Geohydrology and Water Chemistry of Abandoned Uranium Mines and Radiochemistry of Spoil-Material Leachate, Monument Valley and Cameron Areas, Arizona and Utah

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CONTENTS

FIGURES

FIGURES—Continued

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	*By*	*To obtain*
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
square foot (ft^2)	0.0929	square meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
ounce	28.3495	gram
pound (lb)	0.45359	kilogram
ton	1.102	megagram
gallon per minute (gal/min)	0.06308	liter per second

In this report, degrees are reported in Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 1.8(°C)+32$$

Chemical concentration and water temperature are given only in metric units. Chemical concentration in water is given in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to 1 milligram per liter. For concentrations less than 7,000 milligrams per liter, the numerical value is about the same as for concentrations in parts per million. Specific conductance is given in microsiemens per centimeter (µS/cm) at 25 degrees Celsius. Radioactivity is expressed in picocuries per liter (pCi/L), which is the amount of radioactive decay producing 2.2 disintegrations per second in a unit volume (liter) of water.

Sea Level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—A geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called *Sea Level Datum of 1929*.

Geohydrology and Water Chemistry of Abandoned Uranium Mines and Radiochemistry of Spoil-Material Leachate, Monument Valley and Cameron Areas, Arizona and Utah

By Steve A. Longsworth

ABSTRACT

Abandoned uranium mines in the Monument Valley and Cameron mining districts that have partially filled with water were studied to define hydrologic and chemical characteristics of mine water and shallow ground water and to evaluate possible chemical interactions of shallow ground water and the mine-spoil material that will be used in mine reclamation. Uranium mines in the Monument Valley area were established predominantly in channel-fill deposits within the Shinarump Member of the Chinle Formation. The Shinarump Member yields ground water to wells and may yield water to the Moonlight and Radium Hill mines. Depth-to-water measurements in the area of the Moonlight and Radium Hill mines indicate that local ground-water flow is from the southeast to the northwest along the trend of Oljeto Wash. In the study area near Cameron, uranium was mined from channel-fill deposits within the Petrified Forest Member of the Chinle Formation. Units of the Petrified Forest Member do not yield ground water to wells in the area, but fractures in the lower part of the Petrified Forest Member are probable pathways for upward flow of ground water from the Shinarump Member. Depth-to-water measurements were not sufficient to determine local ground-water flow directions, although previous investigations determined that regional flow in the area is toward the Little Colorado River. In the Cameron area, water in mines can originate from several sources. Most of the mines receive water from surface inflow of rainfall runoff, but ground water also may be transmitted to open pits and drill holes in the subsurface through fractures or along faults in the Petrified Forest Member.

Uranium-238 activities in shallow ground water from mines ranged from 150 to 14,000 picocuries per liter and radium-226 activities ranged from 0.10 to 110 picocuries per liter. Uranium-238 activities in pit water from mines ranged from 11 to 22 picocuries per liter. Radon-222 activities from three ground-water samples ranged from 590 to 250,000 picocuries per liter. Radionuclide activities in well and spring water generally were less than in shallow ground water and pit water. Water from Clay Well spring, which is about 1.9 miles from the nearest mine, contained a uranium-238 activity of 27 picocuries per liter. Radionuclide activities in well and spring water may result from naturally occurring mineralization in water-bearing rock units. The effects of mining activity could not be determined from chemical analyses of well and spring water.

Laboratory-batch tests indicate that radionuclide activities varied in leachate and generally correlated with field gamma measurements. Uranium concentrations in leachate samples ranged from 20 to 7,700 micrograms per liter and radium-226 activities ranged from 0.95 to 34 picocuries per liter. Batch tests were done with material that was 2.00 millimeters and smaller. Particle-size data indicate that spoil material near sampling locations is predominantly gravel and coarser sediments at three of the mines and sand-size sediments at the fourth. The radiochemistry of leachate from coarser sediments was not determined, and the specific rate and magnitude of radionuclide leaching are dependent on site-specific conditions that include the amounts of oxygen and organic material present, temperature, spoil mineralogy, and local ground-water composition.

INTRODUCTION

Uranium was mined on the Navajo Indian Reservation in the Monument Valley area, Arizona and Utah, during 1948-69 and near Cameron, Arizona, during 1950-63. The Monument Valley mining district contains 73 abandoned mines and the Cameron mining district contains 98 abandoned mines, generally along the Little Colorado River. Many of the mines present potential radiation hazards where the mines have partially filled with water. During 1984-87, water near the abandoned uranium mines in the Cameron area was sampled and analyzed to assess the extent of radionuclides and other potential contaminants (Donald Payne, Navajo Nation Division of Water Resources, written commun., 1987). Samples were collected from 49 locations that included springs, wells, mine pits, surface impoundments, and the Little Colorado River. Unfiltered samples were collected at most sites and additional filtered samples were collected from mine pits. Analyses of filtered and unfiltered samples indicated significant radionuclide activity that in several instances exceeded standards of the U.S. Environmental Protection Agency (1985). Reconnaissance sampling and laboratory analyses by the U.S. Geological Survey (USGS) in 1988 were done to define ranges of general radionuclide activities in water from springs, wells, and mine pits.

The Navajo Nation Abandoned Mine Lands Reclamation Department (NAMLRD) has developed reclamation plans that include burial of mine-spoil material within the mines on the basis of naturally occurring radioactivity. Mine spoils consist of non-ore-bearing material that was excavated above ore deposits and lower-grade ore that was set aside for possible future processing. Mobilization of uranium and radium may be of concern if shallow ground water associated with many of the mines is hydrologically interconnected with water that supplies wells or springs used by local Navajo inhabitants. The USGS, in cooperation with the NAMLRD, began a study in August 1991 to assess the chemical characteristics and hydraulic interaction of shallow ground water and mine water and the possible chemical interactions between shallow ground water and spoil material.

PURPOSE AND SCOPE

This report describes the geohydrology of the abandoned mines; the chemistry of mine, well, and spring waters; and the radiochemistry of spoil-material leachate from laboratory-batch tests. A total of 11 mines in the two mining districts were proposed for study on the basis of hazard prioritization and assumptions of hydrologic variability between mines. Field conditions, however, limited data collection to eight mines. Water-level and chemistry data also were collected from one unnamed drill hole, seven wells, and three springs. Data collected by the USGS before the study also are included.

Location and Well-Classification System

The Navajo Indian Reservation is in parts of Apache, Navajo, and Coconino Counties in northeastern Arizona; San Juan County in southeastern Utah; and San Juan and McKinley Counties in northwestern New Mexico. This study encompasses the Monument Valley and Cameron mining districts in northeastern Arizona and southeastern Utah (fig. 1). Local well numbering is based on Bureau of Indian Affairs administrative districts and numbered 15-minute quadrangles within each district (fig. 2). Well numbers consist of two main parts. The first part is a numeral that designates the Bureau of Indian Affairs' district and either

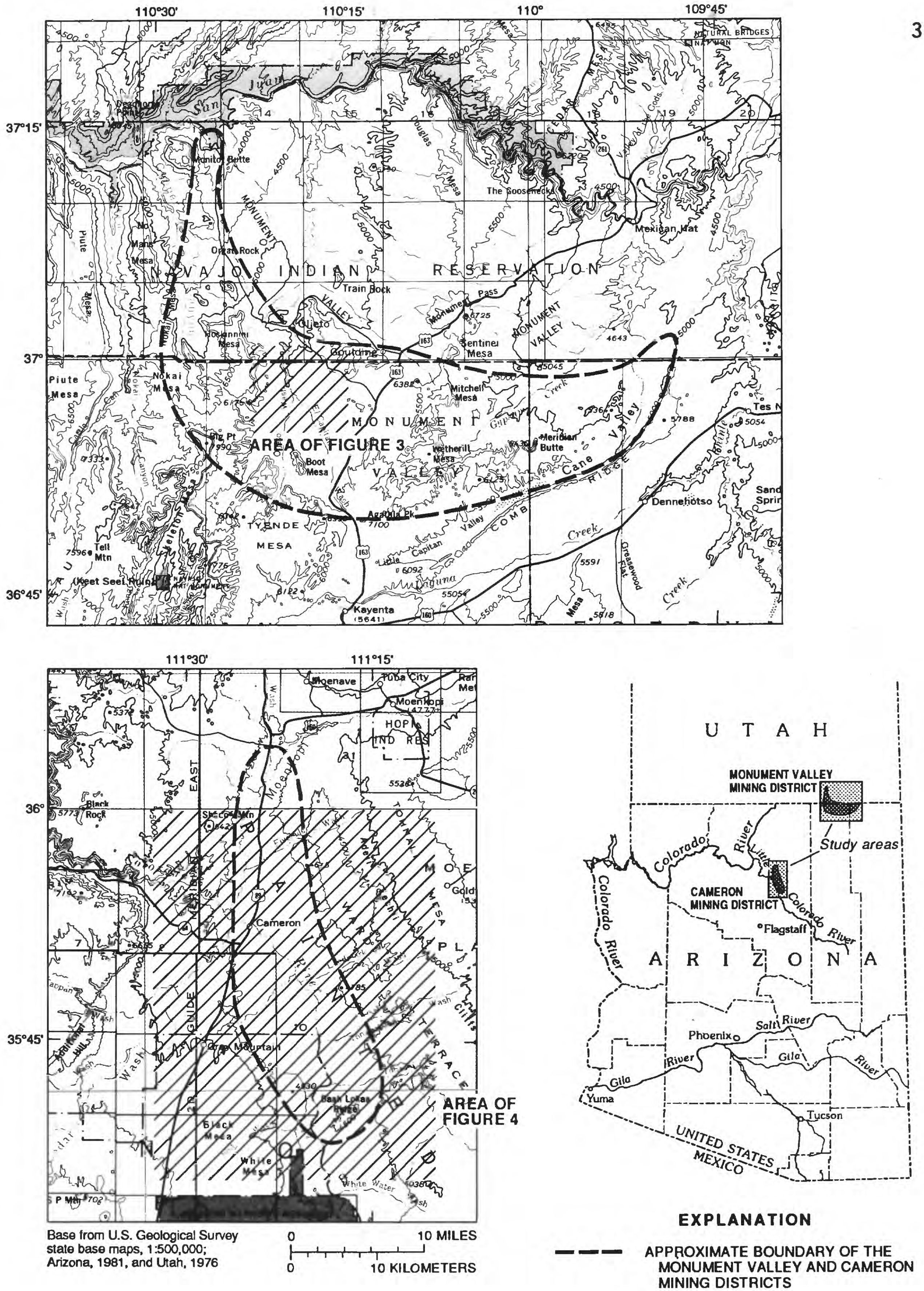


Figure 1. Location of study areas and Monument Valley and Cameron mining districts.

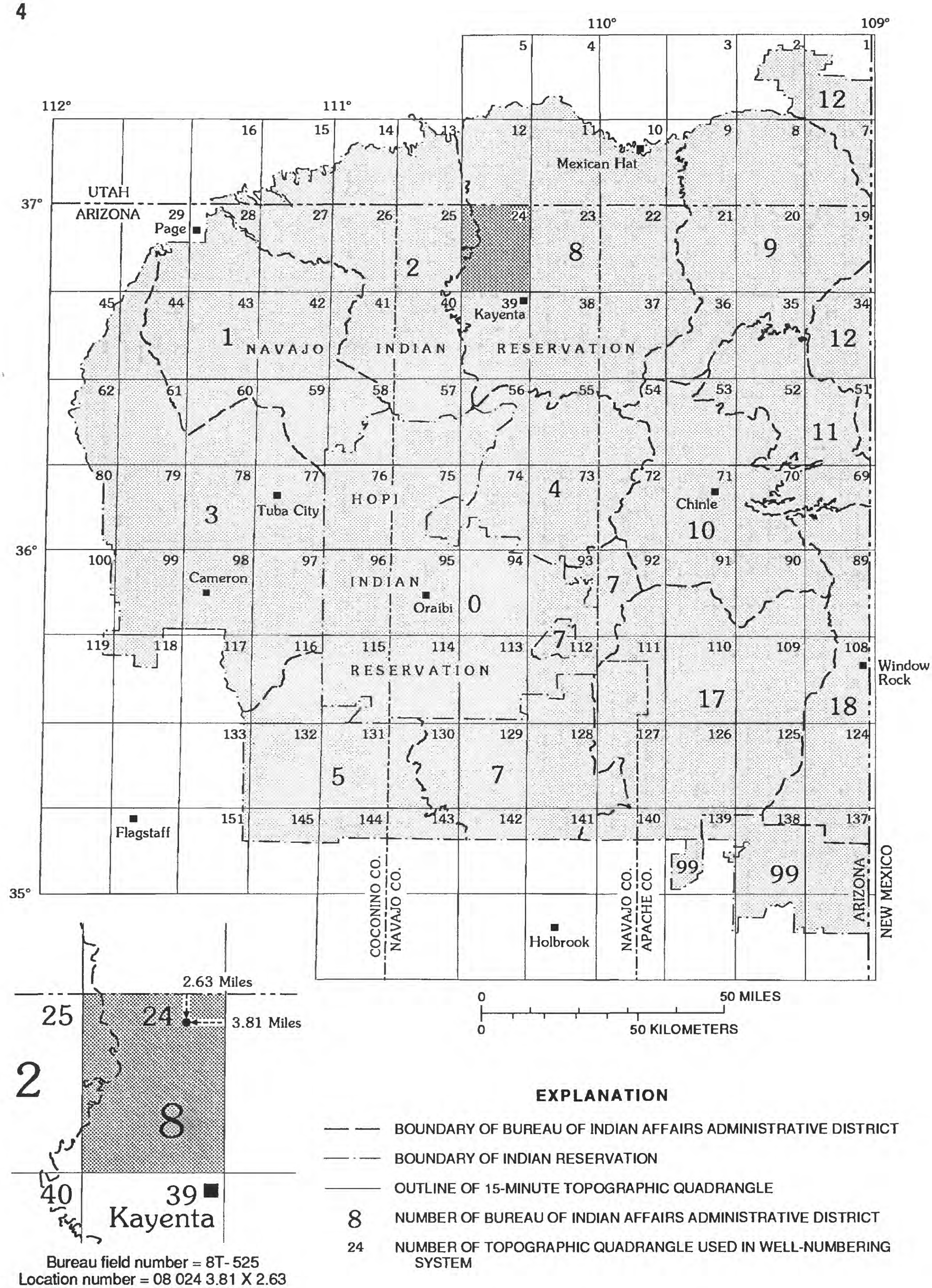


Figure 2. Bureau of Indian Affairs administrative districts, 15-minute quadrangles, and well-numbering system.

