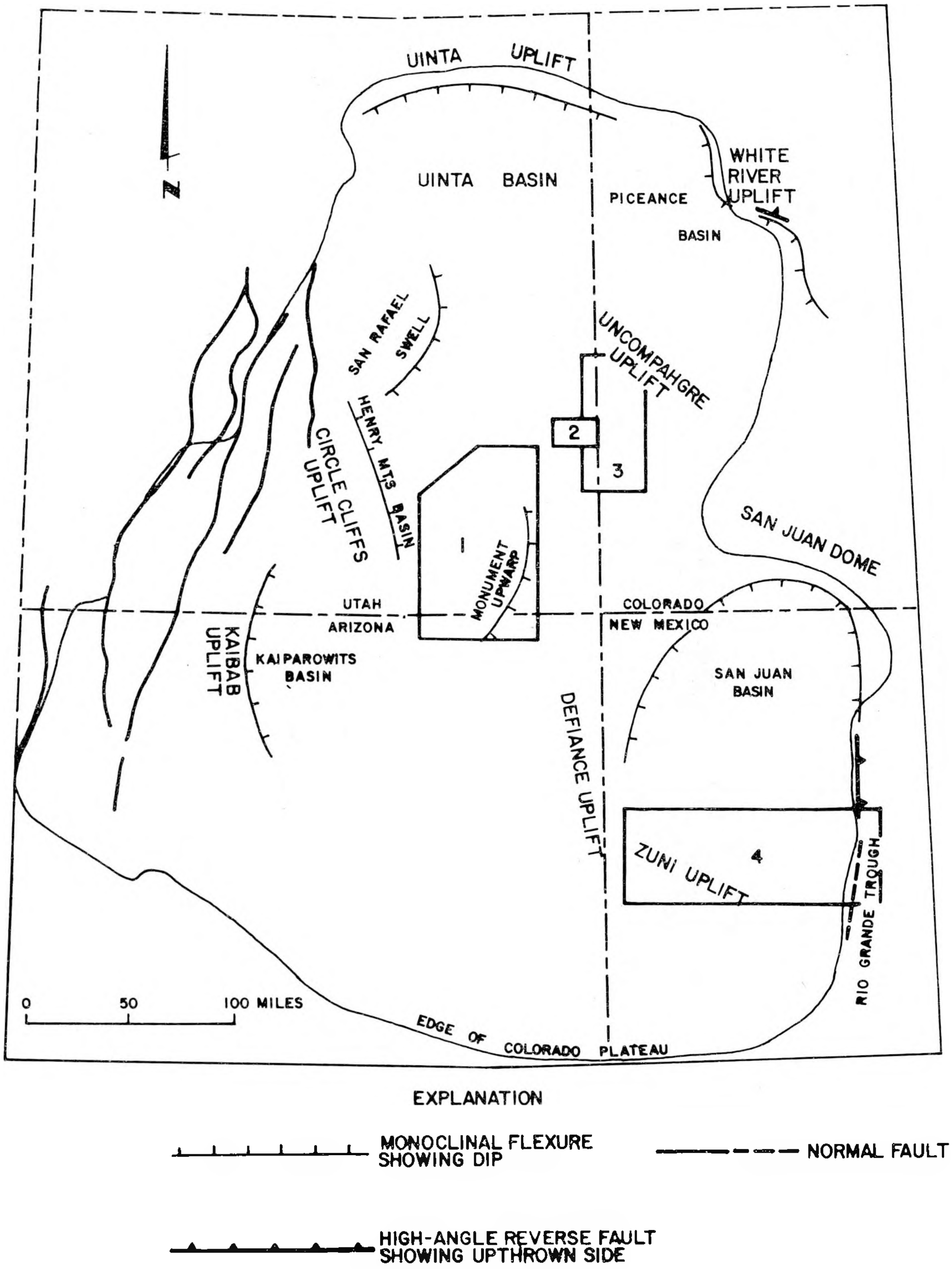


Figure A.6. Principal uranium mining districts of the Colorado Plateau: (1) Monument Valley - White Canyon; (2) Lisbon Valley; (3) Uravan Mineral Belt; and (4) Grants/Laguna.[7]

A.5.2 Ore Deposits

The principal uranium minerals in the unoxidized ores are uraninite and coffinite; in the oxidized ores, carnotite with some tyuyamunite are the representative minerals. Vanadium-bearing clays are the main vanadium minerals in both the oxidized and unoxidized ore. Montroseite is the main reduced vanadium species, and upon oxidation, carnotite, hewettite, maetahewettite, pascoite, rauvite, fervanite, and hummerite are formed; these minerals, however, account for only an insignificant portion of the total vanadium. The ores of the Uravan Mineral Belt have vanadium-to-uranium ratios of 3:1 to 10:1 and no significant deposits of one metal have been found without the other. Associated trace metals are molybdenum, copper, silver, selenium, chromium, nickel, cobalt, rare earths, and manganese.[7]

A.6 AMBROSIA LAKE DISTRICT, GRANT'S MINERAL BELT

A.6.1 Stratigraphy

The Morrison Formation is the host for most of the uranium deposits in the Ambrosia Lake District (see Figure A.6). It is underlain by the Bluff Sandstone of Late Jurassic age and is overlain by the Dakota Formation of Early Cretaceous Age. The Morrison Formation is divided into three members: the Recapture, the Westwater Canyon, and the Brushy Basin Member (Figure A.7).

The Recapture Member is composed of alternating variegated greenish-grey mudstone, purplish and greyish red silty sandstone, and minor amounts of white and buff, coarse-grained, lenticular sandstones. This member varies in thickness from 137 to 232 ft (41.5 to 70 m).

The Westwater Canyon Member is a fluvial arkosic sandstone interstratified with minor amounts of mudstone. The member ranges in thickness from 30 to 270 ft (9 to 82 m). This unit was deposited by anastomosing streams which produce a complex of discontinuous channel sands. The grain size of the sandstones varies from very fine to very coarse.

The Brushy Basin Member consists of gray, greenish-gray, and yellow siltstone and mudstone with scattered thick sandstone lenses that are similar in lithology to the Westwater Canyon Sandstones. The total thickness of this member is between 62 and 128 ft (19 to 39 m). One sandstone bed near the base of the Brushy Basin Member is widespread and is known as the Poison Canyon Tongue. In some places in the district, it rests upon the Westwater Canyon Member and is indistinguishable from it; elsewhere it is separated from the Westwater Canyon Member by about 40 ft (12 m) of mudstone. Near Laguna, a thick sandstone channel in the Brushy Basin Member of the Morrison has been named the Jackpile Sandstone, which is the host rock for uranium ore at the Jackpile Mine.

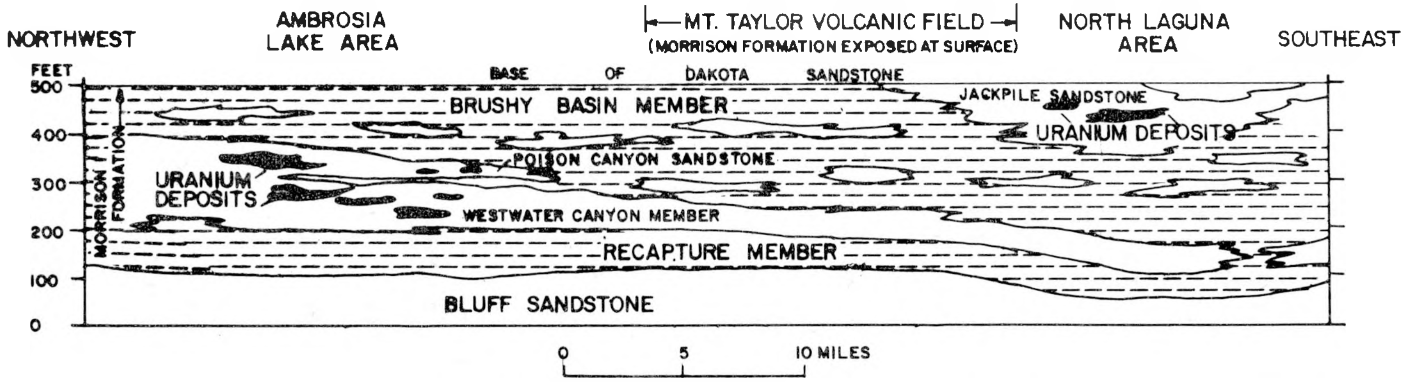


Figure A.7. Cross section of the Ambrosia Lake District, New Mexico showing the stratigraphy of the Morrison Formation.[9]

A.6.2 Ore Deposits

The uranium ore bodies are typically layered, parallel, or subparallel to the stratification, and occur at all stratigraphic horizons in the Westwater Canyon Member and in the Poison Canyon Tongue of the Brushy Basin Member. The unoxidized ore bodies of Ambrosia Lake have been divided into pre-fault ore and post-fault ore. The pre-fault ore appears to be the dominant type, in which mineralization is strictly controlled by stratigraphic parameters; the post-fault ores are controlled by both stratigraphic and structural features. In the Ambrosia Lake District, individual ore bodies are arranged en echelon, both vertically and horizontally, and are as much as 3,000 ft (909 m) long, several hundred feet (meter) wide, but rarely more than 15 ft (4.5 m) thick.

The principal uranium minerals in the unoxidized deposits are coffinite, uraninite, and uraniferous carbonaceous material. The common secondary uranium minerals found in the Ambrosia Lake District are tyuyamunite, metatyuyamunite, carnotite, zippeite, andersonite, and bayleyite.

The non-ore epigenetic minerals commonly found in the district are pyrite, marcasite, calcite, jordisite, ilsemannite, ferroselite, native selenium, barite, and pascoite. Other minerals identified in the district are autunite, becquerelite, hydrogen-autunite, metatorbernite, phosphuranylite, schoepite, sklodowskite, soddyite, and uranophane.[9]

A.7 GULF COASTAL PLAIN REGION

All of the uranium production from the Gulf Coastal Plain Region is from Tertiary rocks in South Texas, as shown on Figure A.8.

A.7.1 Stratigraphy

The host rocks for the uranium deposits in the Karnes County District are typically sands and sandstones containing volcanic ash, interbedded with bentonitic clays and tuffaceous silts that are locally almost pure volcanic ash. In the Karnes district, considerable amounts of carbonaceous material are present as thin beds of impure lignite. Sands are shallow marine, deltaic-lagoonal and barrier-bar deposits, interbedded with near-shore carbonaceous swamp deposits and beds of water-laid, acid volcanic ash.[10]

In the Live Oak County District of South Texas, the host rocks are fluvial sands which are interbedded with silts and clays. These flood-plain deposits reach a thickness of about 300 feet (100 m).

The Felder uranium deposit in the Oakville District has formed in a carbonate-rich arkose which contains no carbonaceous debris. The ores consist of coffinite and uraninite that coat grains and fill interstices. The reducing agent involved in the precipitation of the uranium is thought to have been hydrogen sulfide from oil and gas reservoirs associated with fault traps.[10]

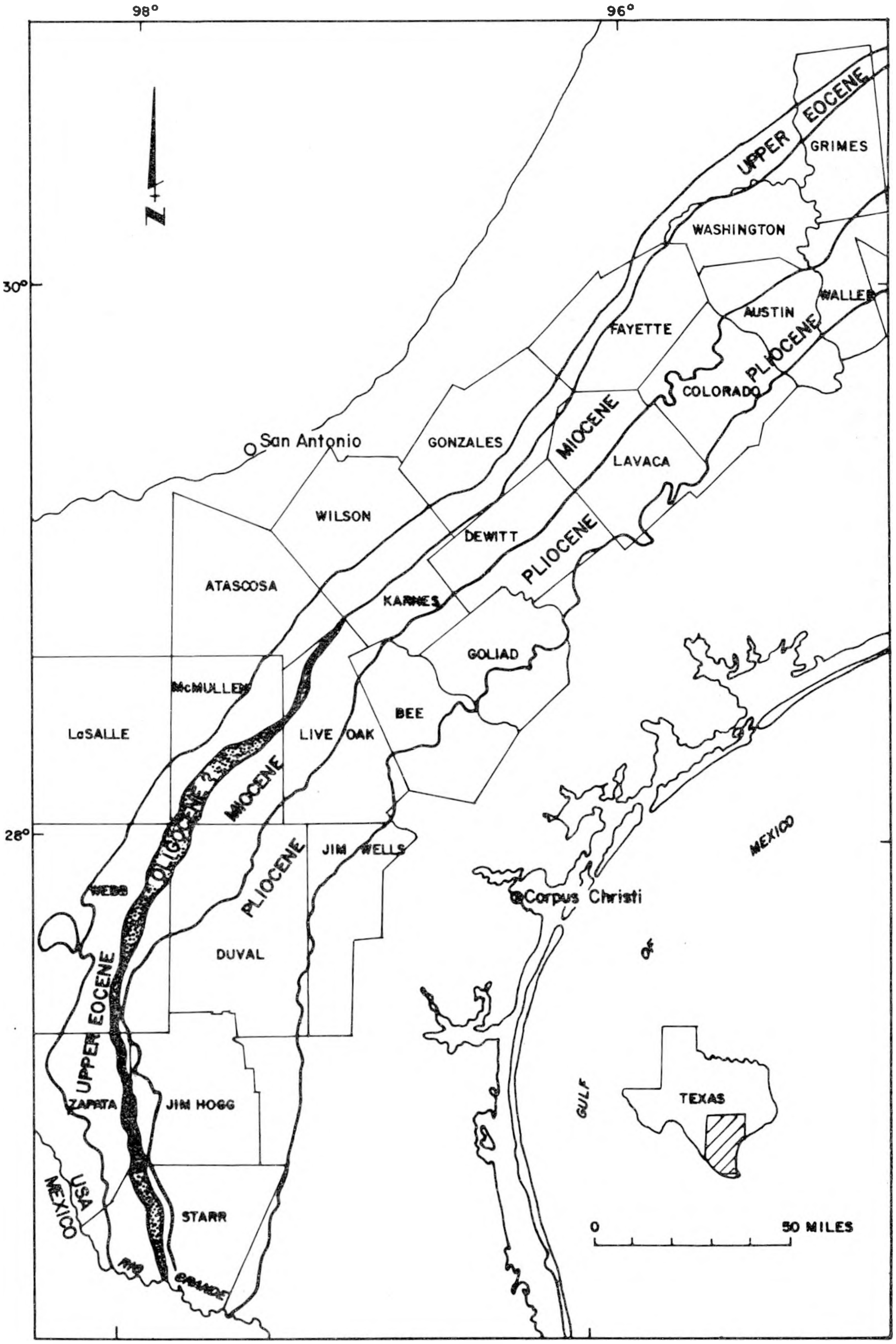


Figure A.8. Outcrop areas of uranium bearing rock on the Gulf Coast of Texas.[10]

A.7.2 Ore Deposits

The uranium minerals found in the oxidized portions of some of the deposits in Texas are uranyl phosphates and silicates. Vanadates are present but are of minor importance. In the reduced portions of the deposits, uraninite and coffinite are the principal ore minerals. Microscopic pyrite is found interstitially in the reduced ore zones in the Oakville District.[10]

A.7.3 Trace Element and Minor Element Distribution

Figure A.9 show the distribution of total iron, uranium, pyrite, selenium, vanadium, arsenic, sulfate, cobalt, copper, and molybdenum along sample traverses from oxidized sandstone, across the ore, and into the reduced zone in front of the ore at two localities in Karnes County and one in Live Oak County, Texas.[2]

A.8 GREAT PLAINS REGION

Most of the historical production of uranium in the Great Plains Region has been from the Southern Black Hills area of South Dakota and Wyoming.

A.8.1 Stratigraphy

Rocks ranging in age from Precambrian to Quaternary are exposed in the Southern Black Hills district, but only two formations in this extensive section appear to be important to uranium mineralization. The Inyan Kara Group of Early Cretaceous age is the principal host unit, and the Minnelusa Formation of Pennsylvanian and Permian age appears to be the main aquifer in the region through which uraniferous waters entered the Inyan Kara Group.

The Minnelusa Formation consists of approximately 1000 feet (303 m) of interbedded sandstone, shale, limestone, dolomite, and anhydrite. The upper half of the section in some localities contains up to 250 ft (76 m) of anhydrite and gypsum in beds up to 25 feet (7.6 m) thick. In other localities throughout the district, no gypsum is found in this section, and only brecciated sandstone and limestones remain. Breccia pipes which generally bottom in the Minnelusa Formation may extend upward for distances of between 200 and 1,300 feet (61 and 394 m); diameters may range from some tens to several hundred feet.[11]

The Inyan Kara Group in the southern Black Hills consists of the Lacota and Fall River Formations of Early Cretaceous Age. The rocks of the group are of continental origin.

The Lacota Formation is composed of the Chilson, Minnewaste Limestone, and Fuson Members and ranges in thickness from 200 to 500 feet (61 to 152 m). The Chilson and overlying Fuson Members consist chiefly of siltstone, claystone, sandstone, and some carbonaceous shale.