a "K," "T," or another letter identifying the source of funds used in the drilling of the well; for new wells and inventories made before 1950, the first letter of the last name of the person who first inventoried the well or spring for the Bureau. The letter "K" is used for wells drilled under the Bureau's drilling program, and the letter "T" is used for wells drilled under the Navajo Tribal Well-Development Program. The second part of the Bureau field number represents the order in which the drilled wells, dug wells, and springs were inventoried in each district. Additional letters used at the end of some designations are obtained from the number of a nearby development that was inventoried previously. These letters are arranged consecutively, beginning with "A."

The location number for wells and springs indicates the position within a 15-minute quadrangle (fig. 2). The three-part number consists of the number of the quadrangle, the distance in miles west of the northeast corner, and the distance in miles south of the northeast corner.

Physiographic Setting

Monument Valley lies along the Arizona-Utah border within the Colorado Plateau but lacks distinct geographical boundaries. The Monument Valley mining district generally extends from near Cane Valley in Arizona on the east to Nokai Mesa on the west and from the San Juan River in southeastern Utah on the north to near Agathla Peak on the south (fig. 1). Differential erosion of nearly horizontal rock layers has formed many canyons, mesas, and monuments. Ephemeral streams drain the valley and are tributary to the San Juan River, which flows from north of the study area to the southwest. Land-surface altitudes in the district range from about 4,700 ft above sea level in Cane Valley to about 6,700 ft on Hoskinnini Mesa in the western part of the district. Annual rainfall was found to be related to altitude and orographic effects (Cooley and others, 1969). Within the mining district, rainfall probably ranges from less than 6 in./yr at the lower altitudes of canyon bottoms to more than 10 in./yr at altitudes of more than 6,000 ft. Long-term weather stations have not been established within the district. Land in Monument Valley is used by the inhabitants for sheep grazing and tourism. Vegetation consists of sparse grasses and desert shrubs at lower altitudes and pinyon-juniper forests at higher altitudes.

The Cameron mining district extends from about 19 mi southeast of Cameron along the Little Colorado River to about 14 mi north along U.S. Highways 89 and 164 (fig. 1). The district is about 8 mi wide along the Little Colorado River and about 4 mi wide north of Cameron. Ward Terrace is a broad sloping ridge along the northeast and east edge of the district and was formed from erosion of sandstone and limestone. Between Ward Terrace and the Little Colorado River are small hummocky hills and gently sloping topography formed from erosion of less resistant rocks. This area is part of the Painted Desert, known for its multicolored bands of rock outcrops. The Moenkopi Wash drains the northern part of the district and is the largest tributary of the Little Colorado River within the district, flowing into the Little Colorado River approximately 3 mi northwest of Cameron. The Little Colorado River channel is broad and shallow in the southeastern part of the district but forms a more narrow, steep canyon downstream near Cameron. The river flows intermittently northwestward across the district and joins the Colorado River in the Grand Canyon. Land-surface altitudes in the district range from less than 4,100 ft at the Little Colorado River northwest of Cameron to about 5,400 ft on Shadow Mountain north of Cameron. Rainfall probably ranges from 6 to 9 in./yr on the basis of differences in land-surface altitudes within the district (Cooley and others, 1969). Long-term weather stations have not been established within the district.

Geologic Setting

Consolidated rocks exposed in the Monument Valley and Cameron areas of the Colorado Plateau are primarily flat-lying sedimentary units ranging in age from Permian to Jurassic. The units are underlain by basement rocks of Precambrian to Permian age that are 2,000 to 7,000 ft below land surface and that crop out outside the study area on the Defiance Plateau, in the Zuni Mountains, and in the Grand Canyon (Cooley and others, 1969, p. 10) about 80 mi southwest of Monument Valley. The sedimentary rocks consist of mudstone, siltstone, sandstone, limestone, conglomerate, coal, and gypsum. Mudstone and siltstone are the most abundant rock types and occur throughout the stratigraphic column. Cooley and others (1969, p. 11) stated that small amounts of gypsum may be present in much of the stratigraphic column. The Shinarump and Petrified Forest Members of the Chinle Formation of Triassic age are important sources of uranium in the Monument Valley and Cameron areas. Tertiary igneous rocks occur as dikes, volcanic plugs, and breccia pipes in the central and eastern parts of the Monument Valley area. Quaternary deposits in the Monument Valley and Cameron areas include dune sand, terrace deposits, and alluvium that overlie the consolidated sedimentary rocks. Lava flows and cinder cones of Quaternary age are present as surface features in the northwestern and western parts of the Cameron area. Large-scale folding, uplifts, and normal faulting have tilted the strata in some areas.

The Monument Valley section of the Colorado Plateau was uplifted during the Late Cretaceous and early Tertiary periods, forming the Monument upwarp, a broad flattened anticline that trends north and south and extends from north of the study area in the Cataract Canyon region of southern Utah to the southern part of Monument Valley in Arizona (Witkind and Thaden, 1963, p. 62). The east flank of the upwarp in this area is marked by Comb Ridge. Subordinate structural elements near the crest of the upwarp are the Organ Rock Anticline, Oljeto Syncline, Agathla Anticline, Tse Biyi Syncline, and Gypsum Creek Dome (Baker, 1936, p. 66-68; Witkind and Thaden, 1963, p. 62-64). Rock units in the west-central part of Monument Valley near the Moonlight and Radium Hill mines are part of the east flank of the Oljeto Syncline. The axis of the syncline approximately follows Oljeto Wash in the Utah and Arizona parts of Monument Valley and follows the west edge of Tynde Mesa beyond the southern extent of Oljeto Wash in Arizona (fig. 1). Rock units on the west flank of the syncline dip eastward at a maximum of 35° and form the east flank of the Organ Rock Anticline. Rock units dip only about 3° to the west on the east flank of the syncline (Witkind and Thaden, 1963, p. 63).

Rocks in the Cameron area generally dip from about 1° to 11° to the northeast. The area lies northeast of the East Kaibab Monocline and southwest of the Black Mesa basin in Arizona. Strata near Shadow Mountain in the northwestern part of the study area are tilted by three small structures—a syncline, anticline, and monocline. The syncline and anticline trend northeastward, and the monocline trends north-northwestward. The faults within the mining district are oriented in directions parallel to the folds.

Mining History

Uranium was discovered in Monument Valley in 1942 and in the Cameron area in 1950. In 1942, the Vanadium Corporation of America began leasing two parcels of land in the Monument Valley area for extracting vanadium ore (Witkind and Thaden, 1963,

p. 68). The parcels contained paleochannels filled with Shinarump deposits and would later be the sites of the Monument No. 1 and Monument No. 2 mines. In 1948, a rich vanadium-uranium deposit was discovered at the Monument No. 2 mine, and production increased as uranium became important (Witkind and Thaden, 1963, p. 69; Chenoweth and Malan, 1973, p. 139). Other deposits were discovered in the late 1940's and early 1950's in Shinarump channels exposed at rim outcrops (Chenoweth and Malan, 1973, p. 139). Between 1955, which was the largest production year, and 1969 when mining ceased, 1,362,000 tons of vanadium-uranium ore was produced from 53 sites in Monument Valley (Chenoweth and Malan, 1973, p. 140). The ore at these sites averaged 0.32 percent U_3O_8, a stable uranium-oxide, and contained 8,730,000 lbs of U_3O_8. Adits and open pits were used for mining shallow deposits, and shafts and inclines were used to reach deeper ore. The ore bodies ranged from a few feet to a few hundred feet long and from less than 1 foot to 12 feet thick. Uranium ore at the Moonlight Mine and other important uranium deposits were discovered in buried channels in the central part of Monument Valley in 1955 and 1956.

In 1950, in the Cameron area, uranium was found in the Kayenta Formation of Jurassic age, which led to further prospecting of the entire area. A Navajo prospector discovered the first commercially significant ore deposit in 1952 within the Petrified Forest Member of the Chinle Formation. Continued surface prospecting supplemented by airborne radiometric surveying identified additional deposits in 1953. As mining developed, shallow exploratory drilling encountered deposits that had no surface expression (Chenoweth and Malan, 1973, p. 141). Shallow deposits were mined by open pits or underground methods. Shafts were used at four sites. Production from these mines reached a peak in 1957 and gradually declined until mining ceased in 1963. During this period, 289,300 tons of ore containing 1,211,800 lbs of U_3O_8 were produced from 98 separate sites. Most of the uranium production came from the 67 ore deposits in the lower part of the Petrified Forest Member. Additional production came from 27 deposits in the sandstone and siltstone member of the Chinle Formation, 3 deposits in the Kayenta Formation, and 1 deposit within a breccia pipe in the Moenkopi Formation. Ore bodies ranged in size from a single fossilized log to a nearly continuous body 450 ft by 300 ft (Chenoweth and Malan, 1973, p. 141).

DESCRIPTION OF STUDY SITES

Two mines in the Monument Valley mining district and six mines in the Cameron mining district were studied during 1991 and 1992. Mines were selected for study on the basis of environmental factors. Initial investigations were at open pits that presented the highest potential health hazard, contained water, and were accessible to personnel and equipment. Some of the selected pits in the Cameron area, however, were dry during field visits. Additional sites were planned for study in the Cameron area, but shallow ground-water samples could not be collected at most sites with available equipment. Water samples also were collected at three existing wells and three spring boxes (springs improved with concrete cisterns and hand pumps; table 1). Site data for shallow wells, mine drill holes, wells, and auger holes and depths to ground water are presented in table 2. Data collected by the USGS before this study in the Cameron area also were used in the study.

Monument Valley Area

Data were collected in the Monument Valley mining district from the Moonlight and Radium Hill mines. The Moonlight mine is in the west-central part of Monument Valley,

Table 1. Site information and water and spoil-material sample types, Monument Valley and Cameron mining districts

[Laboratory analysis codes: C, chemical; B, batch leachate; P, particle size; M, mineralogical. Dashes indicate no data]

Site name and sample identification (figs. 3 and 4, tables 3-8)	Latitude-longitude	Source	Land surface altitude (feet above sea level)	Sample type and laboratory analysis: Mine sites: Pit water	Mine sites: Shallow ground water	Mine sites: Spoil material	Ground water from wells and springs
Monument Valley mining district							
Moonlight mine							
(MVD-1)		Shallow well	[1]5,070		C		
(MVD-2)		Shallow well	[1]5,070		C		
(MVSW-1)	36°57′44″ 110°17′05″	Open pit	[1]5,070	C			
(MVS-1 to MVS-4)		Spoil pile	--------			B	
(MVS-P1 to MVS-P4)		Spoil pile	--------			P	
Radium Hill mine			--------				
(Radium Hill)		Mine drill hole	[2]5,245		C		
(RHS-1)	37°00′08″ 110°18′37″	Spoil pile	--------			B	
(RHS-P1)		Spoil pile	--------			P	
(RHM-1)		Spoil pile	--------			M	
08 024-03.81X02.63 (8T-525)	36°57′41″ 110°19′07″	Well	[1]5,026				C,B
08 024-02.27X03.65 (8K-433)	36°56′50″ 110°17′29″	Well	[1]5,100	Depth-to-water measurement only			
Unnamed 6-inch well near El Capitan Wash	36°57′20″ 110°18′33″	Well	[2]5,040	Depth-to-water measurement only			
Unnamed 4-inch well near El Capitan Wash	36°56′15″ 110°17′37″	Well	[2]5,090	Depth-to-water measurement only			
Unnamed mine drill hole near well 8K-433	36°56′52″ 110°17′17″	Mine drill hole	[2]5,140	Depth-to-water measurement only			

See footnotes at end of table.