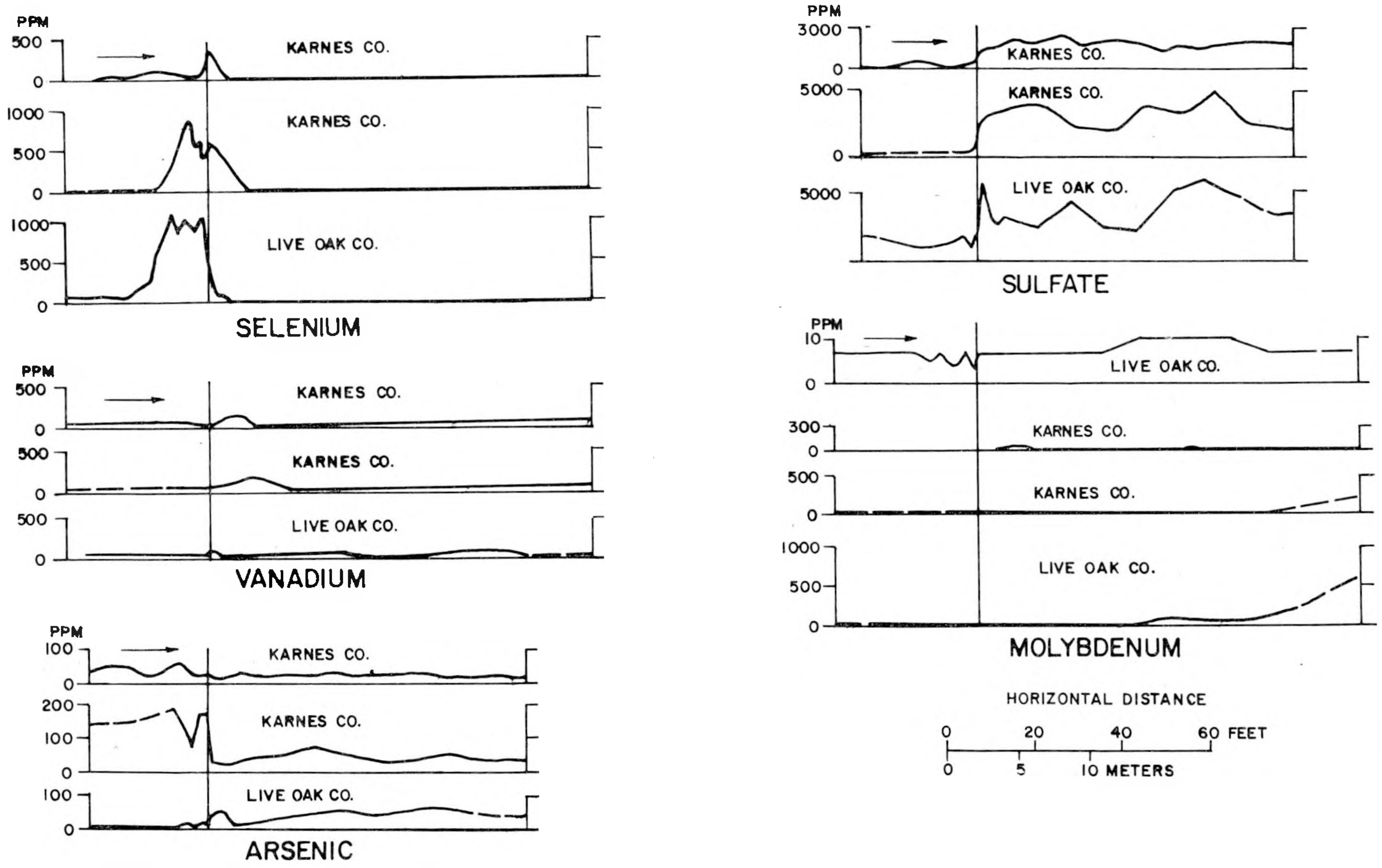


Figure A.9. Distribution of selenium, vanadium, arsenic, sulfate, and molybdenum associated with ore deposits in Texas.[2]

Locally, a lacustrine limestone, called the Minnewaste Limestone Member, overlies the Chilson Member. This unit ranges in thickness from a few inches (cm) to 80 ft (24 m) at its thickest and is commonly brecciated and recemented with calcite.[11]

The Fall River Formation is composed of sandstone, siltstone, and mudstone, 100 to 160 ft (30 to 43 m) thick. The formation is similar to the underlying Lacota and also consists principally of lenticular channel and floodplain deposits, characterized by rapid facies changes.

A.8.2 Ore Deposits

The ore deposits in the southern Black Hills district are confined to four units of the Inyan Kara Group. These units are the moderately carbonaceous Fluvial Unit 1 in the Chilson Member of the Lacota Formation, noncarbonaceous Fluvial Unit 4 of the Fuson Member of the Lacota Formation, the noncarbonaceous Fluvial Unit 5 of the Fall River Formation, and the highly carbonaceous sandstones and siltstones of the lower unit of the Fall River Formation.

The ore deposits associated with the reducing sediments are often partially oxidized and the ore-forming minerals commonly found are corvusite, rauvite, carnotite, tyuyamunite, as well as uraninite and coffinite.[11]

A.8.3 Minor Element Distribution

Figure A.10 shows the distribution of various elements and compounds relative to the oxidation-reduction interface in some uranium deposits of the southern Black Hills. The distribution of the various elements is generally similar to that in other mining districts.

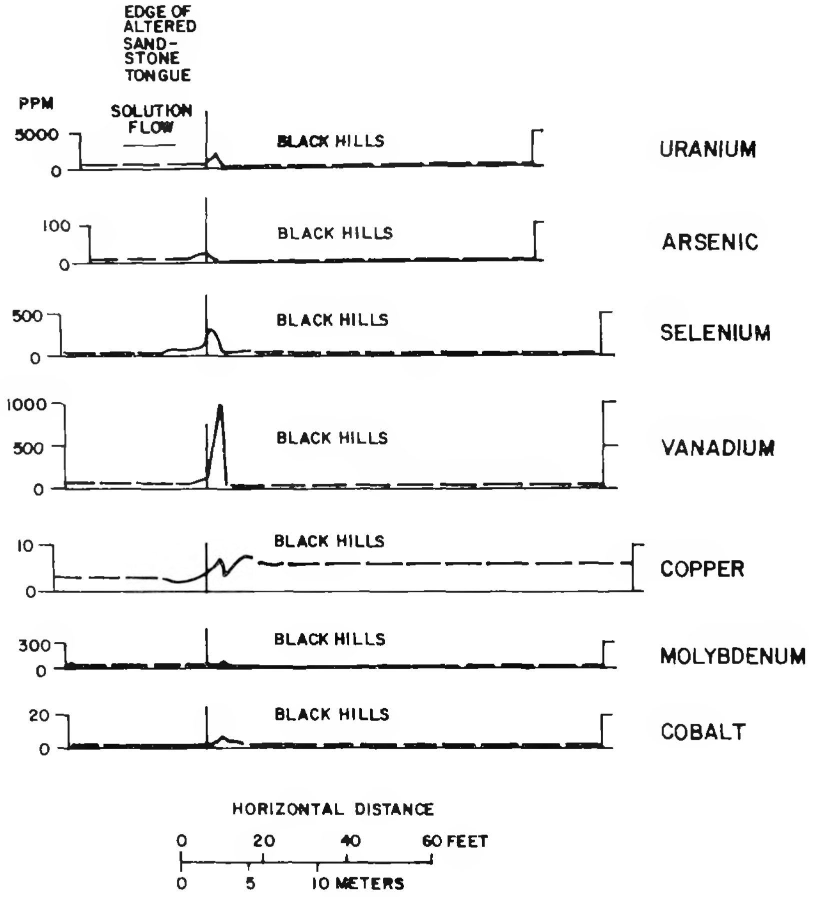


Figure A.10. Distribution of trace elements associated with ore deposits in the Black Hills, South Dakota.[2]

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Appendix B

REGIONAL HYDROLOGY

B.1 THE WYOMING BASINS

B.1.1 Geographical Features

The mountain ranges of the Middle Rocky Mountains and the Black Hills, and the intervening structural basins of Wyoming, began to form during the Laramide (late Cretaceous) mountain-building period. The mountains have cores of igneous and metamorphic rock. Erosion of the mountains provided the sediments that have accumulated in the subsiding basins since early Tertiary time. Thus, as much as 6,600 ft (2,000 m) of predominantly fluvial, deltaic, and lacustrine Tertiary deposits overlie the older rocks at the centers of individual basins. Additionally, lignite and bituminous coal are found in nearly all Wyoming basins and oil shale is present in the Green River Basin. The sedimentary strata are major aquifers throughout the basins and locally are reservoir rocks for petroleum and natural gas. Moreover, about 30 percent of the United States' reserves of uranium are found in the Wyoming basins.

The principal basins, ranges, and other structural elements of the Wyoming area are shown in Figure B.1. A generalized geologic section (Figure B.2) through the Powder River and Bighorn basins of northern Wyoming is representative of other basins in the region.

Landforms are highly variable; they include the deeply dissected and glaciated high mountain ranges and the nearly flat-lying or gently inclined sedimentary rocks of the basins. Rolling hills, plains, river terraces, mesas, and badlands are common features. The older strata, adjacent to the uplifts, dip basinward at steeper angles and form hogbacks in the foothills.

Precipitation varies from 20 to more than 35 in. (50 to 90 cm) per year in the forested mountain ranges, most of it falling as snow. Precipitation in the eastern plains, which occurs mostly in the spring and early summer, is about 12 to 16 in. (30 to 40 cm) annually. In the western basins, precipitation is about 6 to 8 in. (15 to 20 cm), which is only marginally adequate to sustain the region's vast grasslands. Irrigation is required for dependable crop production, and in areas where water supplies are available and the growing season is sufficiently long, as in the lower North Platte and Bighorn river areas, crops such as corn, sugar beets, and potatoes can be grown.

B.1.2 Surface-Water Hydrology

With the exception of the Great Divide Basin that drains internally, the Wyoming basins that have a potential for in-situ leach mining or where the method is presently (1978) in use are located to the northeast of the continental divide and thus drain in that direction to the Missouri

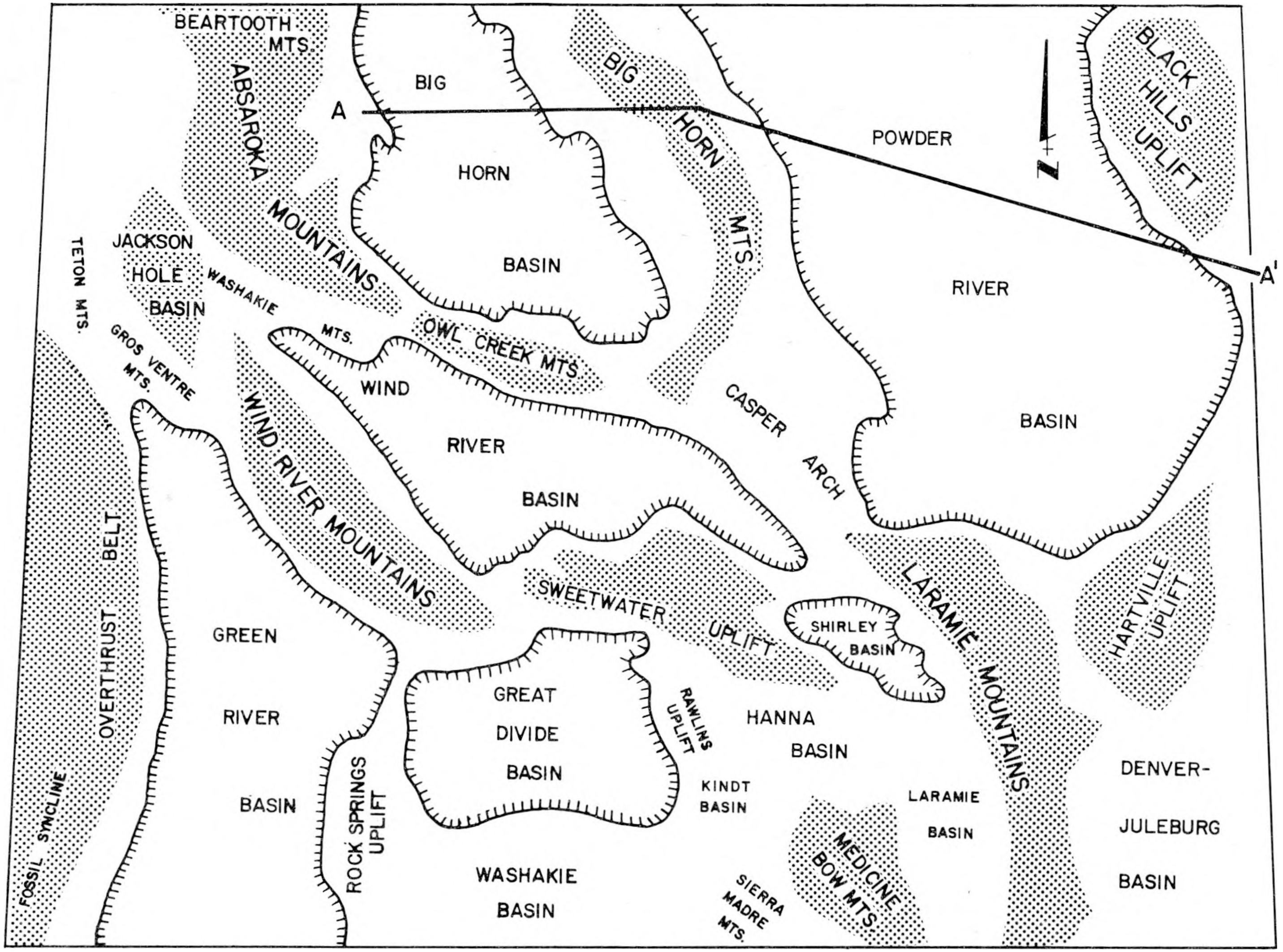

Figure B.1. Geologic structure of Wyoming.

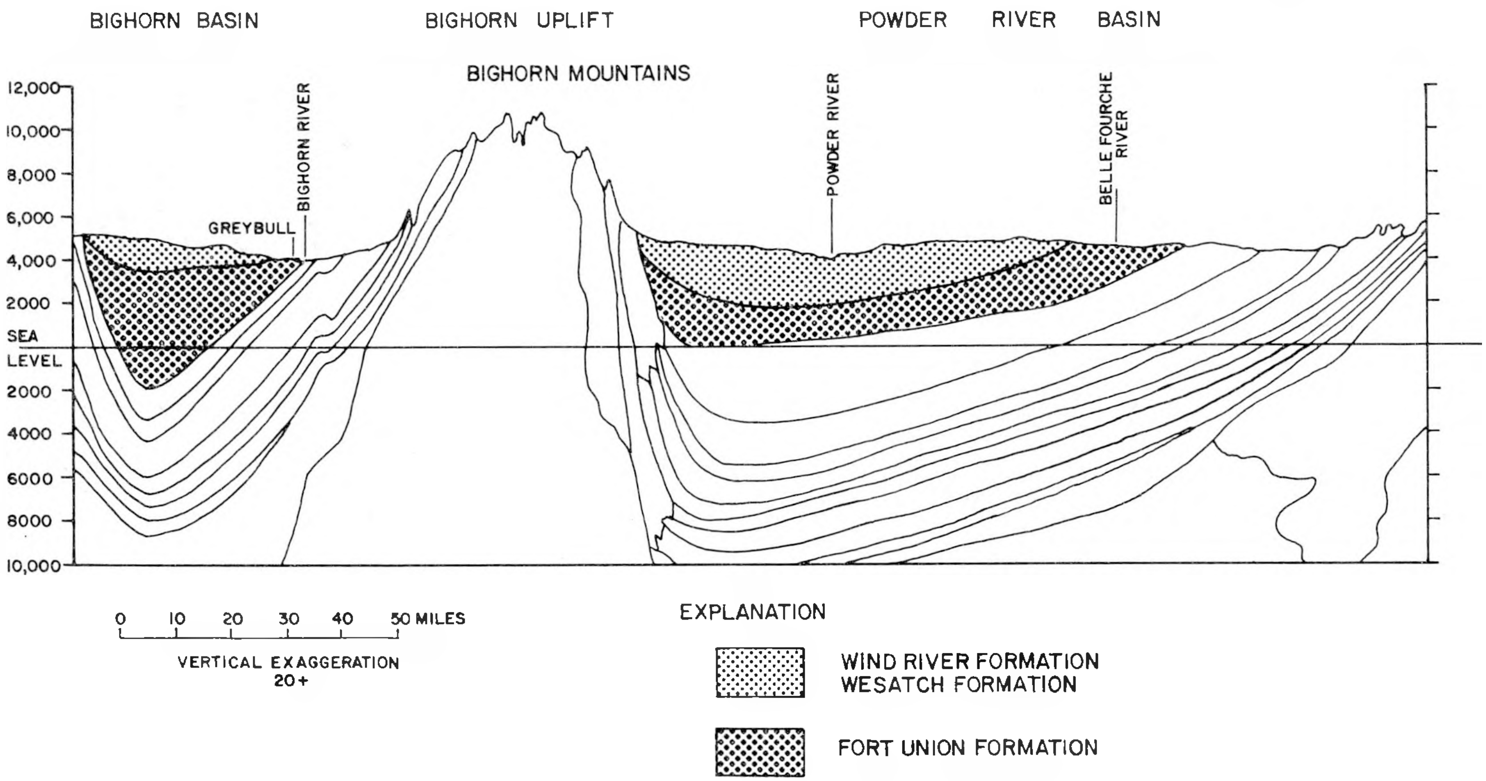

Figure B.2. Geologic cross section (A-A') through the Big Horn and Powder River Basins, Wyoming.[1]

River. The Green River Basin, which may have uranium deposits suitable for in-situ leach mining, is part of the Upper Colorado River Basin and drains southwesterly. Of the tributaries to the Missouri River, the largest within Wyoming is the Bighorn River and its major tributary, the Wind River. The Powder River structural basin is drained by the north-flowing Powder and Tongue Rivers, and by the Belle Fourche, Little Missouri, and Cheyenne Rivers, flowing to the northeast and east. The North Platte River, within Wyoming, receives considerable inflow from drainage of the Laramie Mountains and drains the Shirley Basin and Crooks Gap areas; major tributaries are the Medicine Bow and Sweetwater Rivers. In addition to these rivers, there are others of perennial flow in their upper reaches, but most stream channels have only intermittent flow. Drainage basins and their relation to the region's structural basins are shown in Figure B.3.