Table 1. Site information and water and spoil-material sample types, Monument Valley and Cameron mining districts—Continued

Site name and sample identification (figs. 3 and 4, tables 3-8)	Latitude-longitude	Source	Land surface altitude (feet above sea level)	Sample type and laboratory analysis: Mine sites: Pit water	Mine sites: Shallow ground water	Mine sites: Spoil material	Ground water from wells and springs
Cameron mining district							
Jeepster No. 1 mine							
(JSW-1)	35°56′38″ 111°24′02″	Open pit	[3]4,225	C			
(JS-1 to JS-4)		Spoil pile	--------			B	
(JS-P1 to JS-P4)		Spoil pile	--------			P	
(JSM-1)		Spoil pile	--------			M	
(Auger hole)		Auger hole	[3]4,225	Depth-to-water measurement only			
Jack Daniels mine							
(JDD-1)	35°54′21″ 111°24′01″	Shallow well	[3]4,190		C		
(JDSW-1)		Open pit	[3]4,190	C			
(JDS-1 to JDS-4)		Spoil pile	--------			B	
(JDS-P1 to JDS-P4)		Spoil pile	--------			P	
(JDM-1)		Spoil pile	--------			M	
Manuel Denetsone No. 2 mine (M.D.-45)	35°50′27″ 111°21′06″	Mine drill hole	[3]4,159		C		
Ramco No. 20 mine (Ramco No. 20 NW)	35°44′16″ 111°17′54″	Open pit	[3]4,211	C			
03 098-05.03X08.25 (Clay Well spring)	35°52′28″ 111°20′21″	Spring box	[2]4,220				C
03 117-02.67X05.77 (Yellow Spring)	35°39′53″ 111°17′51″	Spring box	[2]4,465				C
03 098-07.70X09.60 (Little Colorado Spring)	35°51′42″ 111°23′43″	Spring box	[2]4,160				C

See footnotes at end of table.

Table 1. Site information and water and spoil-material sample types, Monument Valley and Cameron mining districts—Continued

Site name and sample identification (figs. 3 and 4, tables 3-8)	Latitude-longitude	Source	Land surface altitude (feet above sea level)	Sample type and laboratory analysis			
				Mine sites			Ground water from wells and springs
				Pit water	Shallow ground water	Spoil material	
Cameron mining district—Continued							
03 098-06.07X11.16 (3T-539)	35°50′15″ 111°21′18″	Well	[1]4,161				C
03 098-08.46X07.21 (Arizona Inspection Station well)	35°54′01″ 111°24′09″	Well	[2]4,185				C,B
Juan Horse No. 3 mine (Auger hole)	35°51′44″ 111°21′57″	Auger hole	[3]4,108	Depth-to-water measurement only			
Juan Horse No. 4 mine (Auger hole)	35°51′16″ 111°21′38″	Auger hole	[3]4,108	Depth-to-water measurement only			
Farm Project "A" well 03 098-07.40X10.40 (FPA)	35°50′57″ 111°22′32″	Well	[2]4,138	Depth-to-water measurement only			
03 117-01.65X04.76 (Balokai Spring)	35°40′51″ 111°16′46″	Spring box	[2]4,458				C
Yazzie No. 312 mine (Yazzie No. 312)	35°52′20″ 111°22′20″	Open pit	[2]4,150	C			

[1] Surveyed.
[2] Determined from U.S. Geological Survey topographic map.
[3] Determined from Navajo Nation Abandoned Mine Lands Reclamation Department topographic map.

Arizona, about 1.8 mi east of the junction of El Capitan and Oljeto Washes (fig. 3 and table 1). The site includes two spoil piles and an oval-shaped pit approximately 750 ft long by 525 ft wide and 134 ft deep. The land-surface altitude is approximately 5,200 ft at the pit rim and 5,066 ft at the pit bottom. Uranium ore was mined from a paleochannel in the Shinarump Member that was cut into the underlying Moenkopi Formation and from the upper 15 ft of the Moenkopi Formation (Malan, 1968, p. 799). Ground water was seeping into the pit during mine inspections made between 1957 and 1967 (C.M. McConnell and L.G. Anderson, engineers, U.S. Geological Survey, written communs., 1957, 1958, 1967). During field investigation for this study, about 5,000 ft^2 of the pit bottom was covered with as much as 4 ft of water.

The Radium Hill mine in Utah is about 3 mi northeast of the Moonlight mine (fig. 3) and consists of a drill hole approximately 2 ft in

Table 2. Site data for shallow wells, mine drill holes, wells, and auger holes and depths to ground water, Monument Valley and Cameron mining districts

[X, open hole; ?, unknown]

Site name (field identification; figs. 3 and 4, tables 3-8)	Site type	Depth of hole (feet below land surface)	Open interval [screen or perforations (feet below land surface)]	Date depth to ground water measured	Depth to ground water (feet below land surface)
Monument Valley mining district					
Moonlight mine					
(MVD-1)	Shallow well	1.7	0.7-1.7	10-15-91	0.4
(MVD-2)	Shallow well	1.9	.9-1.9	10-16-91	.2
Radium Hill mine					
(Radium Hill)	Mine drill hole	96	X	10-17-91	86.8
08 024-03.81X02.63 (8T-525)	Well	383	17-81 248-383	10-17-91	Flowing
08 024-02.27X03.65 (8K-433)	Well	46	32-38	10-17-91	15.8
Unnamed 6-inch well near El Capitan Wash	Well	151	?	10-17-91	9.8
Unnamed 4-inch well near El Capitan Wash	Well	145	?	10-17-91	5.8
Unnamed drill hole near well 8K-433	Mine drill hole	156	X	10-17-91	56.2
Cameron mining district					
Jeepster No. 1 mine (auger hole)	Auger hole	7.0	X	10-31-91	3.5
Jack Daniels mine (JDD-1)	Auger hole	7.8	X	11-01-91	6.5
Manuel Denetsone No. 2 mine (M.D.-45)	Mine drill hole	33	X	11-02-91	16.3
03 098-06.07X11.16 (3T-539)	Well	188	81-188	11-02-91	24.1

Table 2. Site data for shallow wells, mine drill holes, wells, and auger holes and depths to ground water, Monument Valley and Cameron mining districts—Continued

Site name (field identification) (figs. 3 and 4, tables 3-8)	Site type	Depth of hole (feet below land surface)	Open interval [screen or perforations (feet below land surface)]	Date depth to ground water measured	Depth to ground water (feet below land surface)
Cameron mining district—Continued					
03 098-08.46X07.21 (Arizona Inspection Station well)	Well	50	?	11-02-91	23.8
Juan Horse No. 3 mine (auger hole)	Auger hole	9.1	X	11-05-91	7.3
Juan Horse No. 4 mine (auger hole)	Auger hole	12.4	X	11-04-91	9.2
Farm Project "A" well 03 098-07.04X10.40 (FPA)	Well	54	?	11-06-91	12.6

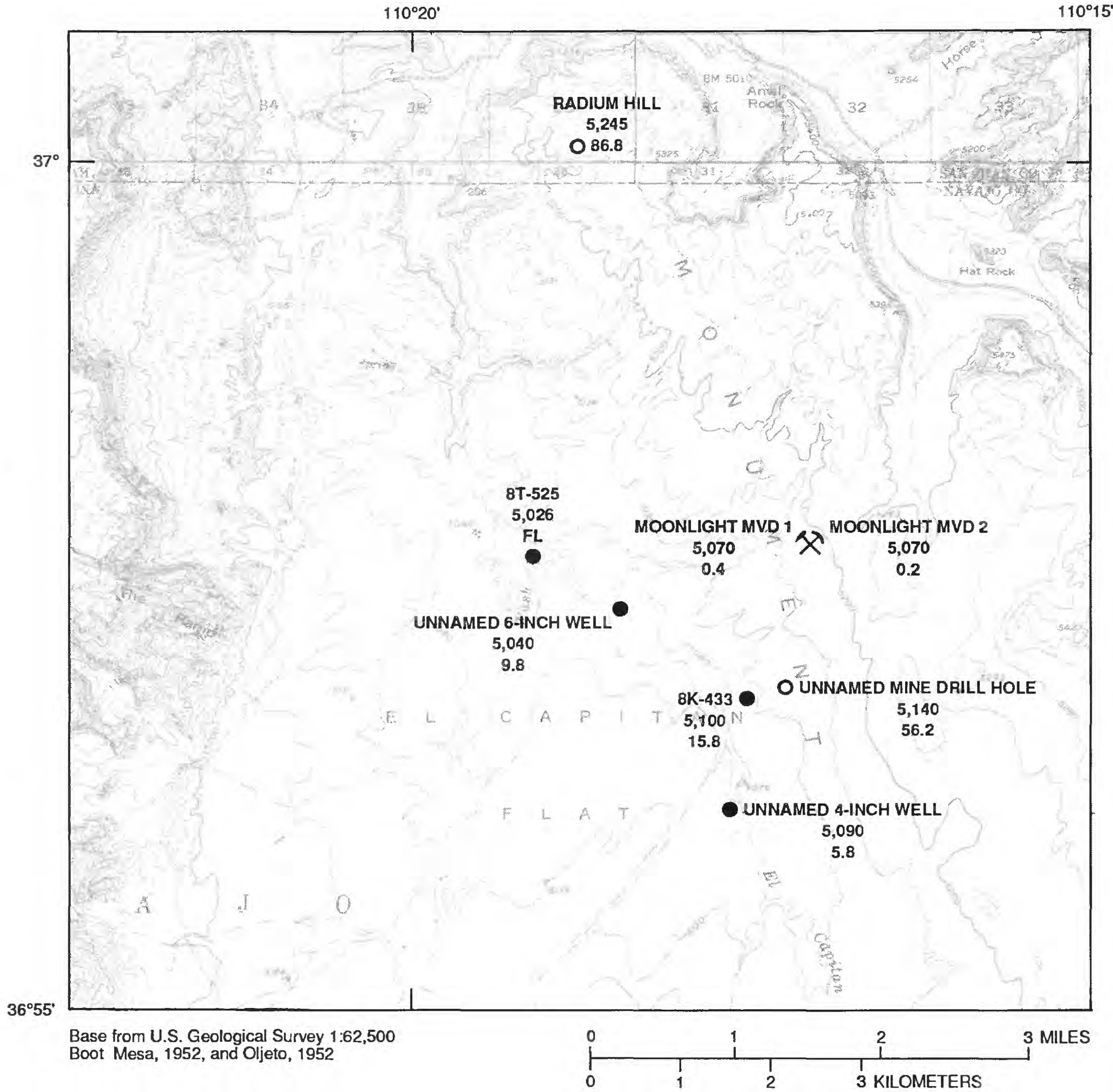
diameter and 96 ft deep, five spoil piles, and an inclined shaft. Uranium ore was extracted at the mine from one or more paleochannels in the Shinarump Member. The depth and lateral extent of the channel or channels were not determined.

Ground-water samples were collected from well 8T-525 (08 024-03.81X02.63), approximately 1.8 mi west of the Moonlight Mine near the junction of El Capitan and Oljeto Washes (fig. 3), for laboratory chemical analysis and for use in laboratory-batch tests. The well was drilled to a depth of 383 ft; however, measurements during this study indicated an obstruction or casing collapse at 82 ft. Ground water near the well is under artesian conditions and flows out of the casing at land surface. Depth to water was measured in well 8K-433 (08 024-02.10X3.00), in two abandoned wells along El Capitan Wash, and in an unnamed mine drill hole (fig. 3 and table 2). Well 8K-433 is about 1.1 mi south of the Moonlight Mine and supplies water to a stock tank.

Cameron Area

Data were collected from the Jeepster No. 1 mine about 4.7 mi north of Cameron and approximately 300 ft west of U.S. Highway 89 (fig. 4 and table 1). The mine consists of an elliptical pit approximately 200 ft wide at the north end, 80 ft wide at the south end, and 700 ft long. Spoil materials are in two piles on the ground near the south end of the pit. During mining operations, uranium ore was extracted from as deep as 60 ft below land surface in a carbonaceous sandstone lens within the Petrified Forest Member of the Chinle Formation (Scarborough, 1981, p. 153). About 15 ft of sediment has accumulated in the northern part of the pit since the cessation of mining in 1957. Loose surface material has been transported into the pit by wind and by rainfall runoff entering the south end of the pit along the access ramp.