About 80 percent of the annual streamflow, largely resulting from snowmelt, occurs from April to July. During the remainder of the year, baseflow is primarily sustained by effluent ground water. There are considerable departures from average discharges due to variations in precipitation from year to year. The average annual discharge (1948-1968) of the Bighorn River at the northern boundary of Wyoming is about 3.68 million ac-ft (4,540 hm^3), all of which originates within the State. The second largest discharge is that of the North Platte River, 1.22 million ac-ft (1,505 hm^3), about 43 percent of which is from watersheds in Colorado. Major diversions for irrigation are made from these rivers. The average annual discharge of the Powder River is 0.42 million ac-ft (518 hm^3), of which about 16 percent is used for irrigation. Average annual discharges of the principal rivers in the Wyoming basins ea and estimates of major uses of surface water are given in Table B.1.

The streams of northeastern Wyoming carry a considerable silt load during times of high flow, as the result of sparse vegetative cover, the incompetent nature of the surficial deposits, or poor farming practices. Total dissolved solids not only vary with stage and season, but there are wide variations in chemical quality in adjacent areas. Although most of the waters are hard and contain from less than 500 to more than 2,000 mg/l of TDS, they are generally suitable for irrigation and livestock use. The more highly mineralized waters commonly are of the calcium or sodium sulfate type, reflecting ground-water inflow from areas containing gypsum deposits. Another natural source of salinity is the hot springs (3,500 mg/l TDS) in the Bighorn River Basin.

The major use of surface water in northern and eastern Wyoming is for irrigation, amounting to 1.7 million ac-ft (2,100 hm^3) per year or 94 percent of total diversions, the remainder being small amounts for municipal, domestic, stock, and industrial uses. A summary of surface-water use, by river basin, is included in Table B.1. Of a total industrial use of 16,400 ac-ft (20 hm^3), about one half is used by the coal-mining and allied industries, while the oil and gas, mining, cement, and other industries consume the remainder. It is anticipated that the needs of the petroleum industry for surface and ground water will decline as early as 1980 as the result of reservoir depletion. Large amounts of

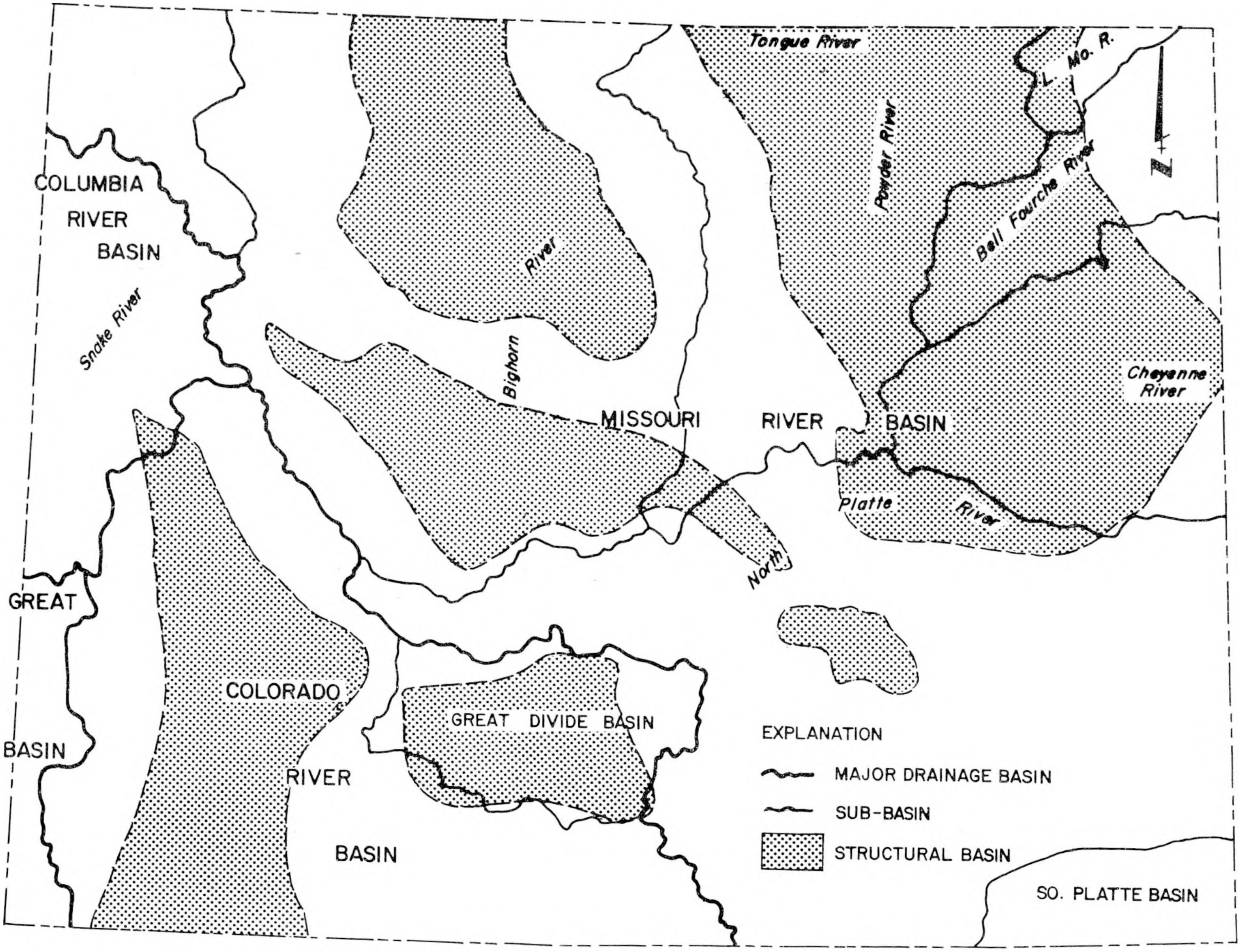

Figure B.3. Drainage and structural basins of Wyoming.

TABLE B.1
AVERAGE DISCHARGE AND WATER USE OF RIVERS IN NORTHERN AND EASTERN WYOMING2)
(Acre-feet)

		Surface-Water Use (1973)			
River Basin	State Line Outflow	Irrigation	Municipal, Domestic, & Stock	Industrial	Total
Bighorn River	3,676,100	1,007,400	5,700	2,200	1,015,300
Tongue River	386,300	77,100	2,400	1,000	80,500
Powder River	419,100	66,100	2,100	700	68,900
Little Missouri River	35,400	1,800	100	---	1,900
Belle Fourche River	96,700	1,500	1,000	1,000	3,500
Cheyenne River	85,700	4,500	600	1,700	6,800
Niobrara River	7,300	3,000	---	---	3,000
North Platte River	1,745,700	573,600	7,300	9,000	589,900
So. Platte River Basin	19,200	3,500	3,000	800	7,300
Total	6,471,500	1,738,500	22,200	16,400	1,777,100

water, however, will be required by the coal industry in the coming years, particularly in the Powder River Basin, where consumption is expected to increase from about 3,000 ac-ft to 468,000 ac-ft (3.7 to 577 hm^3) in 2020.[2] Presumably the needs of the coal and related industries will be met by transbasin surface-water diversions, possibly from the Green or Bighorn River basins. Present and future needs of the uranium mining and milling industries presumably can be met with ground water.

B.1.3 Ground-Water Hydrology

Ground water in the Wyoming basins is found principally in sedimentary strata of Tertiary age, and in more recent alluvial and terrace deposits along major drainageways. Some older sedimentary strata, such as the Madison Limestone, are important aquifers because of their high transmissive capacities.

Shallow ground water in the basins is found under water-table or perched conditions, while the deeper aquifer systems are commonly confined. Recharge to the confined aquifers is in their outcrop areas, adjacent to the mountain ranges. The principal source of ground-water recharge to all aquifers is the direct infiltration of precipitation or the infiltration of streamflow derived from precipitation in the mountain ranges. In the central portions of the basins, precipitation is low and generally inadequate to effect direct recharge of water-table aquifers, except where it might be concentrated intermittently in stream channels. In the lower reaches of perennial streams, ground water is generally effluent, sustaining the baseflow of rivers throughout most of the year. Thus, ground-water flow in the water-table aquifer is controlled by the position and gradient of the rivers, and generally is from areas of high elevations toward the rivers, and then northerly and easterly where the rivers leave the basins.

The unconsolidated alluvial sands and gravels and terrace deposits near the major rivers of northeastern Wyoming commonly yield 500 to more than 1,000 gpm (31 to 63 l/s) to individual wells. Their thickness averages 50 ft (15 m), except near the North Platte River, where alluvium extends to about 300 ft (91 m) and well yields as high as 3,000 gpm (190 l/s) have been reported.[2]

Late and middle Tertiary rocks are predominantly fluvial and lacustrine claystones, siltstones, and sandstones, with tuffaceous siltstones and conglomerates, and include the Arikaree and White River formations. These strata have been largely eroded in the Powder River Basin; the sandstones of these formations are useful aquifers, which may yield several hundred gpm (tens of l/s) from depths of 600 ft (180 m).

The most extensive water-bearing units are the early Tertiary strata in the central portions of the major basins. These are alternating, lenticular shales and sandstones, interbedded with coal and carbonaceous shales of fluvial and lacustrine origin. The units are included in the Fort Union Formation, which is more than 3,000 ft (900 m) thick in parts of the Powder River Basin, as well as the Wasatch and the corresponding Wind River and Battle Spring Formations. These rocks are characterized by abrupt facies changes and by their generally low permeability. Wells commonly yield only 5 to 10 gpm (0.3 to 0.6 l/s) of water of fair to poor quality, although yields as high as 1,000 gpm (63 l/s) have been reported.

Older sedimentary strata have been downfolded in the subsiding basins and are exposed on the flanks of the uplifts. The rocks of late Cretaceous age are similar to the overlying Tertiary rocks in that they consist of shales, carbonaceous shales, some coal, and interbedded sandstones. The latter may be the only available aquifers in some areas; yields are generally low, but may be as high as 500 gpm (31 l/s) from fracture zones. Other Mesozoic formations are generally poor aquifers, consisting of extensive shale sections, interbedded with gypsum and clayey sand, or calcareous sandstones of low permeability.

Rocks of Paleozoic age also crop out adjacent to the mountains and dip basinward to a depth of 10,000 ft (3,000 m) and more. They are shales, calcareous shales, sandstones, limestones, and dolomites. The Tensleep and Amsden formations of Pennsylvanian age are predominantly sandstones that can yield several hundred gpm (tens of l/s) from fracture zones. The Madison Limestone, of Mississippian age, is capable of very high yields from zones of solution channeling. Common productivity is several hundred gpm (tens of l/s), but yields as high as 9,400 gpm (590 l/s) have been reported. Wells completed in fracture zones in the igneous and metamorphic rocks of the mountain ranges generally yield less than 25 gpm (1.5 l/s).

Distance from recharge areas and changes in lithology and permeability of all aquifers cause a considerable vertical and horizontal variation in water quality. Thus, water from the shallow alluvial aquifers and from Tertiary strata may contain from less than 200 to more than 4,000 mg/l of TDS. In the fresher waters, calcium, sodium, and bicarbonate are the dominant ions, whereas the more mineralized waters contain a larger portion of sulfate. The waters are moderately to very hard, but generally suitable for livestock and irrigation use. In many areas of the basins, they are only marginally suitable for domestic use. Ground water in the deeper Tertiary and older strata, including the Madison Limestone, may contain several thousand mg/l TDS, requiring demineralization for some uses if alternate sources are not available. Moreover, in many widely scattered areas of petroleum and natural gas production, the ground water in the reservoir structures may be highly saline, containing as much as 200,000 mg/l TDS.

Some chemical analyses of ground water and water from springs in the Powder River and Shirley basins are given in Table B.2. The data are representative of the fresher ground water in Tertiary strata, with TDS content ranging from 160 to 1,250 mg/l. The dominant ionic constituents are calcium, sodium, sulfate, and bicarbonate; chlorides are characteristically low, ranging from 2 to 32 mg/l. The analyses shown pertain to water samples taken within and close to uranium-ore bodies, and also from sources distant from areas of known uranium mineralization.

TABLE B.2
CONCENTRATIONS OF SELECTED CONSTITUENTS IN GROUND WATER, WYOMING[3,5,6]
(in mg/l)1/

	Shirley Basin				Powder River Basin			
Parameter	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
TDS	1,250	309	160	568		402	452	376
Total Hardness as $CaCO_3$	383	116	92	388		222	55	12
pH	8.2	7.6	7.8	7.0		7.9	8.5	8.8
Ca	114	40	24	126		61	19	4.3
Mg	24.0	3.9	7.8	18.0		17.0	1.9	0.49
Na	268	67	22	14		56	137	122
K	8.4	6.4	2.0	8.4		9.0	2.8	1.3
HCO_3	116	280	134	190		268	103	105
CO_3	0	0	0	0		0	2	9
Cl	32	6.0	2.0	4.0	6.0	8	12	10
SO_4	794	24	29	243	141	119	224	124
NO_3 (as N)	.14	.48	.57	1.5			.05	.03
NH_3 (as N)							.1	.15
F	.6	.1	.4	.1	.2		.34	.64
B	–	–	–	.63	.2		.1	.1
Fe	.01	.09	.00	7.6			.02	.03
Mn	.49	.00	.00	.00			.005	.0001
Pb					0.002		.02	.02
Cd					.002		.005	.005
Cr					<.001		0.11	.005
Hg					<.0001		.0001	.0001
Zn					.007		.04	.12
Ni							.01	.01
As	.00	–	–	.00	.0015		.02	.01
Se	.001	.002	–	.000	<.001		.018	.007
Mo							.1	.04
Cu					<.001		.005	.01
V							.042	.001
U µg/l	14	76	30	26	95		215	1.5
Ra-226 pCi/l	6.8 ± 1.4	1.9 ± .4	2.4 ± .5	2 ± .4	470	0.56	141 ± 12	0.1 ± .4

1/ Except pH, U, and Ra-226.

Consumptive use of ground water in northeastern Wyoming (Table B.3) was 202,200 ac-ft (250 hm^3) in 1973, or about 9 percent of total water consumption. More than one half of the total ground-water consumption was for irrigation, particularly in the Platte River Basin, where ground-water use for irrigation is expected to increase about threefold by the year 2000. A similar increase is forecast for the Bighorn River area, while irrigation use in the other northeastern Wyoming River basins is expected to continue at about present rates.[2] A relatively small amount of ground water, 29,100 ac-ft (36 hm^3), was used in 1973 for municipal and domestic supply and to meet stock requirements. Ground-water consumption for industrial uses was about 45,600 ac-ft (56 hm^3) in 1973, largely by the petroleum, coal, mining, and other industries. The use of ground water in the secondary recovery of petroleum presumably will decline as the result of reservoir depletion in the next few years, whereas larger amounts will be needed by the uranium mining and milling industries. In part, the greatly increasing requirements of the coal and related energy industries may be met by ground water in the future. Relatively large supplies can be obtained from artesian wells tapping the Madison Limestone or Tensleep and Amsden Formations. Demineralization of water from these sources, however, may be necessary for some uses.

Aquifer characteristics, deduced from a small number of pumping tests in the Shirley and Powder River basins, are tabulated in Table B.4. They are believed to be representative of the water-bearing properties of the early Tertiary rocks in other basins of Wyoming.

B.2 COLORADO PLATEAU REGION

Although uranium mineralization in the Colorado Plateau Region is found in sedimentary rocks ranging in age from Cambrian to Eocene, the principal deposits occur in fluvial sandstones of the Morrison and Chinle Formations, of Jurassic and Triassic age. There are three major areas on the Colorado Plateau where in-situ leach mining is applicable: (1) Ambrosia Lake mining district and large adjacent areas of the Grants Mineral Belt, northwestern New Mexico; (2) Monument Valley - White Canyon, southeastern Utah and northern Arizona; and (3) Uravan Mineral Belt, southwestern Colorado and eastern Utah. In a fourth area, the Lisbon Valley District of southeastern Utah, the host rocks (Chinle Formation) apparently are too tightly cemented with calcite to permit in-situ leach mining. These mining areas and the principal tectonic features of the Colorado Plateau are shown on Figure A.6.

B.2.1 Grants Mineral Belt, New Mexico

B.2.1.1 Geographic Features

The Grants mineral belt extends northwesterly from Laguna, New Mexico for about 90 mi (145 m) to the vicinity of Gallup, New Mexico. The belt is about 35 mi (55 km) wide and throughout most of its extent, except along the southwestern margin, uranium is mined from saturated deposits; some mines may be as deep as 2,000 ft (610 m) or more. Potential areas of in-situ leach mining are the Ambrosia Lake Mining District, Smith Lake, Laguna, Church Rock, and Crownpoint.

TABLE B.3
GROUND-WATER USE IN NORTHERN AND EASTERN WYOMING, 1973[2)]
(Acre-feet)

Basin or Area	Irrigation	Municipal, Domestic, and Livestock	Industrial	Total
Bighorn River	12,800	7,300	25,800	45,900
Northeastern Wyoming	8,700	8,100	16,800	33,600
Platte River	106,000	13,700	3,000	122,700
Total	127,500	29,100	45,600	202,200

TABLE B.4
AQUIFER CHARACTERISTICS, SHIRLEY AND POWER RIVER BASINS, WYOMING3,4,5,6)

	(1)	(2)	(3)	(4)
Basin	Shirley	Powder River	Powder River	Powder River
Formation	Wind River	Fort Union	Fort Union	Wasatch
Lithology	Sandstone	Sandstone	Shale	Sandstone
Porosity (percent)	-	29	-	20-35
Permeability (gpd/ft^2)	80	15-25	< 0.002	7-12
Transmissivity (gpd/ft)	8,000	-	-	1,030-1,410
Storage Coefficient	2×10^{-4}	-	-	1.85×10^{-4} - 6.7×10^{-5}
Well Yields (gpm)	400	50-130	-	15-20

The area is dominated by the Zuni Mountains and Mt. Taylor, a volcanic peak whose crest is 11,489 ft (3,470 m) above sea level. On the north flank of the Zuni Mountains, which have a core of igneous rocks, the uplifted and eroded sedimentary rocks form cuestas, hogbacks, and broad valleys. Buttes and mesas, some capped by basalt, and volcanic necks characterize the landscape. The region is semi-arid, with precipitation of about 10 to 12 in. (25 to 30 cm) in the lower areas, and about 16 to 20 in. (40 to 50 cm) at higher elevations. Some precipitation accumulates as snow on the mountains, but most is rainfall during brief, intense storms during the summer.