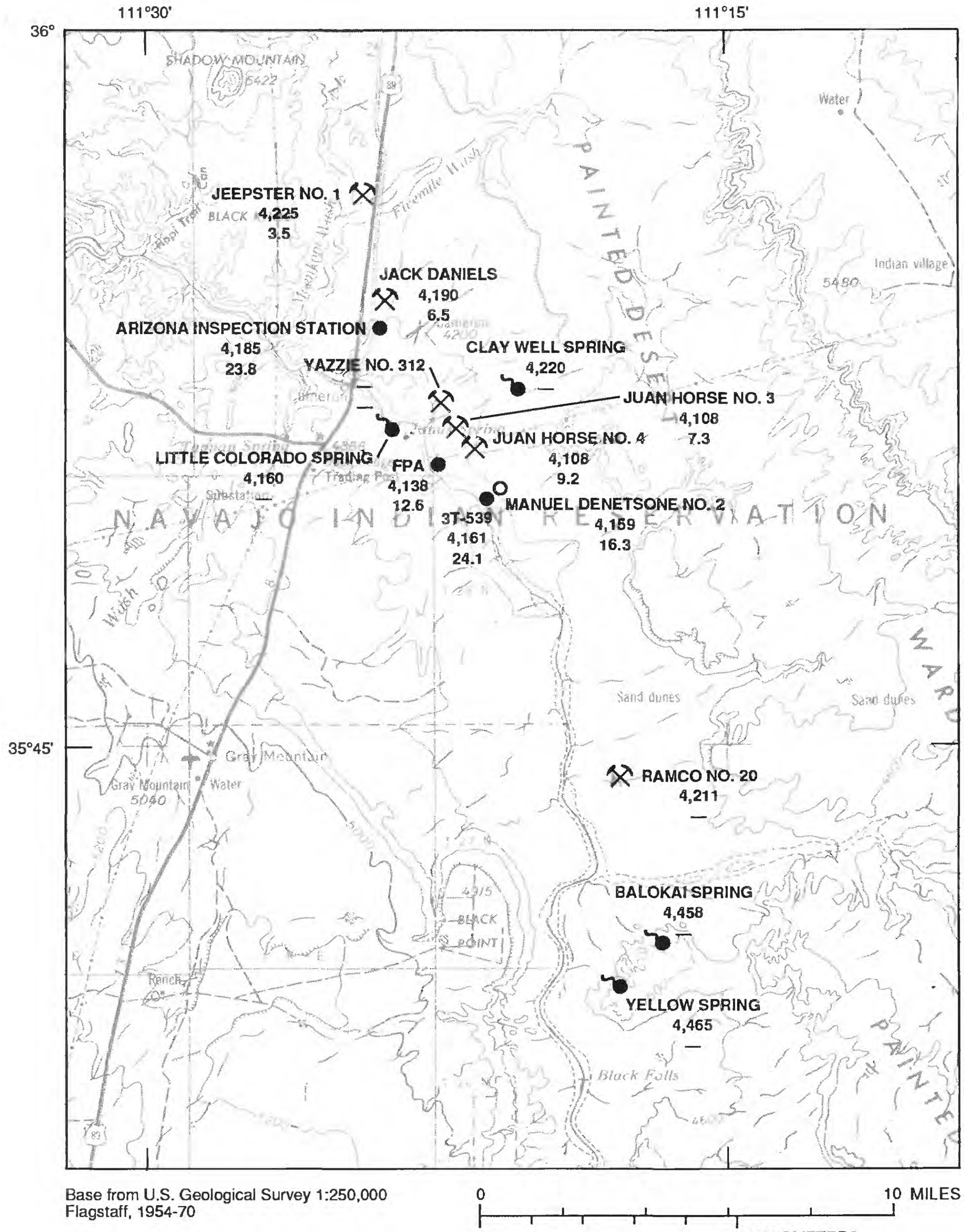
The Jack Daniels mine is about 2.2 mi north of Cameron and about 850 ft east of U.S. Highway 89. The site consists of one main pit



EXPLANATION

8K-433 5,100 15.8	MEASUREMENT SITE—First entry is site name; second entry is altitude of land surface, in feet above sea level; third entry, is depth to water, in feet below land surface; **FL**, flowing
●	WELL
O	MINE DRILL HOLE
⚒	OPEN-PIT MINE—Depth to water measured through shallow well

Figure 3. Depth to water and altitude of land surface for selected wells and mines in the Monument Valley mining district.



EXPLANATION

3T-539 4,161 24.1	MEASUREMENT SITE—First entry is site name; second entry is altitude of land surface, in feet above sea level; third entry is depth to water, in feet below land surface; dash indicates no data
●	WELL
(spring symbol)	SPRING
O	MINE DRILL HOLE
⚒	OPEN-PIT MINE—Depth to water measured through auger hole

Figure 4. Depth to water and altitude of land surface for selected wells, springs, and mines in the Cameron mining district.

and several smaller bulldozer cuts and scrapings that produced ore from five mining claims (Scarborough, 1981, p. 151). The main pit is approximately 450 ft by 250 ft and was about 26 ft deep during mining operations. Uranium ore was mined from a sandstone and siltstone channel near the base of the Petrified Forest Member (Scarborough, 1981, p. 151). During field investigation in 1991, the pit was only 10 to 15 ft deep as a result of an influx of surface sediments since mining ceased in 1962 or 1963. Sediment transported by rainfall runoff may enter the pit through present channels eroded into the west, south, and east sides. Spoil material was placed in at least eight piles on the north, east, and south sides of the pit.

The Manuel Denetsone No. 2 mine is about 4.2 mi southeast of Cameron and 0.5 mi east of the Little Colorado River. The site consists of a main shaft filled with sediment and three open drill holes approximately 2 ft in diameter. Measured depth of the drill hole sampled for this study was 33 ft; however, the hole may have been obstructed or partially caved. Uranium ore was mined at this site from discontinuous, mineralized lenses in carbonaceous sandstone of the Petrified Forest Member (Scarborough, 1981, p. 154).

The Ramco No. 20 mine is about 12 mi southeast of Cameron and about 1.3 mi east of the Little Colorado River. The main pit at this site is part of three mining claims and is about 200 ft by 2,200 ft and about 70 ft deep. The Ramco No. 20 site contains several spoil piles and two smaller pits that are about 200 ft by 400 ft and about 3 to 4 ft deep. Uranium ore was mined in the larger pit from an east- to northeast-trending channel-fill deposit in the Petrified Forest Member (Scarborough, 1981, p. 159). The smaller pits may have resulted from surface scrapings of scour and fill channels also in the Petrified Forest Member and probably were deeper during active mining operations. Water from the small pit on the west edge of the mining property was collected and analyzed for this study. The larger pit did not contain surface water during the field investigation.

The Juan Horse No. 3 and Juan Horse No. 4 mine pits (fig. 4) did not contain surface water during the study period. Uranium ore was mined at these sites from carbonaceous sandstone in the basal part of the Petrified Forest Member of the Chinle Formation (Scarborough, 1981, p. 153).

Data also were collected from existing wells and springs in the Cameron area (fig. 4). Samples were obtained from the Arizona Inspection Station well (03 098-08.46X07.21), well 3T-539 (03 098-06.07X11.16), Yellow Spring (03 117-02.67X05.77), Little Colorado Spring (03 098-07.70X09.60), and Clay Well spring (03 098-05.03X08.25). The Arizona Inspection Station well is about 1.8 mi north of Cameron and 0.35 mi southwest of the Jack Daniels mine. The well is 50 ft deep and supplies water to the Arizona Inspection Station on U.S. Highway 89. The length of the steel well casing is not known. Well 3T-539 is approximately 4.1 mi southeast of Cameron and 0.22 mi east of the Little Colorado River. The well is 188 ft deep, and the steel casing is perforated from 81 to 188 ft. A wind-powered piston pump in the well supplies water to a stock tank. Little Colorado Spring is near the south bank of the Little Colorado River about 1.7 mi southeast of Cameron, Yellow Spring is near the Baah Lokaa Ridge about 16 mi southeast of Cameron, and Clay Well spring is about 4 mi east of Cameron along a wash tributary to the Little Colorado River. The springs were improved by construction of concrete cisterns and hand pumps and are used to supply water to local residents. Depth to water was measured in well 3T-539, the Arizona Inspection Station well, and the unused Farm Project "A" well (03 098-07.04X10.40; fig. 4 and table 2).

Data were collected before this study in 1988 from the Clay Well spring, Yellow Spring, Little Colorado Spring, well 3T-539, Balokai Spring (03 117-1.65X04.76), and the open pit at the Yazzie No. 312 mine (table 1). Balokai Spring, also known as Lee Well, is about 15.5 mi southeast of Cameron and also is an improved spring used by local people. The Yazzie No. 312 mine is about 2.2 mi east of Cameron and about 0.7 mi north of the Juan Horse No. 3 mine.

METHODS OF INVESTIGATION

Sample collection and laboratory analyses were designed to characterize the chemical composition of the shallow ground water and mine water and to approximate the degree of post-reclamation leaching of radionuclides from spoil materials into the shallow ground water. Samples of shallow ground water and mine water were collected and analyzed, and spoil materials were collected and combined in laboratory-batch tests with ground-water samples from two wells that were assumed to be unaffected by mining activity (table 1 and figs. 3 and 4). Additional spoil material was collected for particle-size and mineralogical analyses. Depth to water was measured in hand-augered holes, shallow wells, mine drill holes, and existing wells. Land-surface altitudes were determined from survey and level data, from NAMLRD 1-foot contour-interval topographic maps, or from USGS 7.5-minute topographic maps. Surface gamma activity was monitored at all mines using a hand-held gamma meter.

Water-chemistry data were used to define the areal variability in radionuclide activities and concentrations of other constituents. Laboratory-batch tests provided data on chemical interactions of spoil material and shallow ground water that may occur following mine reclamation. Mineralogical analyses of spoil materials were used to characterize lithology and identify possible mineralogic constraints on radionuclide leaching. Depth to water was measured to characterize hydraulic connections between shallow ground water and abandoned mines and to define ground-water flow directions.

Field Methods

Field data and water samples were collected from shallow wells, pits and drill holes at mines, and existing wells and springs. Ground-water samples were collected at mines through 1.38-inch-diameter stainless-steel shallow wells. The shallow wells were hand-driven from the ground surface or from the bottom of a 3-inch-diameter hand-augered hole to the desired depth. Samples of shallow ground water could not be collected at the Jeepster No. 1, Juan Horse No. 3, or Juan Horse No. 4 mines because the shallow-well screens became clogged by silt and clay in the pit sediments. Ground-water samples were collected from mine drill holes using a polyvinyl chloride (PVC) bailer or a peristaltic pump. Pit-water samples were collected using a peristaltic pump. Water samples were collected from two existing wells using wind- or electric-powered in-well pumps, and water samples from the flowing well and from spring boxes were collected using a peristaltic pump. Depths to water in hand-augered holes, shallow wells, and existing wells were measured using a calibrated steel tape.

Water samples generally were collected after field measurements of temperature, pH, specific conductance, and dissolved-oxygen concentration had stabilized. Raw samples were collected for laboratory pH, specific conductance, and radon analyses; additional samples were filtered on site for alkalinity determinations and dissolved-constituent analyses. Samples for radon analyses were collected at three sites. Pit-water samples from the Jack Daniels and Ramco No. 20 mines had to be centrifuged and filtered at the USGS office in Flagstaff, Arizona, because of large suspended-sediment concentrations. Field alkalinities were not determined for these samples because the samples were not filtered on site.

Water for laboratory-batch tests was collected from well 8T-525 in the Monument Valley area and from the Arizona Inspection Station well in the Cameron area. Sample containers were kept from prolonged exposure to light and excessive temperature variations during transport in order to reduce possible physical and chemical alterations.

Spoil material was collected from the Moonlight, Radium Hill, Jeepster No. 1, and Jack Daniels mines for laboratory-batch tests and particle-size analyses. At each site, gamma measurements were made on several parts of spoil piles to identify the range of natural radiation levels. Approximately 1.0 kg of spoil material was collected from each of three or four subareas and was used to represent the general lithologic composition of a pile or a range of radioactivity within the pile. Material was collected from about 6 to 12 in. below the surface of the piles to limit possible effects of weathering in batch tests. Gamma measurements were made on the surface of the pile and at sample depth. A portion of each of the representative spoil-material samples was split out and collected for particle-size analyses. The remaining material was passed through a No. 10 mesh-size (2.00-mm opening) brass sieve and collected in each of two preweighed, acid-rinsed bottles for use in batch tests. At three of the mines, a portion of spoil material was collected from each representative sample before sieving for mineralogical analyses.

Laboratory Methods

Laboratory work included mixing of water and spoil materials and preparation of leachate samples (batch tests), physical and chemical analyses of water, and particle-size and mineralogical analyses of spoil materials. The batch tests for this study were modified from method D 4319 of the American Society for Testing and Materials (ASTM, 1990). The ASTM test is used to determine the rate at which chemical species in an aquifer travel with respect to the advancing front of ground water. The test can be used to determine distribution ratios of specific chemical species, which then can be used to estimate distribution coefficients for given geochemical conditions. Only ion exchange and adsorption processes within granular porous media, however, are considered in application of the ASTM test. Other important processes that may retard the flow of chemical species relative to ground-water flow include complex formation, precipitation or coprecipitation, oxidation-reduction reactions, and precipitate filtration. Also, because it is a short-term test, the attainment of equilibrium is not presumed. In this study, the test was modified and used to provide an approximation of radionuclide leaching from spoil material after contact with shallow ground water. All requirements of the ASTM test were not met in the modified version because of substantial costs inherent in obtaining advanced equipment and analytical expertise and because the chemical species of concern were components of the solid material rather than the fluid. Only the fraction of spoil material 2.00 mm (millimeter) in diameter and smaller was used in the batch tests because this material presents a large surface area per volume and should provide the greatest potential for radionuclide leaching. Distribution ratios and distribution coefficients were not calculated from the test results.

Laboratory-batch tests and particle-size analyses of spoil material were done at the Chemistry Laboratory of the New Mexico Bureau of Mines and Mineral Resources (NMBMMR) in Socorro, New Mexico. Batch-test procedures consisted of measuring physical and chemical characteristics of the water, combining spoil material with water, agitating the water and spoil mixtures for a predetermined period, measuring physical and chemical characteristics of the material mixtures, and collecting leachate for chemical analyses. Temperature, specific conductance, pH, and carbonate and bicarbonate alkalinity were measured in the water before it was mixed with the spoil material and in the water and spoil-material mixture after the agitation period. Water was combined with the spoil material at a 4-to-1 ratio by weight. For each sample, 2.5 L (liter) of water and 0.625 kg of spoil material were placed into each of two 3-liter Nalgene bottles and the contents stirred thoroughly. The bottles were placed on a rolling device for 12 hours of agitation, then removed to allow the contents to settle for 60 hours. The leachate was centrifuged and passed through a 0.45-micrometer pore-size polycarbonate filter, collected in bottles, and preserved with acid.

Water samples were analyzed at the USGS National Water Quality Laboratory (NWQL) in Arvada, Colorado, and at the International Technology Corporation Laboratory (ITCL) in Richland, Washington. Radiochemical analyses were done at the ITCL, and the remaining analyses were done at the NWQL. Analytical methods used by the NWQL are discussed by Fishman and Friedman (1989). Analytical methods used by the ITCL have been approved by the U.S. Environmental Protection Agency (USEPA).

The NMBMMR also analyzed spoil material for particle-size distribution. Weight percentages were determined of material smaller than 62 μm (micrometers) in diameter, material from 62 μm to 2.00 mm in diameter, and material larger than 2.00 mm in diameter. The range of particle sizes for each sample site provides a general character of the material that will be used in mine reclamation.

Mineralogical analyses of spoil material were done at the USGS office in Sacramento, California. Analyses by X-ray diffractometry were done on spoil samples from three mines to determine major, minor, and trace minerals that made up at least 5 to 10 percent of the sample volume. A sample weighing less than 10 grams was used to compare diffractograms of the minerals present to prepared standards from known minerals. The diffractograms were then used to determine minerals present in each sample.

GEOHYDROLOGY

Monument Valley Area

The Monument Valley mining district lies within the Monument Valley hydrogeologic subdivision of the Navajo Indian Reservation, which is part of the Henry hydrologic basin (Cooley and others, 1969, p. 25 and 40). The Monument Valley subdivision is one of the driest and least favorable areas for development of ground-water supplies in the Navajo country because of the relative impermeability of the sedimentary rocks and because dissection has drained some of the former water-bearing units.

Geohydrologic Units

The consolidated sedimentary rocks in the Monument Valley area generally consist of eolian and fluvial deposits that, in some instances, alternate one with another, are light buff to deep reddish brown, and are about 5,000 ft thick (Witkind and Thaden, 1963, p. 6). The sedimentary rocks range in age from Permian to Jurassic and consist of the Cutler Formation, Moenkopi Formation, Chinle Formation, Glen Canyon Group, San Rafael Group, and Morrison Formation. The Shinarump Member of the Chinle Formation, the Moenkopi Formation, and the De Chelly Sandstone Member and Organ Rock Tongue of the Cutler Formation are part of the C aquifer system in the Monument Valley area (Levings and Farrar, 1977).

The Organ Rock Tongue is predominantly a reddish-brown poorly sorted siltstone with a few thin, very fine grained silty sandstone lenses near the base of the unit. In the upper 25 to 50 ft of the unit, the grain size changes and the unit becomes gradually coarser toward the contact. At the contact with the De Chelly Sandstone Member, the unit is a fine-grained sandstone. The Organ Rock Tongue is from about 670 to 700 ft thick in the Monument Valley area (Witkind and Thaden, 1963, p. 11).

The De Chelly Sandstone Member overlies the Organ Rock Tongue and is a crossbedded grayish-yellow to tan fine-grained sandstone that forms the main part of the monuments and larger mesas in the area. The De Chelly is poorly sorted and is weakly cemented by chalcedony, calcium carbonate, and iron oxide. The unit ranges in thickness from 300 to 550 ft and pinches out near Monitor Butte about 15 mi north of the Arizona-Utah border. In the western part of the Monument Valley area, the De Chelly is about 300 ft thick and decreases in thickness northward (Witkind and Thaden, 1963, p. 13).

The Hoskinnini Member forms the basal unit of the Moenkopi Formation and unconformably overlies the De Chelly Sandstone Member of the Cutler Formation. The unit consists of dark red very fine grained to fine-grained silty sandstone with varying amounts of medium- and coarse-grained sandstone in some beds. Overlying the Hoskinnini Member are the lower siltstone, middle sandstone, and upper siltstone members. The Moenkopi Formation is about 278 ft thick at one location near the San Juan River, about 150 ft thick in the central part of Monument Valley, and about 50 ft thick near Comb Ridge (Repenning and others, 1969, p. 9 and 12).

The Chinle Formation overlies the Moenkopi Formation and is the primary source of uranium ore in the Monument Valley area. The Chinle Formation in this area consists of, in ascending order, the Shinarump, Monitor Butte, Petrified Forest, Owl Rock, and Church Rock Members. Thickness of the Chinle Formation varies because of local thinning and wedging out of members and because of an uneven basal contact with the Moenkopi Formation (Repenning and others, 1969, p. 15; Witkind and Thaden, 1963, p. 21). The Shinarump Member in most areas is light tan to light gray and is composed of a basal conglomerate and an upper part that consists of varying amounts of sandstone, siltstone, and mudstone. The Shinarump probably averages about 75 ft in thickness in the Monument Valley area although it attains a maximum thickness of about 250 ft (Levings and Farrar, 1977). Basal deposits fill channels cut into the underlying Moenkopi Formation (Chenoweth and Malan, 1973, p. 139). These scour-and-fill sediments contain abundant amounts of silicified wood and fossilized plant matter (Chenoweth and Malan, 1973, p. 139; Witkind and Thaden, 1963, p. 23). The contact is marked by a zone of bleaching developed in the underlying Moenkopi Formation. The unit is resistant to weathering and forms a cap rock over older formations on many mesas and buttes.

Deposits of dune sand, alluvium, talus, and landslide blocks of Quaternary age cover large areas of bedrock in the Monument Valley area. Alluvium fills most of the stream washes and in some areas is covered by dune sand. The combined dune sand and alluvium thickness is between about 80 and 100 ft along Oljeto Wash (Witkind and Thaden, 1963, p. 50). Well 8P-331 (08 24-01.47X02.32), about 0.5 mi northwest of the Moonlight mine, penetrates 110 ft of alluvium (Levings and Farrar, 1977); however, this well could not be located during the study.

Occurrence of Ground Water

Although ground water may be found in the alluvium and in all the consolidated sedimentary rocks, it generally is available to wells only in the alluvium and in the relatively more permeable units of the C aquifer (Cooley and others, 1969, p. 7). The alluvium may yield more than 10 gal/min of water to wells. Within the C aquifer, the Shinarump Member may yield 5 to 10 gal/min, the De Chelly Sandstone Member may yield 5 gal/min, and the Organ Rock Tongue may yield 1 to 2 gal/min. The Moenkopi Formation generally does not yield water to wells (Levings and Farrar, 1977). Well 8K-433 is perforated in the Shinarump Member of the Chinle Formation and well 8T-525 is perforated both in the Shinarump and in the De Chelly Sandstone. The perforated or screened intervals in the two unnamed wells near El Capitan Wash are not known; however, the depths of the wells indicate they probably were drilled into the Shinarump. The unnamed mine drill hole near well 8K-433 probably terminates in the Shinarump.

Recharge to the alluvium and the C aquifer is directly from rainfall, from ephemeral streams, or from leakage from underlying water-bearing units (Cooley and others, 1969, p. 40). Alluvium and other surficial deposits are recharged by rainfall, by influent streams, and by discharge from the consolidated aquifers. Recharge to the C aquifer in outcrop areas occurs mostly through fractures and along bedding planes. High rates of evaporation and low permeabilities limit the amount of recharge in the nonfractured parts of the aquifer (Cooley and others, 1969, p. 41). In the area near the Moonlight and Radium Hill mines, ground water generally moves from the recharge areas toward the Oljeto and El Capitan Washes and then eventually flows north and discharges to the San Juan River (fig. 3). Water is withdrawn from domestic and stock wells.

Hydrology of Mines

Channel deposits of the Shinarump Member in the area of the Moonlight and Radium Hill mines generally are more permeable than the overlying Chinle Formation and underlying Moenkopi Formation and yield water to nearby wells. Reports from mine inspections indicate ground-water seepage into the Moonlight mine as early as 1957 (C.M. McConnell, engineer, U.S. Geological Survey, written commun., 1957). Ground-water seepage along the pit walls above the pit floor was not present during field investigation but may occur below the present water surface. Ground water may flow into the pit through permeable sediments, through fractures, or along bedding planes in the Moenkopi Formation, or through coarse sediments in the Shinarump Member (fig. 5). The contact between the Shinarump Member and the Moenkopi Formation was not mapped at the site during this study. Malan (1968) stated that ore extended downward as much as 15 ft into the Moenkopi.

The bottom of the pit at the Moonlight mine contains an unknown thickness of dark-gray to dark-brown unconsolidated sand, silt, and clay that probably is a mixture of material weathered from the pit walls and material transported from areas near the pit rim by wind and rainfall runoff. An access ramp leads into the pit from the west side of the rim but terminates about 60 ft from the pit floor along the west pit wall. The ramp is within an area that generally slopes westward from the pit; however, the ramp drains a small area between the two spoil piles that lie north of the ramp. Small drainage features have been incised into the ramp sediments at the upper part but do not extend along the entire ramp length. Records indicate that the pit was about 145 ft deep when the mine was in operation (Scarborough, 1981, p. 222). During field investigation, the floor of the pit at the south end was about 134 ft from the pit rim and about 3 to 4 ft lower than the floor at the north end. The maximum depth of water in the south end of the pit was about 4 ft in October 1991.

Depth to water and land-surface altitude at the Moonlight mine, at existing wells, and at

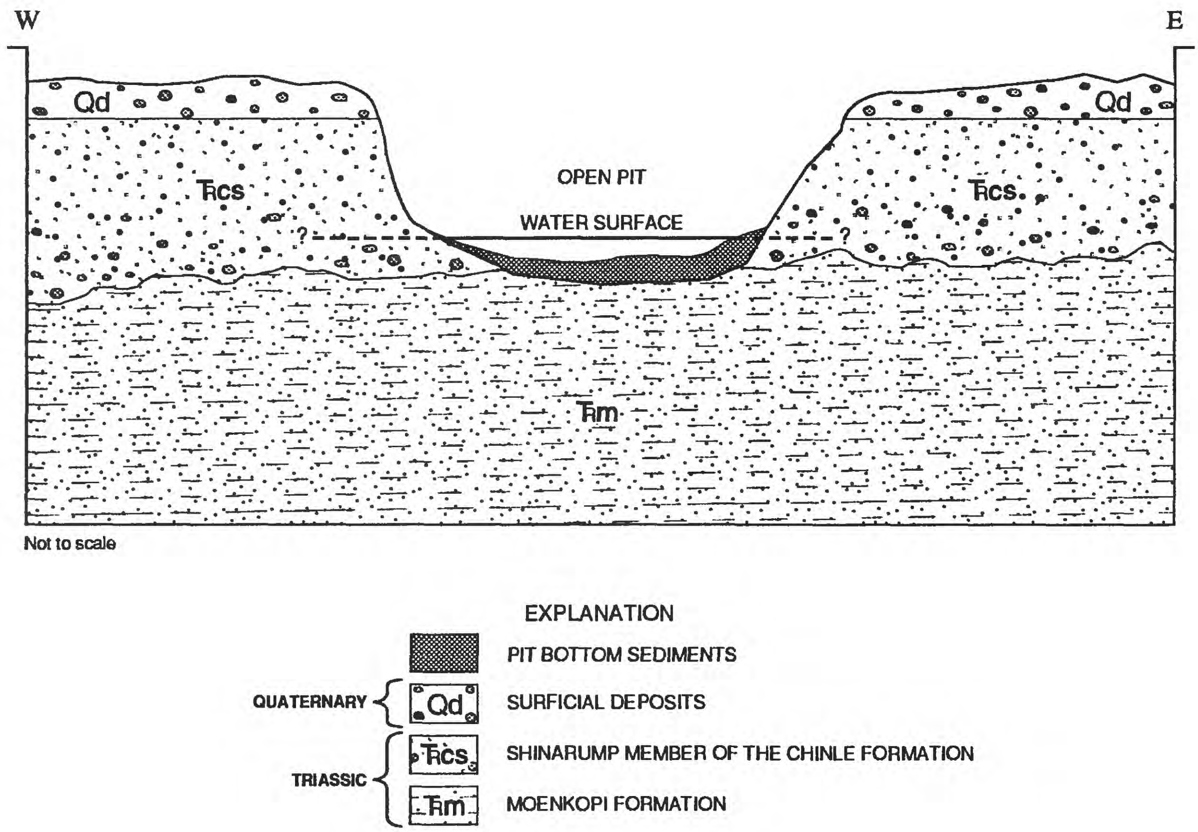


Figure 5. Lithologic units in the Moonlight mine pit, Monument Valley.

the unnamed mine drill hole indicate that local ground-water flow is from the southeast toward the northwest along the trend of Oljeto Wash (fig. 3 and table 2). The depth to water in the Radium Hill drill hole was 86.8 ft from the land-surface altitude of 5,245 ft, indicating a ground-water altitude of approximately 5,158 ft. Ground-water conditions between the Moonlight and Radium Hill mines cannot be established because depth to water in the area between the sites is not known. The thickness of the Shinarump varies significantly within short lateral differences, and the unit may not be water bearing in areas where the basal contact occurs at higher subsurface altitudes. Water in well 8T-525 rises above the top of the casing, indicating local confined ground-water conditions in the Shinarump Member, the De Chelly Sandstone Member, or in both units.