B.2.1.2 Surface-Water Hydrology

Most of the Grants mineral area lies to the southeast of the continental divide, with drainage toward the Rio San Jose or Rio Puerco, which reach the Rio Grande. The western part, incuding the Gallup and Church Rock areas, is drained by the Puerco River, a tributary to the Colorado River. There are no perennial streams in the area; flows are short-lived following heavy rains, and lakes such as Ambrosia or Smith Lakes, located in natural depressions, are normally dry. The only permanent body of surface water is Bluewater Lake, a reservoir on the Azul and Bluewater Creeks. In years of adequate supply, water can be released to permit irrigation of about 2,000 to 4,000 ac (800 to 1,600 ha) in the Bluewater Valley. At a gauging station near Bluewater, about 8 mi (13 km) downstream from the dam, the flow of Bluewater Creek has been as high as 28,930 ac-ft (35.7 hm^3) in 1941, but more commonly is between 500 and 10,000 ac-ft (0.6 to 12.3 hm^3) per year, concentrated in the spring and summer months.[8]

B.2.1.3 Ground-Water Hydrology

Ground water of generally acceptable quality, in amounts sufficient to meet domestic and livestock needs, can be obtained from as many as 16 discrete aquifers in the area. The water-transmitting capacity of most rocks, however, is low and well yields are correspondingly small. The sedimentary rocks, ranging in age from Permian to Cretaceous, dip to the north and northeast. They receive recharge from precipitation in their outcrop areas, on the northeastern flank of the Zuni Mountains, along stream courses, and by infiltration through basalts capping large mesas; elsewhere, in the low-lying areas, precipitation is scant and direct recharge probably is insignificant. Except near their outcrop areas, the aquifers are confined, with general flow direction downdip and northerly, toward the center of the San Juan Basin. Undoubtedly, there are local variations which have not been revealed by existing data. Although there is no direct evidence, chemical data suggest that there is vertical interchange of water from one aquifer to another; some vertical migration presumably occurs along faults and fractures.

In most of the mineral belt, the Westwater Canyon Member of the Morrison Formation (Figure B.4) is the principal aquifer, yielding small to moderate amounts of water that is generally of better chemical quality than water from aquifers above or below. Moderate to very large yields,

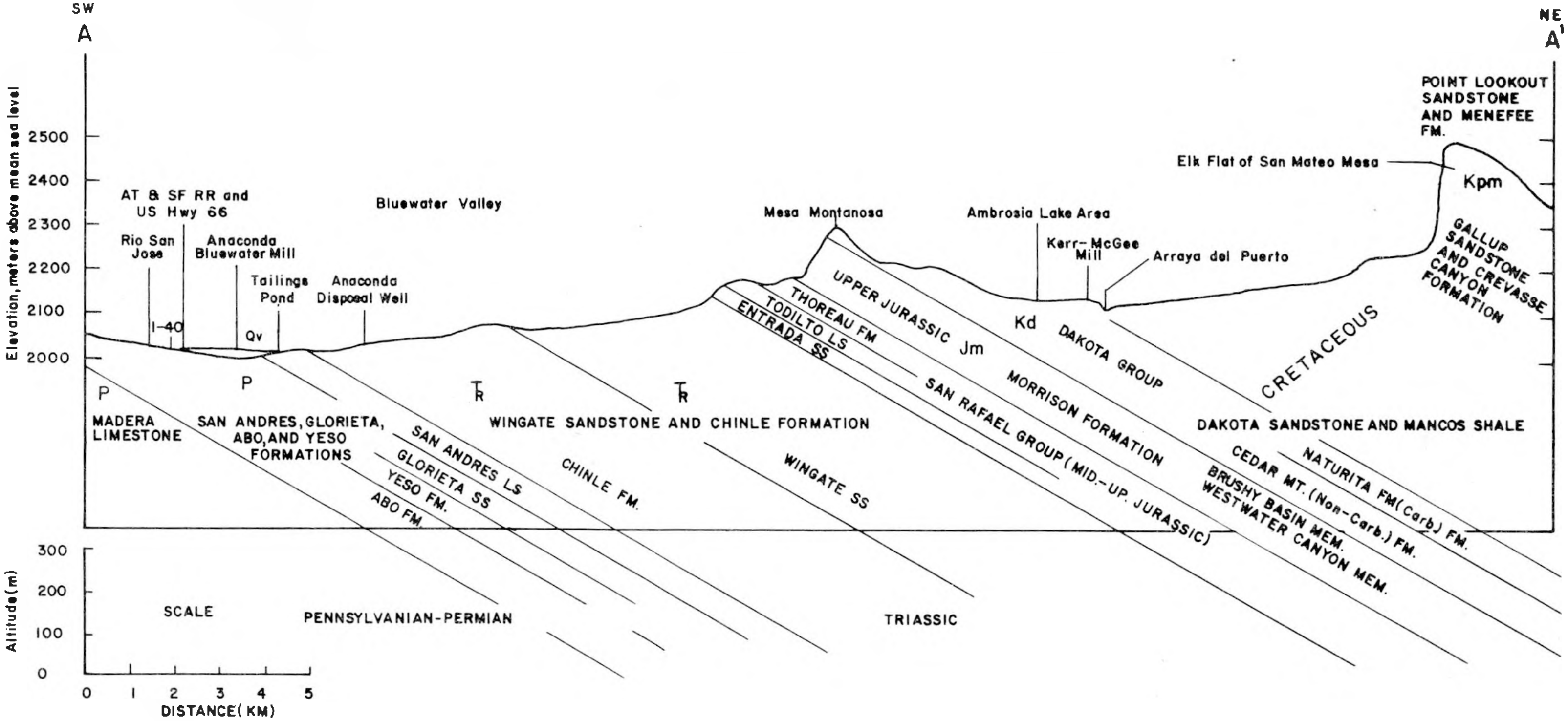

Figure B.4. East-west cross section showing the stratigraphy of the Grants Mineral Belt, New Mexico.[7]

however, are obtained from wells tapping the Glorieta Sandstone-San Andres Limestone aquifer of Permian age, or Quaternary alluvium and basalt at the southern edge of the belt, particularly in the Grants-Bluewater area. The Permian rocks are as much as 370 ft (112 m) thick and commonly yield 100 to 300 gpm (6.3 to 19 l/s). Locally, the San Andres Limestone is cavernous and yields as much as 2,800 gpm (180 l/s) to irrigation, industrial, or municipal wells. Elsewhere, however, it may be less transmissive or it may have been eroded; and water is obtained solely from the Glorieta, which, however, also is capable of substantial yields. Both formations form an aquifer that extends northeastward and underlies the mining areas at progressively greater depths. Downgradient from its area of recharge, water quality deteriorates. Thus, the San Andres, reached near Ambrosia Lake at a depth of 2,918 ft (890 m), yielded water that contained 2,370 mg/l TDS.[9]

The Morrison Formation is overlain by the Dakota Sandstone, of Cretaceous age. In the Grants and Ambrosia Lake areas, the Dakota is of variable thickness, generally between 50 to 150 ft (15 and 45 m), and consists of massive sandstones, conglomerates, siltstone, carbonaceous shale, and coal. Commonly, wells yield about 10 gpm (0.6 l/s) or less of water that is high in TDS; therefore, the Dakota is not used widely for water supply in the area, as water of better quality is generally available from other sources.

The Dakota is overlain and confined by the Mancos Shale, a thick sequence of rather impermeable rocks of Late Cretaceous age. The Gallup Sandstone sub-member yields water, under artesian conditions, that is of poor to fair quality. Sandstones of the overlying units, however, contain water that is of better chemical quality, particularly near areas where recharge through the overlying volcanic rocks is possible. Water from rocks of the Mesaverde Group discharges in many springs; it may be under sufficient artesian head to cause wells to flow, whereas wells tapping the Dakota or Morrison Formations generally do not flow above ground level.

Volcanic rocks of late Tertiary age are common in the Grants area, but they are not a source of ground water. They influence the movement of ground water, in that intrusive dikes may impede ground-water movement and cause spring flow; or they may be permeable enough to permit recharge to the underlying formations. The Cebolleta Mountains and several mesas to the east of Grants are covered by a series of basalt flows. Interconnected voids, vents, and interbeds of ash facilitate recharge to the underlying Cretaceous strata, or cause spring flow at the base of the mesas.

Alluvium and interbedded basalt, of Quaternary age, are a local major source of ground water in the Bluewater-Grants area. Wells up to 370 ft (112 m) deep yield as much as 1,000 gpm (63 l/s) for irrigation or public supply.[10] In most of the area, however, including Ambrosia Lake, the alluvial deposits are relatively thin or fine-grained, and yield only small amounts of water of variable quality.

The chemical quality of water from the alluvial deposits is highly variable; TDS content may range from less than 1,000 to several thousand mg/l, depending on the principal sources of recharge, which are seepage from adjacent formations and ephemeral stream flow.

Chemical analyses of water samples from the principal aquifers are given in Table B.5. The table includes data on radioactivity of seven water samples from wells completed in the Dakota Sandstone and Westwater Canyon Member of the Morrison. While beta-activity in all samples was considerably below the recommended limit, the Ra-226 content of three samples was in excess of 5 pCi/l, the upper limit in drinking water established by the U.S. Environmental Protection Agency.[11]

Prior to 1951, ground-water withdrawals in the Grants area were relatively minor, consisting of about 12,000 ac-ft (14.8 hm^3) per year for irrigation in the Bluewater-Grants Valley and insignificant amounts pumped by widely scattered wells for stock use or domestic supply. Because of the decline of ground-water levels beginning in 1946, initially due to irrigation pumping, the Bluewater Underground Water Basin was established by the New Mexico State Engineer in 1956, to regulate ground-water withdrawals. Water levels had declined as much as 45 ft (13.7 m), but since the late fifties the downward trend has been arrested or reversed. With the development of uranium mines and mills in the area since 1951, increasing demands for water for industry and public supply have been met by a corresponding decrease in irrigation pumping; the total amount of water pumped for all purposes has remained constant at about 13,000 ac-ft (16 hm^3) per year, which apparently is the maximum yield of the Bluewater Basin. Depending on different projected population growth rates for Grants, a large part or all of this amount will be required for municipal supply by the year 2020.[12] In 1951, total municipal and industrial use in the Grants-Bluewater area was only 250 ac-ft (0.3 hm^3); it had increased to 6,050 ac-ft (7.5 hm^3) by 1957, when 90 percent of this amount was used by industry.[8]

Ground-water use by the mineral industries in McKinley and Valencia Counties has been 10,000 ac-ft (12.5 hm^3) in 1970, largely for the mining and milling of uranium in the Grants mineral belt. With growing demand for the processing of fossil fuels, this is expected to increase to about 56,400 ac-ft (69.6 hm^3) by 2020; presumably more than one half of this amount will be required by the uranium industry in the Grants mineral belt.[12,13]

Following the depletion of outcrop and shallow deposits, most of the uranium production in the Grants mineral belt has been from wet-ore bodies within the Morrison Formation. Commonly, seepage into mine shafts from the Morrison or overlying Dakota Sandstone is not excessive and may be at rates of 100 to 400 gpm (6.3 to 25.2 l/s); locally, however, seepage may be 2,000 gpm (126 l/s) or more, particularly where faults or fractures are encountered. Only a small fraction of the water pumped for mine drainage is used in the mining or milling processes and most of it is discharged into formerly dry arroyos, where it infiltrates or evaporates. Although the quality of the pumped way may deteriorate in

TABLE B.5
CONCENTRATIONS OF SELECTED CONSTITUENTS IN GROUND WATER, GRANTS MINERAL BELT, NEW MEXICO 8,9)

Constituent (mg/l) 1/	Alluvium (1)	San Andres Limestone (2)	Dakota Limestone (3)	Morrison Formation			
				(4)	(5)	(6)	(7)
TDS	451	1,350	1,050	426	512	834	1,410
Total Hardness as $CaCO_3$	307	671	278	16	164	240	782
pH	7.6	7.0	7.6	8.3	7.3	7.6	7.8
Ca	39	175	102	5.6	46	59	211
Mg	51	57	33	0.5	12	24	62
Na + K	39	192	204	147	122	191	131
HCO_3	256	472	340	238	220	314	256
CO_3	0	0	0	4	0	0	0
Cl	15	129	25	6.0	8.0	7.0	10
SO_4	147	498	500	123	218	381	794
NO_3 (as N)	1.86	.23	.16	.00	.00	.00	3.39
F	0.4	.2	.4	.4	.4	.5	.6
B	0.3	-	-	-	-	-	-
Fe	-	-	0.2	2.1	.00	4.0	.43
Ra-226 pCi/l	-	-	27 ± 5	42	1.1 ± .2	1.1	10 ± 2
Gross Beta pCi/l	-	-	75 ± 11	49	18 ± 4	69	39 ± 7

1/ Except pH

the course of the mining operations, the water is inherently of good quality and commonly is only slightly radioactive. Total dissolved solids are generally low and much of the water may be suitable for human consumption or other purposes after treatment. Undoubtedly, a large part of the drainage waters can be used beneficially and it has been suggested that some abandoned mine shafts be retained as ground-water collection systems.[14]

The average transmissivity of the Morrison Formation in the Grants area is about 1,400 gpd/ft (17 m^2/day) and is in agreement with values determined for similar low-permeability formations in other mining districts. The specific capacities of wells tapping the Morrison Formation are correspondingly low and range from 0.02 to 1.38 gpd/ft of drawdown (0.004 to 0.28 l/s/m). The average determined from 32 tests in the Grants area is 0.48 gpm/ft of drawdown (0.1 l/s/m).[15]

B.3 SOUTH TEXAS

B.3.1 Geographical Features

Uranium deposits in Texas are found within the west Gulf Coastal Plain Province. The area is bounded inland by the outcrop of the Eocene Jackson Group and extends 100 mi (160 km) downdip to the Gulf of Mexico, paralleling the coast for 300 miles from the Rio Grande to the Brazos River, southwest of Houston. Present mining activity is confined to the inner margins of the area to the southwest (see Figure A.8).

A generally featureless plain rising from sea level to 200 ft (60 m) characterizes the seaward half of the area. Further inland the land rises to about 900 ft (270 m), but altitudes are generally less than 400 ft (120 m). Relief between the highlands and the broad floodplains of the major rivers that cross the region is about 200 to 300 ft (60 to 100 m). Barrier islands extend along the Gulf Coast. Numerous bays characterize the shoreline behind these islands.

Salt domes are locally unusual features. Although many of the domes have no surface manifestation, several form mounds above the flat plain; others are marked by surface depressions that contain small saline lakes.

Most of the region is moisture deficient, as annual precipitation generally is less than potential evapotranspiration. Precipitation ranges from 20 in.(50 cm) along the Rio Grande in the south to 44 in. (110 cm) toward the Brazos in the northeast, where the climate may be considered dry subhumid.[17] To the northeast the region is a treeless prairie; arid shrub vegetation is dominant in the southwest. Because of low precipitation, irrigation is required throughout the region to support crop growth. Irrigation agriculture, however, is a relatively minor activity in the area, which is noted chiefly for its livestock production.

B.3.2 Surface-Water Hydrology

The Rio Grande, Nueces, San Antonio, Guadalupe, Colorado, and Brazos Rivers originate to the northwest, outside of the uranium mining districts of Texas, and flow through and drain the area to the Gulf of Mexico, to the east-southeast. The perennial Lavaca River, however, rises within the mining area. The coastal areas are drained by intermittent streams discharging directly to the Gulf.

The average annual discharge of the rivers that flow through the uranium-mining areas of Texas is approximately 18 million ac-ft (22,200 hm3).[18] Some of this runoff originates in the uranium-mining area, but the exact amount is unknown.

Surface-water quality is quite variable. The Brazos, Colorado, and Rio Grande Rivers have the highest salinity levels. Natural salt seeps, wastewaters from petroleum production, and irrigation return flow are the primary sources of high TDS in river waters. Some reaches of the rivers that flow through the mining area may have a TDS content of up to 250,000 mg/l. In areas that drain directly to the Gulf of Mexico, water generally contains less than 500 mg/l TDS, but salinity may exceed several thousand mg/l TDS during times of low flow. Additionally, the downstream reaches of all rivers are affected by tides.[18]

Because of salinity problems, Texas has undertaken a statewide study of water desalinization in 37 cities. Desalinization was determined to be economically feasible in 11 of these cities; 7 are in the uranium-mining area of Texas.[18]

B.3.3 Ground-Water Hydrology

The Gulf Coast Aquifer underlies most of the Coastal Plain of Texas. The aquifer consists of alternating clay, silt, sand, and gravel beds belonging to the Catahoula, Oakville, Lagarto, Goliad, Willis, Lissie, and Beaumont Formations, which collectively form a regional hydrologically connected unit.[17] The age of these formations ranges from mid-Tertiary to Pleistocene. Some authors prefer to divide this sequence into three separate aquifers: (1) the Catahoula, Oakville, and Lagarto Formations; (2) the Goliad, Willis, and Lissie Formations; and (3) the Beaumont Formation.[18] Additionally, recent alluvium serves as an aquifer in the Rio Grande and Brazos River valleys.