Cameron Area

The Cameron mining district lies within the Painted Desert hydrogeologic subdivision of the Navajo Indian Reservation, which is part of the Black Mesa hydrologic basin (Cooley and others, 1969, p. 23 and 41). The mining district is drained by the Moenkopi Wash and the Little Colorado River. Most rocks of Triassic age that underlie the area do not yield water to wells, and ground-water supplies generally are insufficient or of poor chemical quality for stock and domestic use. Quaternary alluvial deposits and the Shinarump Member of the Chinle Formation transmit water to the existing wells and springs included in this study.

Geohydrologic Units

Consolidated sedimentary rocks exposed in the Cameron mining district are units of the Moenkopi and Chinle Formations of Triassic age. The rocks are mudstones, siltstones, sandstones, conglomerates, and limestones in shades of brown, red, yellow, gray, and purple that generally are easily weathered into badland topography. The combined thickness of these formations ranges from about 1,500 to 1,650 ft within the area (Repenning and others, 1969, figs. 4 and 6). Uranium ore was mined from the Petrified Forest Member of the Chinle Formation at mines included in this study.

The Chinle Formation in the Cameron area is similar in structure and lithology to the Chinle Formation in Monument Valley. In the Cameron area, the basal Shinarump Member overlies the Moenkopi Formation and is about 30 to 60 ft thick. The Shinarump is overlain by the sandstone and siltstone member, the Petrified Forest Member, and, in the northeastern part of the area, the Owl Rock Member. The sandstone and siltstone member is about 100 to 160 ft thick and primarily a sandstone at Cameron (Repenning and others, 1969, p. 18). The sandstone beds are predominantly fine- to coarse-grained quartz and feldspar that contain accessory mica and commonly display crossbedding and banding of light gray, light purple, and yellowish brown. Parts of the beds are conglomeratic and include pebbles that average about 0.5 in. in diameter. The sandstone beds, however, are not as crossbedded or as conglomeratic as the underlying Shinarump Member. The Petrified Forest Member overlies the sandstone and siltstone member and consists of blue, gray, and white mudstone and tuffaceous siltstone that locally includes lenses of sandstone with varying amounts of carbonaceous matter. The sandstone lenses probably are ancient fluvial channel fills and were sources of most uranium ore mined in the area (Chenoweth and Malan, 1973). Bollin and Kerr (1958) stated that fractures in the Petrified Forest Member mudstones and the many faults in the area were pathways for movement of uranium solutions under hydrostatic pressure in the underlying Shinarump Member. The fractures and faults are probable current pathways for ground-water movement from the Shinarump Member into overlying units and open-mine pits. The Petrified Forest Member is about 850 ft thick in parts of the Cameron area but thins southwestward to its updip limit near the Little Colorado River (Repenning and others, 1969, p. 23; Ulrich and others, 1984).

Quaternary alluvium covers older rocks in parts of the Cameron area. Younger alluvium fills the Little Colorado River channel upstream from Cameron, where the channel is broad and shallow. Younger alluvium also fills most of the Moenkopi Wash north of Cameron. The younger alluvium is unconsolidated sand, silt, clay, and minor interbedded gravel. Older alluvial deposits near the Little Colorado River are Pleistocene in age, consist of consolidated gravelly sand with interbedded sand and silt, and are as much as 120 ft thick (Ulrich and others, 1984).

Occurrence of Ground Water

Alluvial deposits yield small quantities of water to springs and to at least one well in the study area. Cooley and others (1969, p. 44 and 46) indicated that within the Navajo Indian Reservation, wells in the alluvium yield from 5 to 275 gal/min and springs generally yield less than 10 gal/min. Springs included in this study occur at contacts between alluvial deposits and impermeable consolidated rock units or possibly where bedding planes or joints in consolidated sediments intersect the land surface.

The blue mudstone unit of the Petrified Forest Member and the sandstone and siltstone member contained ground water in some areas when the mines were in operation. Repenning and others (1969, p. 24) stated that standing water observed in uranium-ore exploration pits near Cameron resulted from ground water in the Shinarump Member flowing through fractures in the overlying blue mudstone unit. The blue mudstone unit does not presently yield water to wells. Ground water also was observed in the sandstone and siltstone member of the Chinle Formation in uranium-test holes. A few wells in the area yield small quantities of water from both the sandstone and siltstone member and the Shinarump Member. Some of the mine pits are underlain by permeable sediments of the Petrified Forest Member, which may be hydraulically connected to the underlying sandstone and siltstone member or Shinarump Member.

The Shinarump Member of the Chinle Formation yields water to at least two wells in the area of the mines studied—well 3T-539 west of the Manuel Denetsone No. 2 mine and the Arizona Inspection Station well south of the Jack Daniels mine. Artesian conditions exist locally in the Shinarump Member where ground water is transmitted through fractures in the lower part of the Petrified Forest Member and into the open pits. According to Cooley and others (1969, p. 41), the regional ground-water flow direction is toward the Little Colorado River, which is the primary area of natural ground-water discharge. Depth-to-water measurements collected for this study from the two existing wells in the Shinarump were not sufficient to determine directions of local ground-water flow. Cooley and others (1969, p. 46) indicated that wells in the Shinarump Member yield from 1 to 60 gal/min.

The alluvium receives ground-water recharge from rainfall, from ephemeral streams, and in some areas, possibly from leakage from deeper water-bearing units. The sandstone and siltstone member and the Shinarump Member probably receive ground-water recharge from deeper water-bearing units because of their limited surface exposure in the area. Depth-to-water measurements are shown in figure 4.

Hydrology of Mines

Water presently contained in the Jeepster No. 1, Jack Daniels, and Ramco No. 20 mine pits may originate from several sources. The three pits receive water from rainfall and surface inflow of rainfall runoff from surrounding areas. Ground water also may move from permeable sediments of the sandstone and siltstone member or the Shinarump Member through fractures or along faults into the lower part of the Petrified Forest Member and into the open pits (fig. 6). Although these pits receive some rainfall runoff, they also retain water through extensive dry periods, which indicates a subsurface water source.

The Juan Horse No. 3 and No. 4 mine pits may receive ground-water flow in a similar manner as the three pits mentioned above. Although the two pits did not contain surface water during field investigation, sediments in the pit bottoms were wet and ground-water levels were less than 10 ft below the pit bottom (table 2).

The Manuel Denetsone No. 2 drill hole terminates in a unit of the Petrified Forest Member and may receive ground-water inflow directly from the underlying sandstone and siltstone member or Shinarump Member or indirectly from fractures or along faults in the mudstone unit of the Petrified Forest Member. Additional water may be contributed by infiltration of rainfall into sediments along the nearby wash, which may be hydraulically connected to the sandstone sediments in the drill hole, or by direct inflow of rainfall runoff into the drill hole at land surface.

Ground-water altitudes in the Cameron area vary significantly in short lateral distances (table 2 and fig. 4). Because of the sparsity and

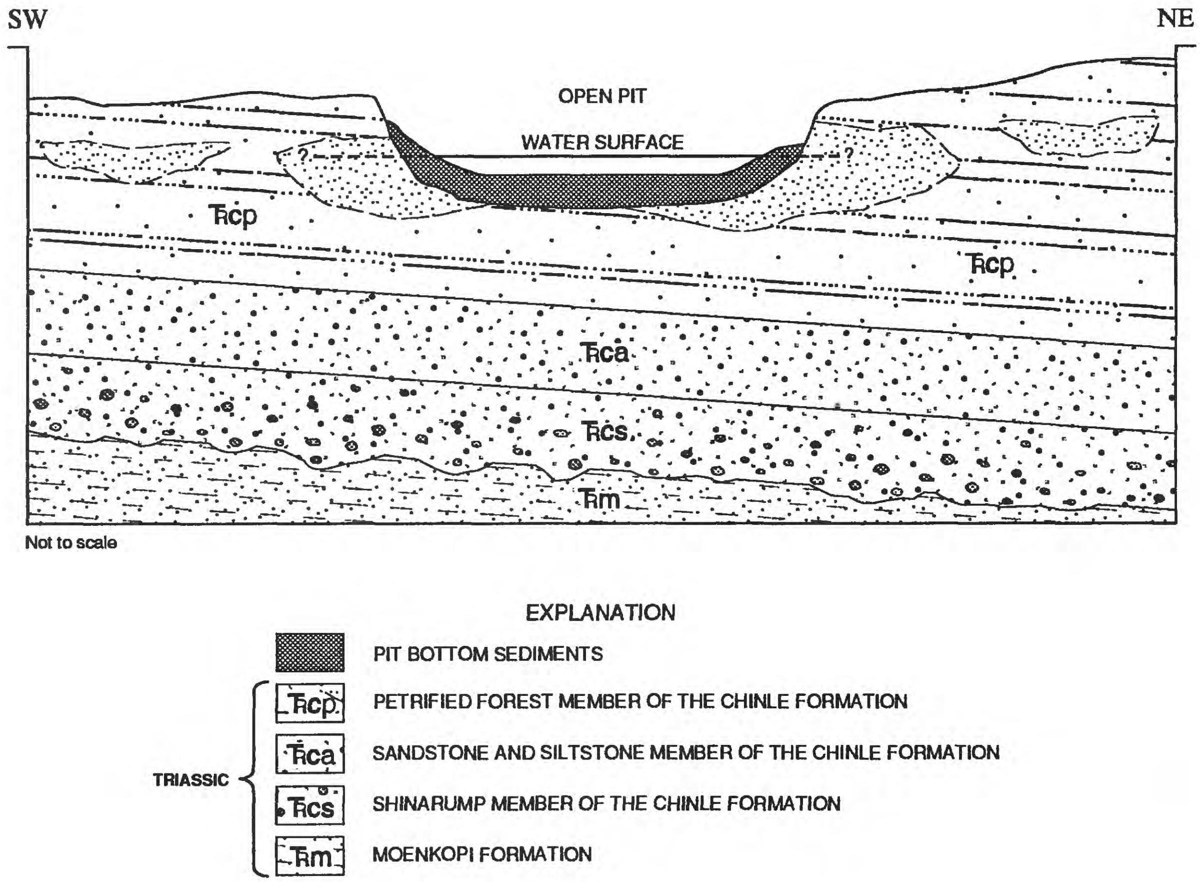


Figure 6. Lithologic units near mine pits studied in the Cameron mining district.

remoteness of wells, relations of local ground-water occurrences cannot be defined with present data. Channel-fill deposits that encompass individual mines and are water bearing probably are not laterally continuous and, consequently, produce local variability in depths to water.

WATER CHEMISTRY

Monument Valley Area

Water-chemistry data from the Monument Valley area include analyses of samples from two mines and one existing well (table 3). Water chemistry at the two mines is influenced by uranium mineralization. Radionuclide activities and concentrations of most dissolved constituents were larger in water from the mines than in water from well 8T-525. Although the fate of the shallow ground water and pit water at the mines is unknown and the quality of water on the Navajo Indian Reservation is not regulated by the State of Arizona, the water-chemistry data from this study are referenced to USEPA drinking-water regulations and State of Arizona aquifer water-quality and surface-water-quality standards for purposes of comparison (U.S. Environmental Protection Agency, 1992; State of Arizona, 1992).

Shallow ground water at the Moonlight mine is characterized by high specific conductance and large radionuclide activities.

Table 3. Field measurements and laboratory analyses of water, Monument Valley and Cameron mining districts

[°C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; dashes indicate no data; <, value is known to be less than the value shown; µg/L, micrograms per liter; pCi/L, picocuries per liter]

Sample identification	Date	Time	Temperature water (°C)	Specific conductance (µS/cm)	pH (standard units)	Carbonate, dissolved (mg/L as CO_3)	Bicarbonate, dissolved (mg/L as HCO_3)	Alkalinity, dissolved (mg/L as $CaCO_3$)	Oxygen, dissolved (mg/L)
Field measurements—Monument Valley mining district									
MVD-1	10-15-91	1745	14.0	5,950	7.0	----	410	336	0.4
MVD-2	10-16-91	1145	15.0	7,200	7.1	----	495	406	.4
MVSW-1	10-16-91	1500	15.0	5,440	8.0	----	395	324	6.2
Radium Hill	12-17-91	1100	10.0	1,680	7.2	----	293	240	----
8T-525	12-17-91	1445	13.5	642	7.5	----	328	269	----
Field measurements—Cameron mining district									
JSW-1	10-29-91	1645	10.5	20,300	9.5	14	48	63	11.2
JDD-1	11-01-91	1600	18.5	2,430	7.4	----	1,070	873	1.6
JDSW-1	[1]10-31-91	1715	4.5	1,090	8.2	----	------	-----	10.4
M.D.-45	11-02-91	1630	19.0	2,240	7.6	----	571	468	.8
Ramco No. 20 NW	11-06-91	1345	15.0	1,420	8.7	----	------	-----	9.9
Clay Well spring	11-05-91	1600	14.5	1,930	8.4	38	620	572	6.2
Yellow Spring	11-07-91	1200	15.0	1,090	7.9	----	277	227	3.3
Little Colorado Spring	12-19-91	1015	5.0	537	8.0	----	234	192	8.2
3T-539	12-20-91	1030	16.0	4,200	7.5	----	322	264	----
Arizona Inspection Station well	12-19-91	1350	19.0	1,040	8.8	9.6	284	233	----

[1]Field measurements made prior to sample collection date.