Fresh water occurs in the Gulf Coast Aquifer to depths of more than 3,000 ft (900 m), and tremendous quantities of water are pumped for industrial, municipal, and irrigation purposes to the northeast of the uranium district.

The aquifer is recharged by precipitation on the surface and seepage from streams crossing outcrop areas. The rate of lateral movement of ground water through the aquifer varies widely but probably averages a few hundred feet per year to the east and southeast. At the surface, however, ground-water flow controlled by local areas of discharge, such as perennial streams, and ground water in the water-table aquifer may flow in a direction other than the regional trend.

Normally, the pressure head in deeper formations of the aquifer is greater than that in shallower formations, as it is derived from distant outcrop areas at higher altitudes. In response to this head difference, deeper artesian water tends to move vertically upward through the confining beds. If the pressure head in deeper aquifers is lower than that of overlying aquifers, water will move vertically downward. Both upward and downward vertical movement are evident throughout the region.

The availability of ground water in south Texas, according to geologic sources, is shown in Table B.6. The major fresh to slightly saline (>3,000 mg/l TDS) aquifers in south Texas are primarily of Tertiary age and may be found to a depth of 3,600 ft (1,100 m). The early Tertiary Jackson Group, which consists of interbedded sandy and tuffaceous shale, calcareous sand, limestone, and lignite beds, is not a major water-supply source because of very low yields. The formation may be tapped in conjunction with other formations to yield adequate water supplies.

The Catahoula, Oakville, and Lagarto Formations, which consist of interbedded volcanic tuff, sand, silt, and clay, are tapped as one aquifer in south Texas. The average discharge of wells tapping the aquifer is about 250 gpm (16 l/s), although yields of 1,000 gpm (63 l/s) have been measured. The specific capacities of wells in this aquifer range from about 2 to 9 gpm/ft of drawdown (0.4 to 1.9 l/s/m).

The Goliad and Lissie Formations, consisting of sand, gravel, silt, and clay, serve as the major aquifer for most of south Texas. The average discharge of wells tapping this aquifer is about 300 gpm (19 l/s), although discharge rates as high as 1,000 gpm (63 l/s) have been reported. The specific capacities of wells in this aquifer range from less than 4 gpm/ft of drawdown to about 17 gpm/ft (0.8 to 3.5 l/s/m). In the uranium-mining areas, only the Lissie Formation, of Quaternary age, is tapped as a water-supply source.

The fresh to slightly saline aquifers described above are underlain by older Tertiary rocks. These include the Carrizo Sand, the Wilcox Group, and the Midway Group. Similarly to the younger rock, these formations consist of interbedded sand, silt, and clay with some thin beds of lignite. These formations generally produce saline water and are sources of oil and natural gas. The aquifers are used extensively for oil-field brine disposal and are being used also to dispose of uranium-leaching wastes.

The chemical quality of ground water varies from fresh to saline, both laterally and vertically. Generally, the fresh water is slightly alkaline, being hard to very hard near the surface, but becoming softer with depth. Quality deteriorates to the south as chloride and sulfate increase. Much of the water pumped carries dissolved natural gas and hydrogen sulfide.

TABLE B.6
GEOLOGIC FORMATIONS AND THEIR WATER-BEARING CHARACTERISTICS IN THE GULF COAST REGION, TEXAS17)

System	Series	Unit	Thickness (feet)	Lithologic description	Water-bearing characteristics
Quaternary	Recent	Alluvium	0- 300	Unconsolidated gravel, sand, silt, and clay.	Yields only small quantities of water except in the lower reaches of the Rio Grande and Brazos River Valleys where moderate to large quantities of water are obtained for public supply, industry, and irrigation.
		Eolian deposits	0- 50+	Unconsolidated sands.	Yields only small supplies of water locally.
	Pleistocene	Beaumont Clay	0-1,500	Unconsolidated, light-colored sands, silts, and clays in upper 200 feet. Predominantly varicolored clays and thin sand lenses in lower part except for a thick basal sand, the Alta Loma of Rose (1943), occurring in the eastern part of the region.	Yields small to moderate supplies of water for public supply, industry, and irrigation throughout most of the central and eastern parts of the region. Most extensively developed in Galveston and Orange Counties and southeastern Harris County where it yields large supplies of water from the Alta Loma Sand of Rose (1943). A poor source of fresh to slightly saline water south of the Nueces River.
		Lissie Formation	0-1,600	Alternating thin to thick beds of light-colored sand, gravel, sandy clay, and clay. Extensive caliche beds in the central and southern parts of the region.	Yields small to large supplies of water for public supply, industry, and irrigation throughout the length of the region. Extensively developed in the central and eastern parts of the region.
Tertiary(?)	Pliocene(?)	Willis Sand	0- 400	Sand and gravel interbedded with silt and clay.	Yields small to large supplies of water for municipal, industrial, and agricultural uses. Extensively developed in the eastern part of the region.

(Continued on next page)

TABLE B.6 (Cont'd)

System	Series	Unit	Thickness (feet)	Lithologic description	Water-bearing characteristics
Tertiary	Pliocene	Goliad Sand	0- 500	Sand, gravel, and lime-cemented sandstone interbedded with variegated clay and silt. Caliche beds present in the southern part of the region.	Yields small to moderate quantities of fresh to slightly saline water for public supply, industry, and irrigation. Extensively developed in some areas of the central and southern parts of the region.
	Miocene(?)	Lagarto Clay	0-1,000	Dominantly massive clay and sandy clay interbedded with sand and sandstone.	Yields moderate quantities of water for public supply, industry, and irrigation east of Bee County. In the southern part of the region, the formation yields only small supplies for domestic and livestock use.
	Miocene	Oakville Sandstone	0-1,650	Dominantly sand and sandstone interbedded with clay and silt.	Yields moderate quantities of fresh to slightly saline water for municipal, industrial, and agricultural purposes on outcrop and several miles downdip throughout the length of the region.
	Miocene(?)	Catahoula Sandstone (eastern part) Cathoula Tuff (central and southern part)	0-1,500	Volcanic ash, tuffaceous clay, clay, and sandstone.	Yields moderate quantities of water on outcrop and a few miles downdip for municipal, industrial, and agricultural uses.
	Oligocene(?)	Frio Clay	0- 600	Predominantly clay, thin beds of sand and silt.	Not an aquifer in the region.
	Eocene	Jackson Group	800-1,300	Sand, silt, tuffaceous sand and clay.	Yields moderate quantities of water for public and industrial supply in Karnes and Polk Counties. The group is of minor importance as an aquifer within the region except possibly in the eastern part where its potential was not determined.

The ground water is generally not suitable for irrigation purposes because of high salinity or alkalinity, or both. It is used for human consumption in the absence of better supplies, although high chloride and sulfate give the water a disagreeable taste. High fluoride and boron levels may cause a health hazard. Table B.7 gives some selected ground-water quality data. Analyses of water samples obtained from uranium ore bodies and surrounding areas are shown in Table B.8. The data include determinations of minor elements and trace metals. Although there is no direct basis for comparison, most of these minor constituents, with the exception of radium-226, uranium, and molybdenum, seem to be present in small amounts or in concentrations below their detection limit.

An estimated 150 mgd (0.58 hm^3/day) of ground water was used in south Texas for all purposes in 1960. About 80 percent was used for irrigation, almost entirely in the Rio Grande Valley. Elsewhere, public and rural water supplies are the primary use of ground water (13 percent of the total).[18]

Although a large volume of ground water is available, is is expected that by the year 2020 ground-water use will be reduced to approximately one-half of the amount used today, largely because of low yields of individual wells and lack of reliability. Consequently, surface-water use is expected to at least triple by the year 2020.

Uranium is currently being leached from the Oakville and Goliad Formations and may be produceable in the Catahoula and Jackson Formations. As previously described, each of these formations consists of discontinuous beds or lenses of interbedded sands, silts, and clays, with volcanic material. The entire sequence is hydraulically interconnected and forms an artesian aquifer. Table B.9 summarizes information on the water-transmitting character of the major rock units.

B.4 SOUTHERN BLACK HILLS

B.4.1 Geographical Features

Uranium reserves in the Great Plains region are relatively minor, amounting to about one percent of the national total. Of these, the principal deposits are in the sandstones of the Inyan Kara Group, of early Cretaceous age, to the south and southwest of the Black Hills. The ore-bearing rocks, extending from southwestern South Dakota into eastern Wyoming, are part of the sequence of sedimentary rocks that have been uplifted with the Black Hills, and generally dip west. The Paleozoic rocks are largely of marine origin and include some evaporite beds, whereas the Mesozoic strata are of marine and terrestrial origin and consist of thick sequences of shale, sandstone, carbonaceous shales, and also some limestones and gypsum. These strata have been truncated by erosion and are exposed in narrow belts surrounding the igneous core of the Black Hills. The outcrop area of rocks of the Inyan Kara Group is commonly less than 5 mi (8 km) wide, but it is about 13 mi (21 km) wide to the east of Edgemont, South Dakota, where many of the uranium deposits

TABLE B.7
CONCENTRATIONS OF SELECTED CONSTITUENTS IN GROUND WATER, GULF COAST REGION, TEXAS[19,20,21]

FORMATION	Ca	Mg	Na	K	HCO_3	SO_4	Cl	TDS	pH
Goliad	21	7.5	308	12	315	162	235	951	7.9
Goliad	21	5.8	599	5.2	268	324	600	1,710	7.7
Oakville	128	14	660	35	366	277	900	2,270	7.7
Oakville	7.1	1.3	514	27	601	0.9	480	1,350	7.5
Oakville	6.6	0.2	646	2.9	390	414	462	1,770	8.3
Catahoula	6.4	0	476	18	322	101	492	1,330	8.0

TABLE B. 8

GROUND-WATER QUALITY IN AND AROUND A MINING SITE IN TEXAS 22)

Parameter	Production Vicinity Average in mg/l 1/	Production Area Average in mg/l
Calcium	118	80
Magnesium	14.0	11.6
Sodium	173	163
Carbonate	0	0
Bi-carbonate	292	281
Sulfate	155	142
Chloride	217	143
Nitrate-N	<.05	<.05
pH	7.3	7.3
Total Dissolved Solids	903	764
Conductivity (μmhos)	1,567	1,310
Arsenic	.014	< .01
Barium	<0.5	<0.5
Boron	0.40	.57
Cadmium	0.003	0.0025
Copper	0.012	0.015
Chromium	<0.01	<0.01
Lead	0.03	0.02
Manganese	0.059	0.046
Mercury	<0.0001	<0.0001
Selenium	0.006	0.005
Silver	<0.002	<0.0023
Zinc	0.081	0.02
Ammonia	<0.01	<0.01
Uranium	0.011	0.181
Molybdenum	0.41	0.2
Vanadium	0.005	0.003
Radium 226 (pCi/l)	10.47	274

1/ except pH, Conductivity, and Radium 226.

TABLE B.9
AQUIFER CHARACTERISTICS, SOUTH TEXAS[19,20,21,23]

Formation	Lithology	Transmissivity (gpd/ft)	Storage Coefficient
Catahoula Tuff & Jackson Group	Interbedded volcanic debris, tuffaceous shale, and clay	2,100	-
Catahoula Tuff	Volcanic tuff, sand, and conglomerate	1,400	4×10^{-5}
Oakville Sandstone	Sand with interbedded silt and clay	10,000	2.4×10^{-4}
Oakville Sandstone	Sand with interbedded silt and clay	14,000	1.3×10^{-4}
Oakville Sandstone	Sand with interbedded silt and clay	8,000	1.1×10^{-4}
Lagarto Clay	Calcareous clay interbedded with sand	7,500	-
Goliad	Sand with gravel and silt	6,700	2.4×10^{-4}
Goliad	Sand with gravel and silt	990	6.2×10^{-4}
Goliad and Lissie	Sand with gravel and silt	23,000	-

are located; others occur to the north and northwest of Edgemont (Figure B.5).

The climate of the area is semi-arid. Precipitation in the western plains of South Dakota is about 16 in. (40 cm) per year, increasing to about 22 in. (56 cm) in the northwestern Black Hills. Precipitation is concentrated in the spring and early summer months and, under average conditions, supports only grazing and dry farming. Wheat can be grown successfully in years of average or above-average rainfall, but periodic crop failures are common.

B.4.2 Surface-Water Hydrology

The Cheyenne River and its northern tributary, Beaver Creek, enter South Dakota about 19 mi (30 km) upstream from Edgemont and are the main streams draining the mining areas to the north. Average annual flow of the Cheyenne River leaving Wyoming is about 64,800 ac-ft (80 hm^3), with maximum flows during spring and early summer. During the remainder of the year, streamflow is variable, but generally too low to permit irrigation. Although base flow is largely sustained by effluent ground water, the Cheyenne River may be partially dry during periods of drought. There is irrigation farming, however, below Angostura Dam, in the southeast of the area (Figure B.5). The chemical quality of river water varies with stage; commonly TDS are in excess of 350 mg/l and may be 1,500 mg/l or more.

B.4.3 Ground-Water Hydrology

Quaternary alluvial deposits are only a minor source of water in the Edgemont area; pertinent data are scant, however. Water is obtained principally from springs and wells tapping the sandstones of the Inyan Kara Group or the deeper carbonate aquifer. The latter includes the Pahasapa Limestone of Early Mississippian (Madison) age and the overlying Pennsylvanian and Permian Minnelusa Formation, consisting of limestone, dolomite, sandstone, shale, and anhydrite. The carbonate aquifer is cavernous and highly permeable and is recharged by direct infiltration of precipitation and substantial stream losses to sinkholes where streams cross the outcrop areas of the Pahasapa and Minnelusa Formations. Ground water from springs and wells near recharge zones is commonly of good quality. With increasing distance downdip, ground water becomes strongly confined and its quality deteriorates, in part by the solution of anhydrite within the Minnelusa. Water from a well tapping the carbonate aquifer near Edgemont contained 2,980 mg/l TDS, almost entirely sodium sulfate. Artesian flow above the land surface is common. High yields of fresh to saline water are obtained from the carbonate rocks and also from the interbedded, fractured sandstones of the Minnelusa.

The carbonate aquifer, locally about 2,100 ft (630 m) thick, is confined by siltstones and shales of the Spearfish and Sundance Formations, of Permian-Triassic and late Jurassic age. These formations have a combined thickness of about 1,150 ft (350 m) and are generally of low permeability.

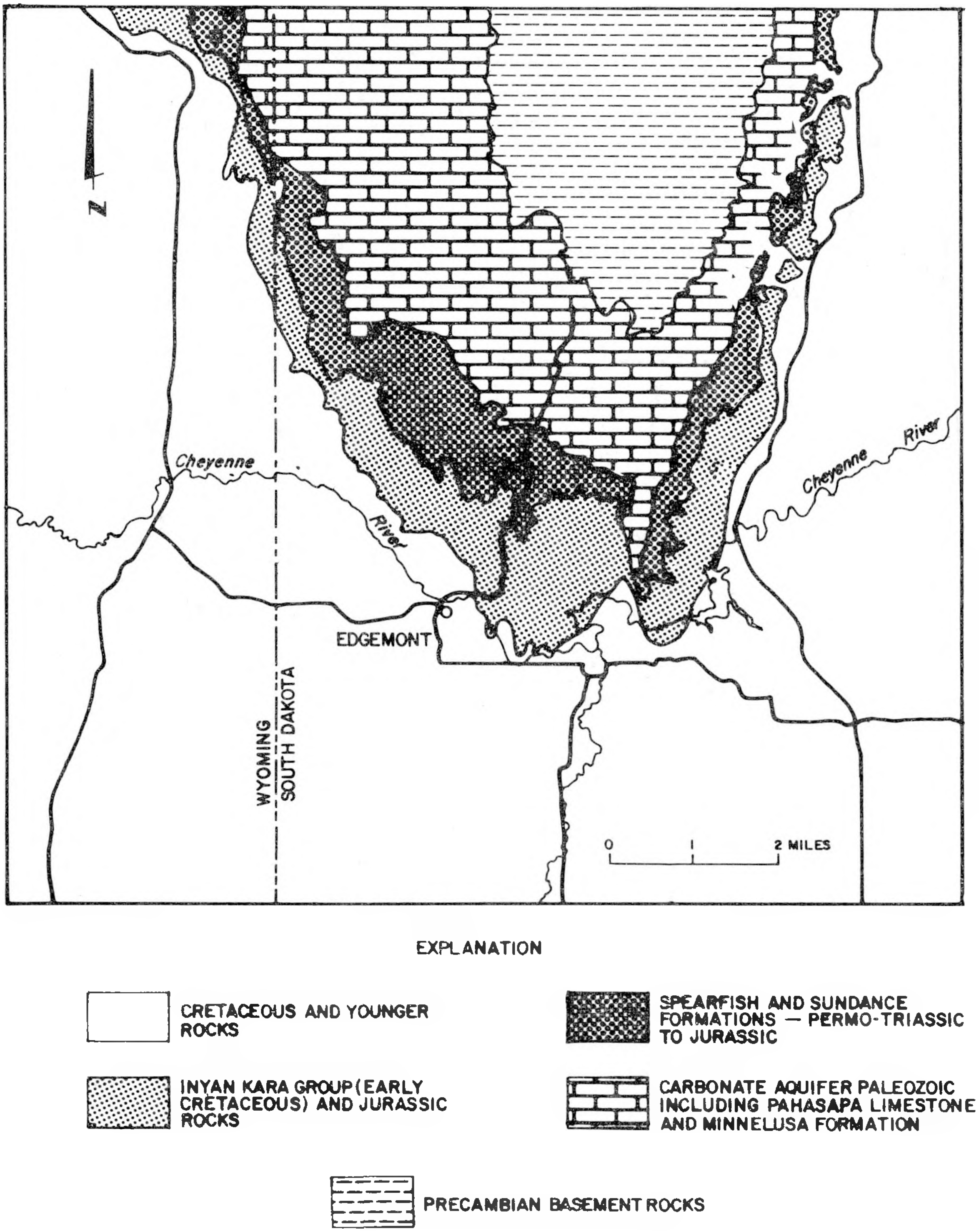

Figure B.5. Geologic map of the Black Hills, South Dakota.[24]

They contain lenses and interbeds of limestones and sandstones that locally yield small amounts of saline water. Moreover, the shales of the Spearfish Formation contain lenses and stringers of gypsum; upon solution, gypsum may be a contributing factor toward ground-water salinity in the area.