Table 3. Field measurements and laboratory analyses of water—Continued

Sample identification	Date	Time	Calcium, dissolved (mg/L as Ca)	Magnesium, dissolved (mg/L as Mg)	Sodium, dissolved (mg/L as Na)	Chloride, dissolved (mg/L as Cl)	Sulfate, dissolved (mg/L as SO_4)	Fluoride, dissolved (mg/L as F)	Nitrogen, nitrite dissolved (mg/L as N)
Laboratory analyses—Monument Valley mining district									
MVD-1	10-15-91	1745	440	540	460	65	3,700	1.8	<0.010
MVD-2	10-16-91	1145	430	640	720	15	4,500	.50	<.010
MVSW-1	10-16-91	1500	430	430	500	51	3,300	2.6	<.010
Radium Hill	12-17-91	1100	300	72	23	23	820	.50	<.010
8T-525	12-17-91	1445	26	18	85	13	66	.50	<.010
Laboratory analyses—Cameron mining district									
JSW-1	10-29-91	1645	620	130	6,000	310	12,000	3.8	<.010
JDD-1	11-01-91	1600	14	2.6	510	76	180	1.1	<.010
JDSW-1	11-07-91	1545	15	.85	240	42	120	.90	<.010
M.D.-45	11-02-91	1630	9.9	2.3	450	260	280	1.6	.010
Ramco No. 20 NW	11-06-91	1345	11	1.3	330	54	63	1.0	<.010
Clay Well spring	11-05-91	1600	5.4	1.8	420	190	130	2.3	<.010
Yellow Spring	11-07-91	1200	28	3.8	200	47	240	2.2	<.010
Little Colorado Spring	12-19-91	1015	31	23	46	26	46	.50	<.010
3T-539	12-20-91	1030	82	31	710	1,000	280	1.3	<.010
Arizona Inspection Station well	12-19-91	1350	2.5	.40	210	110	89	2.7	<.010

Table 3. Field measurements and laboratory analyses of water—Continued

Sample identification	Date	Time	Nitrogen, NO_2+NO_3 dissolved (mg/L as N)	Silica, dissolved (mg/L as SiO_2)	Barium, dissolved (µg/L as Ba)	Beryllium, dissolved (µg/L as Be)	Cadmium, dissolved (µg/L as Cd)	Chromium, dissolved (µg/L as Cr)	Cobalt, dissolved (µg/L as Co)
Laboratory analyses—Monument Valley mining district—Continued									
MVD-1	10-15-91	1745	<0.050	7.7	13	<2	4.0	2	1,700
MVD-2	10-16-91	1145	<.050	8.0	10	<2	4.0	1	1,100
MVSW-1	10-16-91	1500	<.050	.06	43	<2	<3.0	20	9
Radium Hill	12-17-91	1100	.097	13	33	<.5	<1.0	<5	8
8T-525	12-17-91	1445	<.050	8.2	36	<.5	<1.0	<5	<3
Laboratory analyses—Cameron mining district—Continued									
JSW-1	10-29-91	1645	<.050	1.5	<10	<5	2.0	<3	<4
JDD-1	11-01-91	1600	<.050	11	30	<15	<3.0	<20	<9
JDSW-1	11-07-91	1545	<.050	18	100	<.5	<1.0	<5	<3
M.D.-45	11-02-91	1630	<.050	14	110	<2	<3.0	<20	<9
Ramco No. 20 NW	11-06-91	1345	<.050	26	130	<.5	<1.0	<5	<3
Clay Well spring	11-05-91	1600	1.00	16	71	1	<1.0	<5	<3
Yellow Spring	11-07-91	1200	.590	20	37	<.5	<1.0	<5	<3
Little Colorado Spring	12-19-91	1015	2.40	9.3	63	<.5	<1.0	<5	<3
3T-539	12-20-91	1030	<.050	8.2	35	<2	<3.0	<20	<9
Arizona Inspection Station well	12-19-91	1350	8.20	11	26	<.5	<1.0	<5	<3

Table 3. Field measurements and laboratory analyses of water—Continued

Sample identification	Date	Time	Copper, dissolved (µg/L as Cu)	Iron, dissolved (µg/L as Fe)	Lead, dissolved (µg/L as Pb)	Lithium, dissolved (µg/L as Li)	Manganese, dissolved (µg/L as Mn)	Molybdenum, dissolved (µg/L as Mo)	Nickel, dissolved (µg/L as Ni)
Laboratory analyses—Monument Valley mining district—Continued									
MVD-1	10-15-91	1745	40	1,900	<1	640	2,700	3,000	850
MVD-2	10-16-91	1145	200	240	<1	990	1,700	3,600	540
MVSW-1	10-16-91	1500	<30	28	<30	770	65	760	30
Radium Hill	12-17-91	1100	<10	190	<10	65	420	10	10
8T-525	12-17-91	1445	<10	180	<10	78	8	<10	<10
Laboratory analyses—Cameron mining district—Continued									
JSW-1	10-29-91	1645	<10	43	<1	1,200	<10	210	<1
JDD-1	11-01-91	1600	<30	36	<30	190	54	30	<30
JDSW-1	11-07-91	1545	20	26	<10	28	2	10	<10
M.D.-45	11-02-91	1630	<30	95	<30	190	35	70	<30
Ramco No. 20 NW	11-06-91	1345	20	71	<10	32	4	10	<10
Clay Well spring	11-05-91	1600	<10	95	<10	59	<1	10	<10
Yellow Spring	11-07-91	1200	<10	8	10	52	1	<10	<10
Little Colorado Spring	12-19-91	1015	<10	<3	<10	45	<1	<10	<10
3T-539	12-20-91	1030	<30	730	40	320	250	<30	<30
Arizona Inspection Station well	12-19-91	1350	<10	18	<10	150	<1	<10	<10

Table 3. Field measurements and laboratory analyses of water—Continued

Sample identification	Date	Time	Silver, dissolved (µg/L as Ag)	Strontium, dissolved (µg/L as Sr)	Vanadium, dissolved (µg/L as V)	Zinc, dissolved (µg/L as Zn)	Uranium -238, dissolved (pCi/L)	Uranium -234, dissolved (pCi/L)	Uranium -235, dissolved (pCi/L)
Laboratory analyses—Monument Valley mining district—Continued									
MVD-1	10-15-91	1745	<1.0	5,200	<18	770	11,000	11,000	440
MVD-2	10-16-91	1145	<1.0	6,000	<24	690	14,000	14,000	530
MVSW-1	10-16-91	1500	<3.0	7,300	<18	34	-----------	-----------	-------
Radium Hill	12-17-91	1100	1.0	1,300	<6	28	210	230	12
8T-525	12-17-91	1445	<1.0	980	<6	3	.50	.90	<.1
Laboratory analyses—Cameron mining district—Continued									
JSW-1	10-29-91	1645	<1.0	20,000	16	44	22	30	.8
JDD-1	11-01-91	1600	<3.0	490	<18	<9	150	210	5.7
JDSW-1	11-07-91	1545	<1.0	450	48	<3	11	14	.4
M.D.-45	11-02-91	1630	<3.0	410	<18	<9	180	230	8.9
Ramco No. 20 NW	11-06-91	1345	<1.0	350	63	<3	15	20	.6
Clay Well spring	11-05-91	1600	2.0	270	210	4	27	38	1.1
Yellow Spring	11-07-91	1200	<1.0	400	24	8	4.3	5.7	.2
Little Colorado Spring	12-19-91	1015	1.0	970	<6	29	-----------	-----------	-------
3T-539	12-20-91	1030	3.0	5,300	<18	110	-----------	-----------	-------
Arizona Inspection Station well	12-19-91	1350	<1.0	130	46	5	20	24	.9

Table 3. Field measurements and laboratory analyses of water—Continued

Sample identification	Date	Time	Gross alpha, dissolved (µg/L as U-nat)	Gross beta, dissolved (pCi/L as Cs-137)	Gross beta, dissolved (pCi/L as Sr/Yt-90)	Radium 226, dissolved, radon method (pCi/L)	Radon 222, total (pCi/L)
Laboratory analyses—Monument Valley mining district—Continued							
MVD-1	10-15-91	1745	18,000	20,000	15,000	44	53,000
MVD-2	10-16-91	1145	19,000	21,000	16,000	110	250,000
MVSW-1	10-16-91	1500	8,500	11,000	8,100	8.6	----------
Radium Hill	12-17-91	1100	690	300	220	19	----------
8T-525	12-17-91	1445	3.0	6.6	4.9	.16	590
Laboratory analyses—Cameron mining district—Continued							
JSW-1	10-29-91	1645	72	100	76	.25	----------
JDD-1	11-01-91	1600	480	260	200	.10	----------
JDSW-1	11-07-91	1545	23	21	16	.07	----------
M.D.-45	11-02-91	1630	680	360	270	.52	----------
Ramco No. 20 NW	11-06-91	1345	27	35	26	.09	----------
Clay Well spring	11-05-91	1600	95	50	38	.08	----------
Yellow Spring	11-07-91	1200	11	10	7.5	.03	----------
Little Colorado Spring	12-19-91	1015	16	14	10	.30	----------
3T-539	12-20-91	1030	19	24	18	.44	----------
Arizona Inspection Station well	12-19-91	1350	60	37	28	.07	----------

In water samples from shallow wells MVD-1 and MVD-2, concentrations of sulfate, cobalt, iron, manganese, molybdenum, nickel, and zinc were larger than concentrations of these constituents in the pit-water sample (MVSW-1) and concentrations in water from the Radium Hill drill hole and were significantly larger than concentrations in water from well 8T-525. Concentrations of cobalt (1,100 to 1,700 μg/L), iron (240 to 1,900 μg/L), manganese (1,700 to 2,700 μg/L), molybdenum (3,000 to 3,600 μg/L), nickel (540 to 850 μg/L), and zinc (690 to 770 μg/L) in the shallow ground water probably result from secondary mineralization associated with the uranium ore body. Activities of three uranium isotopes, radium-226, and radon-222 were determined in water from the two shallow wells. Uranium-238 activity was 11,000 and 14,000 pCi/L, uranium-234 activity was 11,000 and 14,000 pCi/L, and uranium-235 activity was 440 and 530 pCi/L. Radium-226 activity was 44 and 110 pCi/L, and radon-222 activity was 53,000 and 250,000 pCi/L in water from the two shallow wells. Nickel and radium were the only constituents that exceeded the USEPA primary maximum contaminant levels (MCL's) and State of Arizona aquifer water-quality standards; however, uranium and radon greatly exceeded USEPA proposed MCL's. The MCL for nickel is 100 μg/L and the MCL and State of Arizona aquifer water-quality standards for the combined radium-226 and radium-228 activity are 5 pCi/L. Although there are no present (1992) primary MCL's for total uranium or radon, proposed MCL's of 20 μg/L for uranium and 300 pCi/L for radon are being considered for implementation (U.S. Environmental Protection Agency, 1992). A uranium concentration of 20 μg/L is equivalent to 30 pCi/L of uranium-238.

The pit-water chemistry at the Moonlight mine (MVSW-1) was similar to the chemistry of the shallow ground water, with respect to concentrations of calcium, magnesium, sodium, and sulfate. Concentrations of fluoride, barium, chromium, and strontium, however, were significantly larger, and concentrations of cadmium, cobalt, copper, iron, manganese, molybdenum, nickel, and zinc were smaller in the pit water. Uranium activities could not be determined because of problems during laboratory analysis. Gross alpha activities, however, indicate that uranium activities may be smaller in the pit water than in the shallow ground water. Radium-226 activity in the pit water also was smaller than in the shallow ground water. Dissolved-constituent concentrations and radionuclide activities were below USEPA primary MCL's. Radium-226 (8.6 pCi/L) was the only constituent that exceeded the State of Arizona surface-water-quality standard.

Ground water at the Radium Hill mine generally had lower specific conductance and smaller radionuclide activities than did shallow ground water or pit water at the Moonlight mine. Water at the Radium Hill mine contained a larger silica concentration than shallow ground water or pit water at the Moonlight mine and a larger barium concentration than shallow ground water at the Moonlight mine. Uranium activity in water at the Radium Hill mine was less than in shallow ground water at the Moonlight mine but exceeded the USEPA proposed MCL. Radium-226 activity was less than in shallow ground water at the Moonlight mine but larger than in pit water and exceeded the USEPA primary MCL and State of Arizona aquifer water-quality standard.