The overlying rocks of the Inyan Kara Group, of Early Cretaceous age, contain the area's uranium deposits and are chiefly interbedded sandstones and mudstones, with some conglomerate, carbonaceous shale, and limestone. The heterogeneous sequence of rocks, deposited in stream channels, flood plains, swamps, and lakes, is part of the Lakota and Fall River Formations, which have an aggregate thickness of about 300-660 ft (90-200 m) in the area south of the Black Hills. The Lakota Formation, subdivided into the Chilson, Minnewaste Limestone, and Fuson members, locally overlies the Morrison Formation or Unkpapa Sandstone (Jurassic). The latter may be hydraulically continuous with the rocks of the Inyan Kara Group, whose interconnected sandstone lenses form a major aquifer. Wells tapping the Inyan Kara Group commonly flow above land surface. The aquifer is fairly productive but yields more or less saline water, except near its outcrop areas. In the Edgemont area, ground water from the Inyan Kara Group contains from about 700 to 2,200 mg/l TDS and is commonly of the sodium sulfate or bicarbonate type (Table B.10).

The Inyan Kara aquifer apparently is recharged in part by the upward flow of ground water, under artesian pressure, from the carbonate aquifer below. Upward flow from the cavernous and highly transmissive carbonate rocks is facilitated by the solution of anhydrite beds in the Minnelusa, through collapse and brecciated zones, breccia pipes, and fractures extending to the land surface. It is believed that the large yields of some wells in the Inyan Kara can be attributed to recharge by artesian waters from the underlying Minnelusa Formation.[24] It also has been postulated that the emplacement and local enrichment of uranium deposits in the sandstones of the Inyan Kara Group is by ascending ground waters, controlled by local structures and faults. In the Edgemont area, uranium-bearing sandstones occur above and below the zone of saturation, to a depth of about 2,000 ft (600 m); some of the ore bodies presumably are amenable to mining by in-situ leach mining. A generalized section showing major aquifers, confining zones, inferred ground-water flow direction, and the position of uranium deposits is given in Figure B.6.

B.5 NORTHEASTERN COLORADO

B.5.1 Geographical Features

Uranium deposits amenable to in-situ leach mining are found in the sandstones of the White River Group of Oligocene age near Gover, northeastern Colorado (Figure B.7). The Grover area lies about 38 mi (60 km) northeast of Greeley, Colorado, in the Rocky Mountain Piedmont section of the Great Plains; it includes a narrow elongated area, parallel to Colorado's boundary with Wyoming and Nebraska. Precipitation is about 11 in. (28 cm) annually near Greeley and Grover, increasing easterly to

TABLE B.10

CONCENTRATION OF SELECTED CONSTITUENTS IN GROUND WATER, INYAN KARA GROUP, SOUTH DAKOTA[24]

	Samples in mg/l[1]				
Constituents	(1)	(2)	(3)	(4)	(5)
TDS	991	953	1,034	1,528	2,169
Total Hardness as $CaCO_3$	447	222	139	28	872
pH	7.2	7.7	7.7	7.5	7.1
Ca	118	56	39	5.5	206
Mg	37	20	10	3.4	87
Na	108	211	240	400	283
K	9	9	6	4	20
HCO_3	213	202	232	952	409
CO_3	0	0	0	48	-
Cl	9	24	14	73	8
SO_4	485	428	482	28	1,140
F	0.5	1.0	.9	2.3	.4
Fe	0.05	.11	.75	.07	.07
H_2S	0	0.15	.05	-	0
U, µg/l	6.4	1.7	15	0.01	.4

[1] Except pH and U.

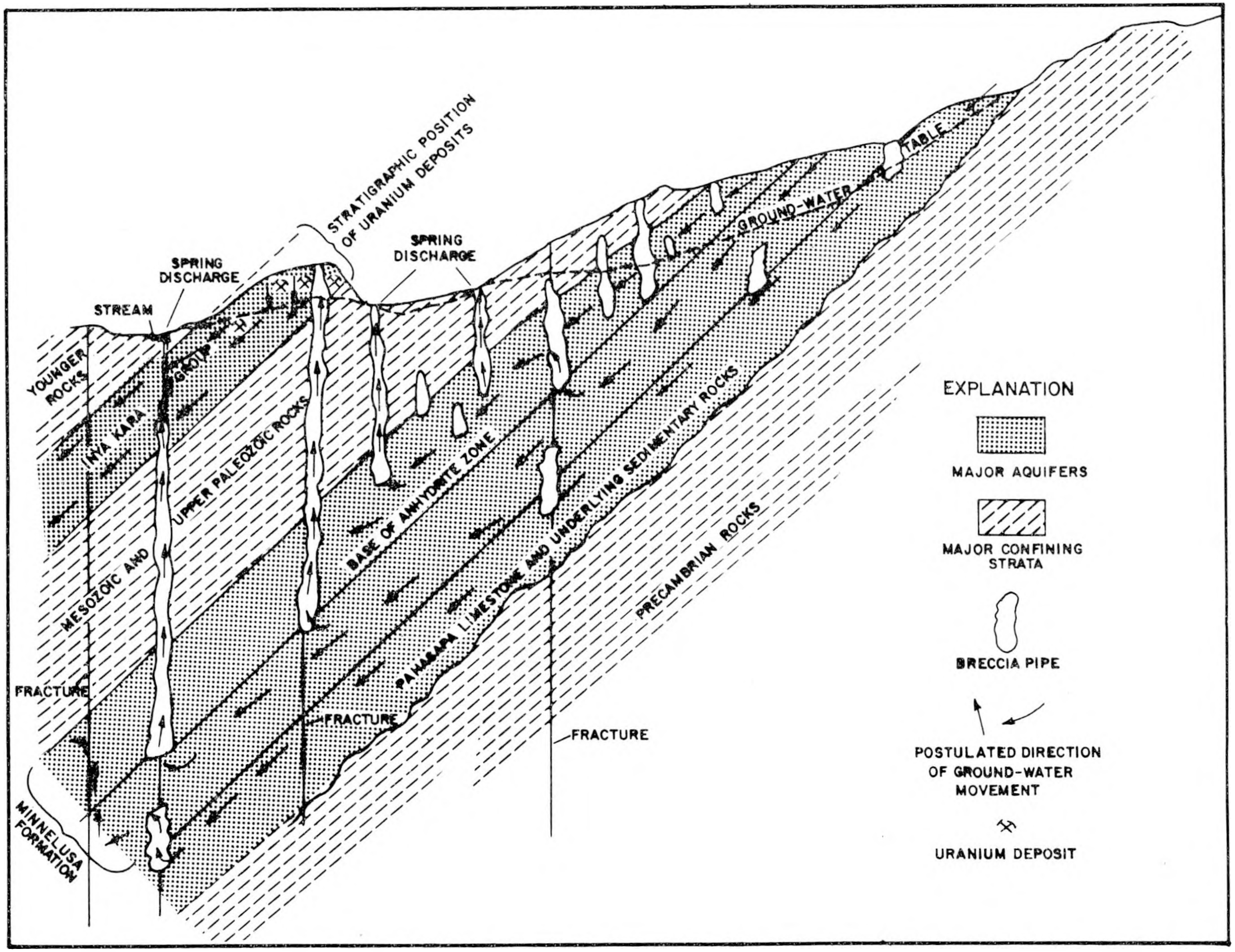

Figure B.6. Cross section showing major aquifers, confining beds, and uranium mineralization on the Black Hills, South Dakota.[24]

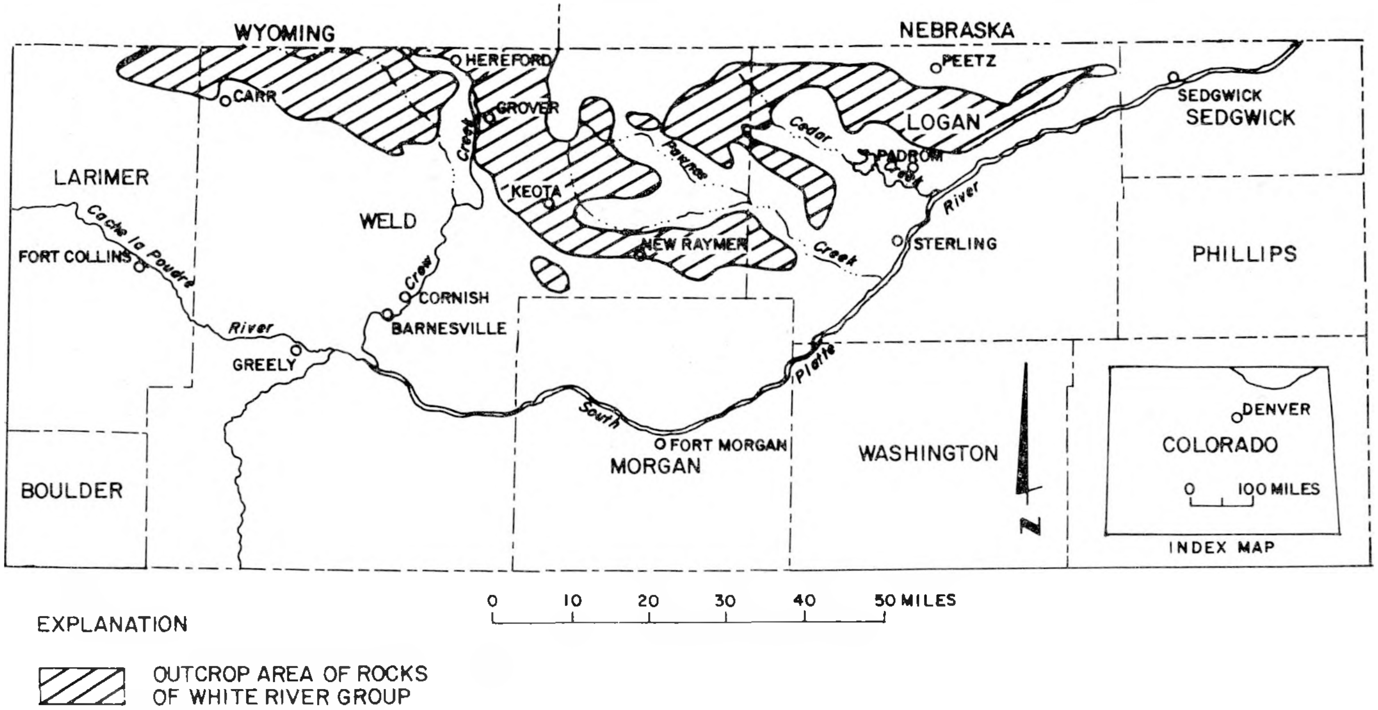

Figure B.7. Map showing the outcroppings of the White River Group in Northeastern Colorado.[25]

about 17 in. (44 cm) near Sedgwick (Figure B.7). The climate is arid to semi-arid, and, as elsewhere on the Great Plains, primarily suitable for grazing and dry farming. There are isolated instances of ground water being pumped for irrigation throughout the area; major areas of irrigation farming, however, are concentrated along Crow Creek, near Hereford and Barnesville, and also on the South Platte River, to the south of the area.

B.5.2 Surface-Water Hydrology

Drainage of the Grover area is southerly and southeasterly, by tributaries to the South Platte River. These are generally ephemeral or intermittent streams, flowing in deeply incised bedrock valleys in their upper reaches, and providing ground-water recharge during times of high flow. The major tributary is Crow Creek, originating in the Laramie Mountains of Wyoming. From 1951 to 1956, Crow Creek flowed at the average rate of 8,700 ac-ft (10.7 m^3) per year near Cheyenne, Wyoming. During this period there was no measurable flow at Barnesville, near its junction with the South Platte River. Within its reach in Colorado, Crow Creek's flow diminishes by irrigation diversions, evapotranspiration, and seepage to the water table along its alluvial channel. Data on the chemical quality of surface waters of the area is scant; the TDS content is variable with stage, generally exceeding 350 mg/l. The waters are moderately to very hard. No instances of increasing salinity due to the return of irrigation waters, as is common in the irrigated areas adjacent to the South Platte River, have been noted for Crow Creek or other small streams in the area.

B.5.3 Ground-Water Hydrology

In the Grover area, Tertiary strata are nearly horizontal or dip slightly to the east, occupying the northern extension of the Denver structural basin. The Mesozoic and Paleozoic rocks forming the basin crop out near the mountain front in the west, dipping steeply to the east; along the eastern flank of the basin, the rocks dip westerly at low angles, toward the basin's center. Where Tertiary strata have been eroded, as along some stream channels and in the southern part of the area, Upper Cretaceous rocks are exposed or are slightly covered by unconsolidated deposits and may be the only available source of ground water. The oldest of these, the Pierre Shale, is about 7,000 ft (2,135 m) thick and yields small to moderate amounts of water from sandstones within the thick sequence of rather impermeable marine sediments. The overlying Fox Hills Sandstone is transitional to a terrestrial environment of deposition and consists of about 400 ft (120 m) of sandstones and sandy shales, with some lignite near the top. It is overlain by as much as 600 ft (180 m) of shales, coal, and sandstones of the Laramie Formation, also of late Cretaceous age. Water from wells tapping the Upper Cretaceous Formations is fresh to moderately saline and generally confined. Most wells yield 10 to 30 gpm (0.6 to 2.0 l/s), for stock and domestic supply. Yields as high as 300 gpm (20 l/s) have been reported for wells penetrating more permeable sands of the Fox Hills Sandstone and Laramie Formation.

The sandstones of the White River Group in the Grover area are a major source of ground water and also contain uranium deposits. The rocks, of Oligocene age, are largely variegated clays and siltstones, with beds and lenses of loose or cemented sandstones, and some conglomerate. The thickness of the White River Group is as much as 600 ft (180 m), but it is highly variable, as the rocks have been deposited on the irregular Cretaceous erosion surface and have been eroded in turn at the end of the Oligocene. Rocks of the White River Group are exposed in a large area to the north of the Upper Cretaceous rocks and extend easterly and westerly from Grover (Figure B.7). Wells tapping the White River Group commonly yield as much as 30 gpm (2.0 l/s) for stock and domestic supplies. Locally, the sandstones are highly fractured and may be overlain by saturated unconsolidated deposits; thus, yields are greatly enhanced and may be as high as 1,400 gpm (90 l/s).

Rocks of mid to late Tertiary age are found in a narrow band in the extreme northern part of the area forming a pronounced south-facing escarpment above the rocks of the White River Group. They are part of the Arikaree Formation, of Miocene age, and the Ogallala Formation, of Pliocene age. The Arikaree has been mapped only in a small area to the west of Hereford, where it is thin and apparently not a source of water supply.[25] The overlying Ogallala Formation, however, is an aquifer that yields small to moderate amounts of water to stock, domestic, and public-supply wells. The formation is as much as 180 ft (55 m) thick and consists of more or less cemented silts, clays, limestone, and caliche, with beds and lenses of sand and gravel that yield water to wells.

Unconsolidated deposits of Quaternary age overlie the area of Cretaceous rocks in northern Morgan County and are also found as terrace deposits and stream alluvium along Crow Creek and in the lower reaches of other drainageways. In many of these areas, the Quaternary deposits are saturated and yield 1,200 to 1,500 gpm (75 to 95 l/s) to irrigation wells, particularly near Hereford and Barnesville. Wherever the surficial deposits are permeable, they permit ground-water recharge from precipitation, as in the extensive area of dune sands southeast of Barnesville.

The chemical quality of ground water from the unconsolidated Quaternary deposits is highly variable, particularly in TDS content and the relative proportions of sodium and sulfate. Available data indicate that TDS range from about 350 to more than 2,000 mg/l and that the water is very hard. In spite of locally high salinity, the waters are generally suitable for most uses, including irrigation. Water from the Ogallala Formation, White River Group, and Laramie Formation commonly contains only about 250 to 450 mg/l TDS and is of the calcium or sodium bicarbonate type. In particular, waters from the Ogallala Formation are hard to very hard. Water from the Fox Hills Sandstone and Pierre Shale is relatively fresh in many areas; locally, however, it may contain 2,000 mg/l of TDS or more. These formations commonly yield water that is high in sodium bicarbonate or sodium sulfate.

With few exceptions, the quality of ground water in the Grover area is suitable for the principal intended uses of domestic, stock, and irrigation supply. Large supplies of water for irrigation can only be obtained from the Quaternary alluvial and terrace deposits, and from the sandstones of the White River Group. No information is available to indicate whether these aquifers are capable of further development. Available pumping-test data are limited to the sandstones of the Laramie and White River Group, which are believed to have similar primary water-bearing characteristics. Wells commonly yield small amounts of water with considerable drawdown; specific capacities of 0.4 to 2.0 gpm/ft of drawdown (0.08 to 0.4 l/s/m) are characteristic of wells tapping unfractured sandstones. Permeabilities of 3 to 6 gpd/ft^2 (0.12 to 0.25 m/d) were determined in some pumping tests.

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Appendix C

TRACE ELEMENT REACTIONS

When used in the text of the discussion, the term trace concentration implies element or ion concentrations in the low parts per million or the parts per billion range; the term minor amounts is synonymous with concentrations greater than trace.

The solubility products (K_{sp}) of pertinent slightly soluble salts are included in the discussion for purposes of comparison. It is important to realize that the K_{sp} of a slightly soluble salt cannot adequately describe the true solubility of that salt in complex aqueous systems such as those expected during solution mining. The solubility product is useful only in making approximate predictions of true solubility. The solubility of a slightly soluble salt is less if an excess of one of its ions is present (common ion effect) and conversely, the presence of ions other than those furnished by a salt itself will generally make the salt more soluble.

C.1 MOLYBDENUM

Molybdenum has been reported with some uranium roll-front deposits. It is usually found as a halo around uranium-ore zones either as disseminated molybdenite (MoS_2), substituted for iron in the pyrite structure, or as slightly soluble molybdate (MoO_4^{-2}) minerals in barren altered rock. The mineral molybdenite is oxidized during in-situ leaching to the highly mobile molybdate ion:

$$2MoS_2 + 9O_2 + 6H_2O \rightarrow 2MoO_4^{-2} + 4SO_4^{-2} + 12H^+ \qquad (C.1)$$

The solution chemistry of molybdenum is different from the chemistry of most common heavy metals. Along with selenium and arsenic, molybdenum is soluble in oxidizing solutions as an anionic molybdate complex. The molybdate ion can form slightly soluble compounds with ferric, lead, and calcium ions. However, most of these molybdates are soluble enough in neutral or slightly alkaline solutions to impart trace concentrations of molybdenum to the solution (equations C.2 thru C.6):

$$2Fe^{+3} + 3MoO_4^{-2} + mH_2O \rightleftharpoons Fe_2(MoO_4)_3 \cdot mH_2O \quad \log K_{sp}=-52 \qquad (C.2)$$

$$PbMoO_4 \rightleftharpoons Pb^{+2} + MoO_4^{-2} \quad \log K_{sp}=-13 \qquad (C.3)$$

$$CaMoO_4 \rightleftharpoons Ca^{+2} + MoO_4^{-2} \quad \log Ksp=-7.2 \qquad (C.4)$$

$$PbMoO_4 + 2HCO_3^{-} \rightleftharpoons PbCO_3 + MoO_4^{-2} + H_2O + CO_2 \qquad (C.5)$$

$$Fe(MoO_4)_3 \cdot mH_2O + 6OH^{-} \rightleftharpoons 2Fe(OH)_3 + 3MoO_4^{-2} + mH_2O \qquad (C.6)$$

The molybdate anion is absorbed on colloidal particles that carry a positive surface charge. Therefore, MoO_4^{-2} will absorb on $Fe(OH)_3$ from acid solutions (pH<5). Above pH 6, the absorption falls off rapidly.

In-situ leach operations dissolve molybdenum where significant concentrations of the element occur in the ore zone. The molybdate ion will be a contaminant in the uranium recovery solution. The anion is sufficiently mobile to remain in the lixiviant. The mobility of MoO_4^{-2} in oxidizing lixiviants is greater under neutral or alkaline conditions than it is under acid conditions. Chemical reduction of the molybdate ion is the most effective means of removing traces of the element from solution.

C.2 SELENIUM

In many roll-front deposits selenium shows a strong association with uranium. The distribution of selenium is similar to uranium in that the trace element responds under oxidizing conditions and is inert under reducing conditions. The element may occur as native selenium, the mineral ferroselite ($FeSe_2$), or it may replace sulfur in the sulfide minerals. The ionic radii of Se^{-2} and S^{-2} are similar to permit substitution. The oxidation of selenides to selenates resembles the oxidation of sulfide to sulfate; the selenite (SeO_3^{-2}) and selenate (SeO_4^{-2}) ion being products of the oxidation reactions.

$$Se + 3H_2O \rightleftharpoons SeO_3^{-2} + 6H^+ + 4e^- \qquad (C.7)$$

$$SeO_3^{-2} + H_2O \rightleftharpoons SeO_4^{-2} + 2H^+ + 2e^- \qquad (C.8)$$

The ability of lixiviant to retain selenite and selenate in solution is limited by several reactions possible during leaching. Both the selenite and selenate ion form insoluble salts with ferric iron ($Fe_2(SeO_3)_2$), mercury (Hg_2SeO_3 and $HgSeO_3$), and lead ($PbSeO_3$). Freshly precipitated $Fe(OH)_3$ absorbs the anions from acid solutions and selenium can be purged from solution by coprecipitating with carbonate.

The mobility of selenium in oxidizing lixiviants resembles that of molybdenum to some extent. Leaching uranium ore containing significant amounts of selenium introduces trace amounts of the element into the lixiviant. As with molybdenum, chemical reduction of the lixiviant solution will result in precipitation of selenium.

C.3 ARSENIC

Arsenic is the third trace element likely to persist in solution in anionic form (AsO_3^{-3} and AsO_4^{-3}). Likely sources of arsenic are the common sulfides arsenopyrite ($FeAsS_2$), orpiment (As_2S_3), or realgar (AsS), usually associated with pyrite in the reduced ore zones. However, significant occurrences of arsenic in roll-front deposits are rare. Arseniferous minerals respond to oxidation in much the same way as do the common sulfides. The arsenite (AsO_3^{-3}) ion is the species most likely to form first. Arsenite can be oxidized to arsenate by strong oxidizing agents such as hydrogen peroxide:

$$AsO_3^{-3} + H_2O \rightleftharpoons AsO_4^{-3} + 2H^+ + 2e^- \qquad (C.9)$$

$$AsO_3^{-3} + H_2O_2 \rightarrow AsO_4^{-3} + H_2O \qquad (C.10)$$

The mobility of both anions is limited by precipitation reactions with cations solubilized during leaching. Arsenic forms slightly soluble salts with the alkaline earths and very insoluble salts with iron, copper, lead, zinc, cadmium, nickel, and cobalt. The arsenate ion will replace phosphate in any secondary apatite minerals forming during leaching. Ferric hydroxide will adsorb arsenite and arsenate from acidic lixiviants.

Very little arsenic can be expected in lixiviant solution. The small amounts present in the typical ore deposit will be dissolved and most likely reprecipitated in the immediate vicinity.

C.4 MANGANESE

In reducing environments, the stable manganese compounds are those in the +2 oxidation state; in strongly oxidizing environments the +4 oxidation predominates. The product of complete oxidation is pyrolusite (MnO_2):

$$MnCO_3 + 1/2\ O_2 + H_2O \rightarrow MnO_2 + H_2CO_3 \qquad (C.11)$$

$$MnSiO_3 + 1/2\ O_2 + 2H_2O \rightarrow MnO_2 + H_4SiO_4 \qquad (C.12)$$

The behavior of manganese in the leaching environment is noteworthy because of chemical similarity to iron. Under alkaline conditions, hydrate manganese oxides form colloids having adsorptive properties similar to those of $Fe(OH)_3$. Coprecipitated with $Fe(OH)_3$, manganese oxides are capable of absorbing heavy metals from solution in much the same way as the hydrated iron oxides.

If the lixiviant solution is somehow reduced, Mn^{+2} can remain in solution as stable bicarbonate and sulfate complexes:

$$Mn^{+2} + HCO_3^- \rightleftharpoons MnHCO_3^+ \qquad (C.13)$$

$$Mn^{+2} + SO_4^{-2} \rightleftharpoons MnSO_4 \qquad (C.14)$$

The mobility of these reduced complexes is somewhat controlled by several adsorption mechanisms that can remove the complexes from solution.

C.5 VANADIUM

Vanadium can occur either as complex uranium vanadate minerals in the altered rock next to the roll-front oxidation-reduction interface or incorporated into the lattice structure of associated montmorillonite clays in both the mineralized and barren zones of the deposit. Most vanadate minerals in the altered zones are slightly soluble in typical lixiviants. The reduced vanadium reported in some clays could be oxidized and solubilized by lixiviants:

$$V_2O_3 + H_2O_2 + 4HCO_3^- \rightarrow 2VO(CO_3)_2^{-2} + 3H_2O \qquad (C.15)$$

$$V_2O_3 + 2H_2O_2 + 2CO_3^{-2} \rightarrow 2VO_3^- + 2HCO_3^- + H_2O \qquad (C.16)$$

Tetravalent vanadium is the oxidation state likely to predominate in solution:

$$VO(CO_3)_2^{-2} \rightleftharpoons VO^{+2} + 2\ CO_3^{-2} \qquad (C.17)$$

The solution chemistry of the VO^{+2} ion shows similarities with the UO_2^{+2} ion. The tetravalent VO^{+2} ion can coprecipitate with calcite and gypsum, adsorb on hydrated iron and manganese oxides, and exchange with clays. All three mechanisms tend to restrict the mobility of V^{+4}.

C.6 COPPER

Trace amounts of copper have been reported in all sedimentary uranium deposits. The copper can occur as disseminated sulfides associated with pyrite in the reduced ore zones or substituted for calcium, magnesium, and iron in gangue minerals. The mechanisms responsible for oxidizing iron sulfides can also oxidize any copper sulfides. For example, the chalcopyrite can oxidize in the oxygenation mode according to equation 18:

$$4CuFeS_2 + 17O_2 + 10H_2O \rightarrow 4Cu^{+2} + 4Fe(OH)_3 + 8SO_4^{-2} + 8H^+ \qquad (C.18)$$

And, the sulfide can oxidize in the ferric ion mode according to equation C.19:

$$CuFeS_2 + 4Fe^{+3} + 3O_2 + 2H_2O \rightarrow Cu^{+2} + 5Fe^{+2} + 2SO_4^{-2} + 4H^+ \qquad (C.19)$$

Similar equations can be written for chalcocite (Cu_2S) or bornite (Cu_5FeS_4).

The common form of copper in solution is the simple divalent ion (Cu^{+2}) or one of numerous stable complexes of this ion. The Cu^+ ion is unstable at concentrations greater than 10^{-7} molar. Under oxidizing conditions, compounds of Cu^{+2} with common anions are all soluble. However, above pH 7 several precipitates may form. Malachite or azurite may precipitate from bicarbonate-carbonate solutions and chrysacolla may precipitate from solutions high in dissolved silica and low in carbonate:

$$2Cu^{+2} + HCO_3^- + 2OH^- \rightarrow Cu_2(OH)_2CO_3 + H^+ \qquad (C.20)$$

$$3Cu^{+2} + 2CO_3^{-2} + 2OH^- \rightarrow Cu_3(OH)_2(CO_3)_2 \qquad (C.21)$$

$$Cu^{+2} + H_4SiO_4 + H_2O \rightarrow CuSiO_3 \cdot 2H_2O + 2H^+ \qquad (C.22)$$

If hydrogen sulfide is introduced into the copper-bearing lixiviants, chovellite precipitates:

$$Cu^{+2} + H_2S \rightarrow CuS + 2H^+ \qquad (C.23)$$

The mobility of copper in oxidizing environments is limited by both reprecipitation and adsorption reactions. However, reprecipitation is less effective than adsorption as the mechanism for removing copper from solution. Generally, the mobility of copper is less in solutions that are not acid. The Cu^{+2} ion is adsorbed strongly by clays and, to a lesser extent, even by quartz. The adsorption capacity of clays for copper increases with pH. Hydrated iron and manganese oxides are effective adsorbents for Cu^{+2}. These adsorption mechanisms are strong enough to keep the concentration of copper in solution at trace levels.

C.7 ZINC

The chief source of zinc in sedimentary uranium deposits is probably the mineral sphalerite (ZnS). Sphalerite will react with oxidizing agents in the lixiviant and oxidize to Zn^{+2} and SO_4^{-2}:

$$ZnS + 4H_2O_2 \rightarrow Zn^{+2} + SO_4^{-2} + 4H_2O \qquad (C.24)$$

Sphalerite can be oxidized by ferric iron;

$$\begin{aligned} &ZnS + 2Fe^{+3} + 3/2O_2 + 3SO_4^{-2} + H_2O \rightarrow \\ &\quad Zn^{+2} + 2Fe^{+2} + 2H^+ + 4SO_4^{-2} \end{aligned} \qquad (C.25)$$

or react with cupric copper;

$$ZnS + Cu^{+2} \rightarrow CuS + Zn^{+2} \qquad (C.26)$$

In bicarbonate lixiviants, sphalerite can be altered to smithsonite ($ZnCO_3$):

$$ZnS + 2O_2 + 2HCO_3^- \rightarrow ZnCO_3 + H_2CO_3 + SO_4^{-2} \qquad (C.27)$$

$$ZnS + O_2 + 2CaCO_3 + H_2O \rightarrow ZnCO_3 + CaSO_4 + Ca^{+2} + 2HCO_3^- \qquad (C.28)$$

The solution chemistry of zinc is restricted to Zn^{+2} ion. Zinc forms salts with all common anions. Most salts tend to be somewhat soluble and appreciable zinc can remain dissolved even in fairly alkaline solutions. Two exceptions are the salts formed with phosphate ($Zn_3(PO_4)_2$) and with arsenate ($Zn_3(AsO_4)_2$); both compounds are highly insoluble. Another mechanism that will control the transport of zinc by lixiviants is adsorption on hydrous oxides and clay minerals, although Zn^{+2} is less strongly adsorbed on clays than is Cu^{+2}.

In an oxidizing lixiviant, divalent zinc is more mobile than divalent copper and higher concentrations can be expected. Re-establishing reducing conditions in the leaching environment will diminish zinc solubility:

$$Zn^{+2} + HS^{-} \rightarrow ZnS + H^{+} \qquad (C.29)$$

C.8 LEAD

The lead reported in uranium deposits can be either radiogenic or chemical. Chemical lead may occur as the mineral galena (PbS); radiogenic lead may be present at the rare mineral plattnerite (PbO_2). The oxidation of the sulfide by either hydrogen peroxide or ferric iron can be depicted by rather simple equations:

$$PbS + 4H_2O_2 \rightarrow PbSO_4 + 4H_2O \qquad (C.30)$$

$$PbS + 2\ Fe^{+3} + 3/2\ O_2 + 3SO_4^{-2} + H_2O \rightarrow$$

$$PbSO_4 + 2Fe^{+2} + 3SO_4^{-2} + 2H^{+} \qquad (C.31)$$

However, the oxidation scheme in true leach solutions may be complex: for example,

$$PbS + 2H_2CO_3 \rightleftharpoons Pb^{+2} + 2HCO_3^{-} + H_2S \qquad (C.32)$$

$$H_2S + 2O_2 \rightleftharpoons SO_4^{-2} + 2H^{+} \qquad (C.33)$$

$$Pb^{+2} + SO_4^{-2} \rightleftharpoons PbSO_4 \qquad (C.34)$$

$$H^{+} + HCO_3^{-} \rightleftharpoons H_2O + CO_2 \qquad (C.35)$$

The lead in the radiogenic mineral plattnerite is already in the very high +4 oxidation state, and the compound PbO_2 can act as a powerful oxidizing agent.

$$PbO_2 + 4H^{+} + 2e^{-} \rightarrow Pb^{+2} + 2H_2O \qquad (C.36)$$

Lead is the least mobile of the common trace elements. Its mobility is limited by the number of insoluble secondary minerals that can precipitate with divalent lead. For example,

$$PbSO_4 \rightleftharpoons Pb^{+2} + SO_4^{-2} \quad \log K_{sp}=-7.8 \qquad (C.37)$$

$$PbCO_3 \rightleftharpoons Pb^{+2} + CO_3^{-2} \quad \log K_{sp}=-16 \qquad (C.38)$$

$$PbSeO_3 \rightleftharpoons Pb^{+2} + SeO_3^{-2} \quad \log K_{sp}=-12 \qquad (C.39)$$

$$Pb_3(AsO_4)_2 \rightleftharpoons 3Pb^{+2} + 2AsO_4^{-3} \quad \log K_{sp}=-35 \qquad (C.40)$$

$$Pb_3(PO_4)_2 \rightleftharpoons 3Pb^{+2} + 2PO_4^{-3} \quad \log K_{sp}=-42 \qquad (C.41)$$

C.9 BARIUM AND FLUORIDE

The transport of barium and fluoride dissolved during leaching is limited by precipitation and coprecipitation reactions. The solubility of barium is typical of the alkaline earths. Free Ba^{+2} could be purged from the lixiviant solution by coprecipitation with calcite and gypsum. Even trace amounts of sulfate limit the solubility of barium to below 1 ppm:

$$BaSO_4 \rightleftharpoons Ba^{+2} + SO_4^{-2} \quad \log K_{sp} = -10.1 \tag{C.42}$$

Additionally, barium is rapidly adsorbed on precipitated oxides and hydroxides of iron and manganese.

Similarly, the mobility of fluoride ion is curtailed by precipitation as CaF and $Ca_5(PO_4)_3F$:

$$CaF_2 \rightleftharpoons Ca^{+2} + 2F^{-} \quad \log K_{sp} = -10.3 \tag{C.43}$$

$$5Ca^{+2} + F^{-} + 3PO_4^{-3} \rightarrow Ca_5(PO_4)_3F \tag{C.44}$$

C.10 MERCURY AND CADMIUM

Any significant deposition of mercury or cadium with roll-front uranium is rare. The minute amounts of mercury and cadmium that could be placed in solution would probably be purged by adsorption and precipitation. However, the most reliable mechanism for removing all traces of cadmium and mercury is lixiviant reduction and precipitation as the insoluble sulfides:

$$CdS \rightleftharpoons Cd^{+2} + S^{-2} \quad \log K_{sp} = -26.1 \tag{C.45}$$

$$HgS \rightleftharpoons Hg^{+2} + S^{-2} + S^{-2} \quad \log K_{sp} = -51.8 \tag{C.46}$$

C.11 URANIUM DAUGHTER ELEMENTS

The geochemical mobility of radium, thorium, radon, and other decay products of uranium during and after leaching operations is not, at present, well defined, and further research is recommended.

The solution chemistry of radium resembles that of the alkaline earths. Analogous to the alkaline earths, radium precipitates as insoluble sulfates and carbonates. The sulfate and carbonate of Ra^{+2} are lower in solubility than the corresponding calcium and barium sulfate and carbonate. Thorium forms fairly insoluble fluorides and along with radium is precipitated from solutions by adsorption on hydrous iron and manganese oxides.

Appendix D

MECHANICS AND CHEMISTRY OF URANIUM RECOVERY

Uranium is recovered from the pregnant lixiviant using an ion-exchange process; either solvent extraction or resin ion exchange can be used. Both involve the exchange of ions between the solution and either the solid resin or the organic solvent. This exchange is highly selective and provides an almost quantitative recovery of uranium from the aqueous media. It has not been feasible in conventional mills to apply solvent-extraction lixiviants whereas resin ion exchange is successful in such applications. Solvent-extraction processes are subject to formation or organic emulsions which can contaminate the recirculatory lixiviant.

The application of ion-exchange methods is based on the exchange of an anionic complex of uranium in solution with an anion on the resin. The ion-exchange resins used are generally strong base anionic in nature. Figures D.1 and D.2 present two flow sheets representing the uranium recovery process.

D.1 ION-EXCHANGE PROCESSES

There are two types of ion-exchange equipment available--moving bed and fixed bed. The chemistry of the process is independent of the equipment types.

D.1.1 Fixed Bed Ion Exchange

Fixed bed ion exchange utilizes a series of multiple columns for uranium adsorption from the solution onto the resin. The pregnant lixiviant is pumped into and through the first and subsequent columns. The effluent from the trailing column is devoid of uranium but has an increased chloride concentration. The uranyl ion complex in solution displaces the chloride ion on the resin. The columns are operated in this manner until the leading column is loaded, i.e., the resin will not adsorb additional uranium. The leading column is taken out of the system and the second column becomes the leading column and a fresh column is placed in service at the end of the line.

The leach solution from the loaded column is displaced by water. The uranium is eluted from the column (with $NaHCO_3$ + NaCl) producing a solution rich in uranium (10-15 gpl U_3O_8).

D.1.2 Moving Bed Ion Exchange

The moving bed ion-exchange processes are continuous counter current systems in which the resin and solutions are moving in opposite directions. The resin is loaded with uranium in an adsorption column containing several stages. The pregnant lixiviant is fed into the bottom stage of the column at a rate that is sufficient to expand the

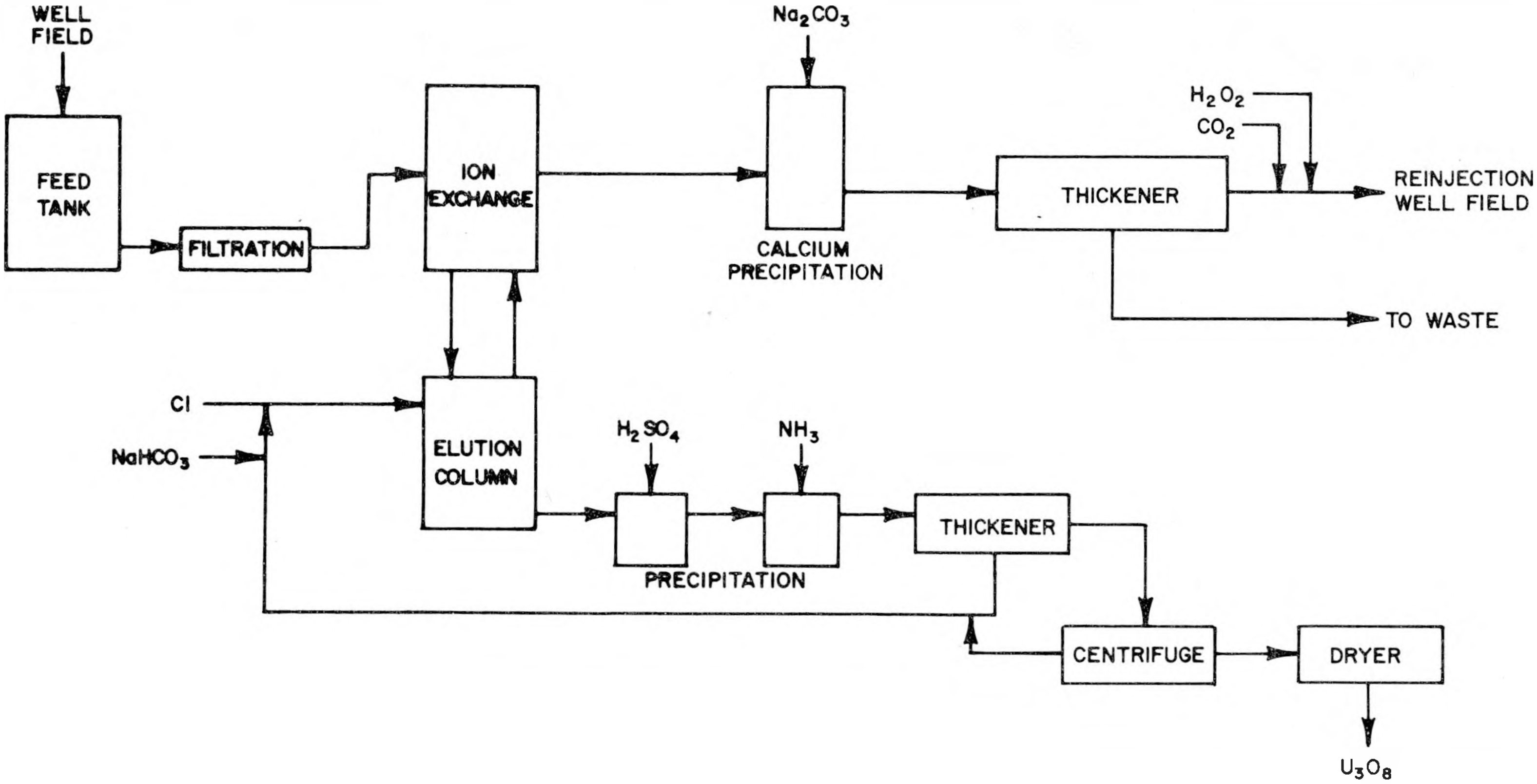

Figure D.1. Generalized flow sheet depicting a uranium recovery process that utilizes precipitation for calcium removal.

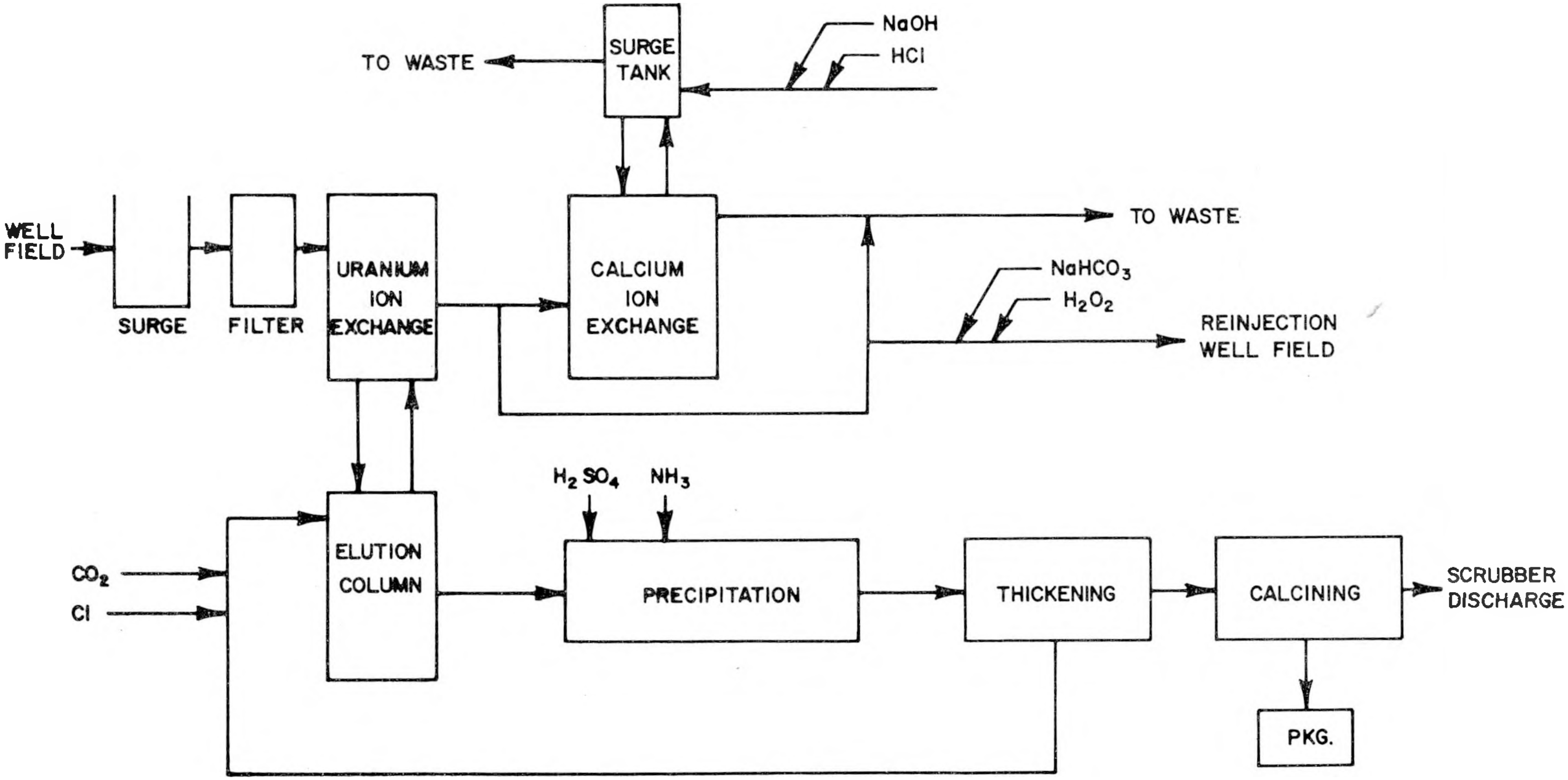

Figure D.2. Generalized flow sheet depicting a uranium recovery process that utilizes ion exchange for calcium removal.

resin bed but not wash the resin bed from the stage. The solution moves upward through the stages of the column and overflows devoid of uranium. The resin is transferred downward through the column and is transferred as loaded resin to an elution column.

The elution column is operated in the same fashion as the adsorption column; barren eluant is fed into the bottom of the column moving counter to the resin flow. The pregnant eluate solution overflows the top of the column. The stripped resin is transferred from the elution column to the adsorption column for reloading.

D.1.3 Uranium Precipitation

The uranium in the pregnant eluate is precipitated by: (1) the addition of a strong base such as sodium hydroxide, (2) acidifying to destroy the carbonate followed by precipitation with a base, or (3) heating to expel the ammonia and carbon dioxide with the direct precipitation of the uranium oxide.

The addition of the strong base such as sodium hydroxide for the precipitation of the uranium has the disadvantage of requiring excess sodium hydroxide for complete precipitation. The excess hydroxide must be bled off; therefore, the eluant cannot be recycled through the system.

The addition of acid to the pregnant eluate to destroy the carbonate followed by uranium precipitation by a base is used to advantage in a closed eluant system. After the precipitation is complete and a liquid solid separation is made, the liquid can be recycled through the system after chemicals are added to replenish those consumed in the process.

The use of steam or heat for the decomposition of the bicarbonate has the disadvantage of only being applicable to systems utilizing ammonium lixiviants. No reagents are required in the precipitation step; however, additional auxiliary equipment is required to recover the ammonia and carbon dioxide expelled during the process.

The slurry produced by uranium precipitation must be densified. A thickener is used to separate a clear eluant solution from the thickened solids. The clear solution is recycled through the elution process. The thickened solid slurry is further densified prior to the final drying process. This is accomplished by either centrifuging or filtration.

Finally, water is removed from the final uranium product by low temperature drying or calcining. The final product is packaged in 55-gal (209-l) drums for shipment.

D.1.4 System Bleed

In addition to leaching uranium from the ore body, the mining process will extract varying amounts of other elements including calcium, magnesium, and radium. It is necessary to control these elements to prevent the plugging of the system piping, the wellbore, and the formation. Control is accomplished by removing calcium from the system.

The method selected for calcium removal is a function of the amount to be removed. In situations where small volumes of calcium are produced, a bleed stream is used for calcium control. If large volumes of calcium must be removed, the entire circulating stream might be treated to remove the calcium.

The removal of calcium is accomplished by either precipitation followed by liquid/solid separation or ion exchange. The precipitation of calcium plus magnesium and radium is accomplished by raising the pH of the solution with ammonia, sodium hydroxide, or sodium carbonate, thus causing the precipitation of calcium carbonate. Following liquid/solid separation in a thickening device the clear solution overflow is recycled through the well field while the underflow is impounded as a waste.

The calcium control is also maintained by the use of an ion-exchange process similar to that used to recover the uranium from pregnant lixiviant. This operation can be utilized on either the total stream or a bleed stream. The mechanics of the operation are the same as those described for the uranium extraction.

D.2 PROCESS CHEMISTRY

The solubility of hexavalent uranium ion complexes permits the in-situ leach mining of uranium. The dissolution of uranium is selective, leaving behind nearly insoluble metal complexes. Section 2 details the chemical process taking place in-situ. Presented below is the chemistry of the above-ground phases of uranium recovery.

D.2.1 Resin Ion Exchange

The ion-exchange resins used in the uranium industry are of the strong base anionic type, and contain quaternary ammonium functional groups as their active ion constituent. The resins are highly ionized, and are usable over a wide pH range and therefore are used in either the acid or alkaline leach system.

In the alkaline system, the tetravalent uranyl tricarbonate complex predominates; uranyl trisulfate complex is predominant in the acid system. Typical reactions between the mobile ion adsorbed on the resin and the uranium ions in solution (R designating the resin group) are as follows:

$$4RCl + (UO_2)(SO_4)_3^{-4} \rightarrow R_4UO_2(SO_4)_3 + 4Cl^- \quad \text{(Acid)} \qquad (D.1)$$

$$4RCl + (UO_2)(CO_3)_2 \rightarrow R_2UO_2(CO_3)_2 + 2Cl^- \quad \text{(Alkaline)} \qquad (D.2)$$

Other metal anion complexes dissolved during the leaching may also be absorbed to the resin. Resin affinity for these complexes is controlled by pH, temperature, oxidation, state, and concentration.

D.2.2 Elution

The elution of the uranium from the resin is the reverse of the loading process. The eluant contains an excess of chloride ions that exchanges in the resin with the uranium complex;

$$R_2(UO_2)(CO_3)_2 + 2Cl^- \rightarrow 2RCl + UO_2(CO_3)_2 \quad \text{(Alkaline)} \qquad \text{(D.3)}$$

$$R_4(UO_2)(SO_4)_3 + 4Cl^- \rightarrow 4RCl + UO_2(SO_4)_3^{-4} \quad \text{(Acid)} \qquad \text{(D.4)}$$

In the ion-exchange process, the uranium concentration in the solution has increased from about 0.15 g/l U_3O_8 in the pregnant lixiviant to about 10 g/l U_3O_8 in the pregnant eluant.

D.2.3 Precipitation

The preferred method for uranium precipitation in alkaline systems is to add acid to the pregnant eluant to a pH of 1-2 to destroy the carbonate. In some plants the solution is heated to boiling to aid in the dissolution. The removal of the carbon dioxide is followed by neutralization with ammonia to precipitate the oxide of uranium. For acid leach systems, no pH adjustment is necessary prior to uranium precipitation by ammonia.

$$NH_4(UO_2)(CO_3) + HCl \rightarrow (UO_2)(Cl_2) \downarrow + CO_2 \uparrow + H_2O + NH_4Cl \quad \text{(Alkaline)} \qquad \text{(D.5)}$$

$$2(UO_2)(Cl_2) + 6NH_3 + H_2O \rightarrow (NH_4)_2\, U_2O_7 \downarrow + 4NH_4Cl \quad \text{(Alkaline)} \qquad \text{(D.6)}$$

$$2H_4(UO_2)(SO_4)_3 + 14\, NH_3 + 3\, H_2O \rightarrow (NH_4)_2(U_2O_7) \downarrow + 6(NH_4)_2(SO_4) \qquad \text{(D.7)}$$

D.2.4 Calcium Removal

The effluent from the ion-exchange circuit contains calcium, magnesium, and other ionic species that must be controlled. The control of the calcium and magnesium can be accomplished by a resin ion-exchange process similar to that used in the uranium circuit. The resin used is a cationic resin. The typical reaction in this ion exchange is:

$$Ca^{+2} + RNa \rightarrow R_2Ca + 2Na^+ \qquad \text{(D.8)}$$

$$Mg^{+2} + 2RNa \rightarrow R_2Mg + 2Na^+ \qquad \text{(D.9)}$$

$$Ra^{+2} + 2RNa \rightarrow R_2Ra + 2Na^+ \qquad \text{(D.10)}$$

The amount of calcium that must be removed is a function of the ore body and lixiviant concentration and pH and must be equal to the amount of calcium leached in the process.

An alternate method of calcium control is the precipitation from solution as insoluble carbonates by the addition of either sodium carbonate or ammonium carbonate as indicated in the following reaction:

$$Ca^{+2} + (NH_4)_2CO_3 \rightarrow CaCO_3 \downarrow + 2NH_4^+ \qquad (D.11)$$