Well 8T-525 yields water from the Shinarump Member of the Chinle Formation and the underlying De Chelly Sandstone Member of the Cutler Formation. The quantity of water transmitted to the well by each formation is not known. Dissolved-constituent concentrations generally were less, and radionuclide activities were significantly less in water from well 8T-525 than in water from the mines. The radon activity of 590 pCi/L, however, exceeded the USEPA proposed MCL. Smaller dissolved-constituent concentrations and smaller radionuclide activities in water from the well may result from less extensive uranium mineralization in the Shinarump Member near the well and from dilution by ground water from the De Chelly Sandstone.

Cameron Area

Water-chemistry data for the Cameron area include analyses of samples collected for this study from four mines, two existing wells, and three springs (table 3) and before this study from one mine, one existing well, and four springs (table 4). Dissolved-constituent concentrations and radionuclide activities in water from sites in the Cameron area generally were less than in water from the Monument Valley area. Analyses of ground water from the Jack Daniels and Manuel Denetsone No. 2 mines show significant radionuclide activities resulting from interaction with uranium minerals near the pits. The radionuclide activity of water from the remaining sites was significantly less than in water from the Jack Daniels and Manuel Denetsone No. 2 mines.

Analyses of water from the Jeepster No. 1, Jack Daniels, Manuel Denetsone No. 2, and Ramco No. 20 mines show significant variation in dissolved-constituent concentrations and radionuclide activities. Pit water from the Jeepster No. 1 mine (JSW-1) contained the greatest amount of dissolved constituents and contained significantly larger concentrations of calcium, sodium, chloride, sulfate, fluoride, strontium, and lithium than water from the remaining sites and water from the Monument Valley area. These large concentrations may indicate that the ore deposits were more mineralized at the Jeepster No. 1 mine or that the pit received little rainfall runoff and lost a significant quantity of water to evaporation before sampling. None of the constituent concentrations exceeded USEPA MCL's or State of Arizona water-quality standards. Uranium-238 activities in pit water from the Cameron sites ranged from 11 to 22 pCi/L.

The largest uranium-238 and gross alpha activities were in ground water from the Jack Daniels mine (JDD-1) and the Manuel Denetsone No. 2 drill hole (M.D.-45). Uranium-238 activity was 150 and 180 pCi/L, and gross alpha activity was 480 and 680 pCi/L, respectively, for the JDD-1 and M.D.-45 samples. Ground water from the Manuel Denetsone No. 2 drill hole also had the largest radium-226 activity (0.52 pCi/L); however, the radium-226 activity in the JDD-1 sample (0.10 pCi/L) was exceeded by activities in pit water from the Jeepster No. 1 mine (0.25 pCi/L) and in water from well 3T-539 (0.44 pCi/L). Because radium-228 activities were not determined on field-collected water samples, comparisons with the USEPA MCL and State of Arizona water-quality standards of a combined radium-226 and radium-228 activity of less than 5 pCi/L could not be made conclusively on samples with radium-226 activities of less than 5 pCi/L. Chemical analyses of water from the laboratory-batch tests, however, indicate that spoil material adjacent to the mines contains radium-228 activities equal to or less than radium-226 activities. Because all the radium-226 activities in water from the Cameron mines were below 1.0 pCi/L, it is probable that the combined radium activities would be below 5 pCi/L. Samples JSW-1, JDD-1, M.D.-45, and Ramco No. 20 NW each contained total uranium activities greater than 30 pCi/L, which is equivalent to the USEPA proposed MCL of 20 μg/L. Uranium activities were not determined in pit water from the Yazzie No. 312 mine collected in 1988, but gross alpha activity was less than in water from the four mines included in this study. The Yazzie No. 312 pit did not contain water during field investigation for this study.

Dissolved-constituent concentrations in water from wells and springs in the Cameron

Table 4. Additional field measurements and laboratory analyses of water from sites in the Cameron mining district

[°C, degrees Celsius; μS/cm, microsiemens per centimeter; mg/L, milligrams per liter; dashes indicate no data; pCi/L, picocuries per liter; μg/L, micrograms per liter]

Field measurements

Sample identification	Date	Time	Temperature water (°C)	Specific conductance (μS/cm)	pH (standard units)	Carbonate, total (mg/L as CO_3)	Bicarbonate, total (mg/L as HCO_3)	Alkalinity, total (mg/L as $CaCO_3$)
Clay Well spring	12-06-88	1215	8.0	-------	8.7		-----	572
Yellow Spring	12-05-88	1530	-----	865	8.0	-----	212	174
Little Colorado Spring	12-06-88	------	-----	-------	------	-----	-----	-----
3T-539	12-05-88	1650	-----	2,200	8.1	-----	253	207
Balokai Spring (Lee Well)	12-05-88	------	-----	1,390	8.0	-----	-----	283
Yazzie No. 312 (mine pit)	12-06-88	1320	8.0	-------	8.7	120	454	572

Laboratory analyses

Sample identification	Date	Time	Uranium -238, dissolved (pCi/L)	Uranium -234, dissolved (pCi/L)	Gross alpha, dissolved (μg/L as U-nat)	Gross beta, dissolved (pCi/L as Cs-137)	Gross beta, dissolved (pCi/L as Sr/Yt-90)	Radon 222, total (pCi/L)
Clay Well spring	12-06-88	1215	20	29	110	46	30	-------
Yellow Spring	12-05-88	1530	---	---	22	8.2	5.8	-------
Little Colorado Spring	12-06-88	------	---	---	19	9.4	7.1	1,700
3T-539	12-05-88	1650	---	---	6.3	6.4	4.1	-------
Balokai Spring (Lee Well)	12-05-88	------	---	---	23	9.9	6.6	-------
Yazzie No. 312 (mine pit)	12-06-88	1320	---	---	21	6.5	4.9	-------

area generally were similar to concentrations in water from the mines with a few exceptions. Concentrations of sodium, chloride, and sulfate were significantly less in water from the Little Colorado River Spring than in water from the mines or other wells and springs. Concentrations of iron, lead, and manganese were significantly greater in water from well 3T-539 than in water from the mines or other wells and springs.

Radionuclide activities in water from wells and springs generally were less than in shallow ground water and pit-water samples. Uranium-238 (27 pCi/L), gross alpha (95 pCi/L), and gross beta (50 pCi/L) activities in water from the Clay Well spring were larger than in pit water from mines. Radionuclide activities were greater in water from the Arizona Inspection Station well than in two of the three pit-water samples. Uranium activities could not be determined in water from the Little Colorado Spring or well 3T-539 because of problems during laboratory analysis and were determined only in water from Clay Well spring as part of the 1988 analyses (table 4). A water sample collected from the Little Colorado Spring in 1988 contained 1,700 pCi/L of radon-222, and water collected from the spring in 1991 contained 0.30 pCi/L of radium-226. Water from well 3T-539 contained the second largest radium-226 activity (0.44 pCi/L). Radon activity in the Little Colorado Spring exceeded the USEPA proposed MCL. The chemistry of water from wells and springs included in this study probably is influenced by the abundance of mineralized sediments in the water-bearing units. The smaller radionuclide activities in pit water and well and spring water, relative to activities in shallow ground water, may represent the background levels of these constituents for the area. Data from this study, however, were not sufficient to determine representative background levels.

RADIOCHEMISTRY OF SPOIL-MATERIAL LEACHATE

Spoil-material samples were selected for laboratory-batch tests on the basis of field gamma measurements (table 5). Additional samples were collected for particle-size and mineralogical analyses to identify physical characteristics.

Particle-size data from spoil materials used in laboratory-batch tests indicate that spoil piles are gravel and coarser sediments near sample sites at the Moonlight, Radium Hill, and Jack Daniels mines and are predominantly sand at the Jeepster No. 1 mine (table 6). Sediment size may be important in the rate and magnitude of radionuclide leaching from spoil materials after mine reclamation. Smaller sediment sizes have correspondingly larger surface areas per unit volume and thus would allow for a greater degree of chemical interaction between spoil materials and shallow ground water. Laboratory-batch tests were done using sediments 2.00 mm in diameter and smaller; therefore, the amount of radionuclides that would leach from coarser spoil material is unknown. Although smaller-sized material presents greater surface area for chemical interactions, the inclusion of larger materials during reclamation may allow for increased water velocities because of increased pore size and entrain additional oxygen that would increase mobilization of uranium. For the pH conditions in this study, uranium minerals generally are more soluble under oxidizing conditions and less soluble under reducing conditions (Drever, 1988, p. 337). Langmuir (1978, p. 555), however, stated that uranium in natural waters generally is complexed with carbonate, phosphate, and other compounds that significantly increase solubility of uranium minerals at intermediate oxidation potentials. Actual leaching rates and movement of radionuclides would depend on site-specific conditions that include the amount of oxygen and organic material present,

Table 5. Sample locations and field gamma measurements of spoil material, Monument Valley and Cameron mining districts

[µR/hr, microroentgens per hour; dashes indicate no data]

Sample identification	Date	Sample area (sub part)	Sub-sample	Gamma measurements (µR/hr) At surface	Gamma measurements (µR/hr) At sample depth
Monument Valley mining district					
Moonlight mine					
MVS-1	10-15-91	North pile	1	22	----
			2	22	21
			3	19	18
			4	19	19
MVS-2	10-15-91	Northwest pile (SW)	1	470	330
			2	205	90
			3	345	270
MVS-3	10-15-91	Northwest pile (NW)	1	95	50
			2	630	360
			3	65	50
MVS-4	10-15-91	Northwest pile (N)	1	60	43
			2	65	55
			3	115	----
Radium Hill mine					
RHS-1	12-17-91	Southwest pile	1	205	295
			2	185	285
			3	190	320
Cameron mining district					
Jeepster No. 1 mine					
JS-1	10-29-91	Southeast pile	1	18	20
			2	18	23
			3	19	23

Table 5. Sample locations and field gamma measurements of spoil material, Monument Valley and Cameron mining districts—Continued

Sample identification	Date	Sample area (sub part)	Sub-sample	Gamma measurements (µR/hr) At surface	Gamma measurements (µR/hr) At sample depth
Cameron mining district—Continued					
Jeepster No. 1 mine—Continued					
JS-2	10-29-91	South pile	1	19	23
			2	100	200
			3	29	27
JS-3	10-29-92	West pile	1	18	21
			2	21	5
			3	14	19
JS-4	10-29-92	North pile	1	47	70
			2	60	95
			3	105	150
Jack Daniels mine					
JDS-1	10-31-91	Southeast pile	1	140	190
			2	70	110
			3	39	50
JDS-2	10-31-91	South pile	1	35	39
			2	115	220
			3	130	195
JDS-3	10-31-91	Northeast pile	1	65	85
			2	27	39
			3	60	75
JDS-4	10-31-91	North pile	1	49	60
			2	48	75
			3	33	34

Table 6. Particle-size data from spoil material, Monument Valley and Cameron mining districts

[>, greater than; mm, millimeter; µm, micrometer; <, less than]

Sample identification (corresponding batch test sample)	Percentage of total weight		
	Gravel and larger (> 2.00 mm)	Sand (62 µm to 2.00 mm)	Silt and clay (< 62 µm)
Moonlight mine			
MVS-P1 (MVS-1)	68	27	5
MVS-P2 (MVS-2)	67	29	4
MVS-P3 (MVS-3)	80	17	3
MVS-P4 (MVS-4)	35	57	8
Radium Hill mine			
RHS-P1 (RHS-1)	63	25	12
Jeepster No. 1 mine			
JS-P1 (JS-1)	17	68	15
JS-P2 (JS-2)	20	63	17
JS-P3 (JS-3)	17	66	17
JS-P4 (JS-4)	13	63	24
Jack Daniels mine			
JDS-P1 (JDS-1)	58	25	17
JDS-P2 (JDS-2)	60	29	11
JDS-P3 (JDS-3)	61	31	8
JDS-P4 (JDS-4)	55	35	10

temperature, spoil mineralogy, and local ground-water composition (Langmuir, 1978, p. 558).

Data from X-ray diffractometry analyses of spoil samples from the Radium Hill, Jeepster No. 1, and Jack Daniels mines were used to identify minerals that composed at least 5 to 10 percent by volume of each sample (John Neil, U.S. Geological Survey, written commun., 1992). All the samples contained quartz as a major or minor constituent. Although gypsum appeared to be the most abundant mineral in the Radium Hill sample, it may have appeared exceptionally high because of the increased intensity of X-ray diffraction from aligned cleavage fragments. The Radium Hill sample probably contained the most gypsum; however, quartz probably would have appeared predominant in the analyses if a larger sample volume had been used. Quartz was most likely the most abundant mineral in all the samples. In addition to gypsum and quartz, the Radium Hill sample contained kaolinite, a trace amount of muscovite, and possibly calcite. The Jeepster No. 1 sample, in addition to quartz, also contained kaolinite, gypsum, one or two unidentified 10- to 14-angstrom clays, a trace amount of orthoclase, and possibly muscovite and calcite. The Jack Daniels sample, in addition to quartz, also contained kaolinite, orthoclase, one or two unidentified 10- to 14-angstrom clays, intermediate plagioclase, and trace amounts of calcite and gypsum. Spoil material from the Moonlight mine was not collected for mineralogical analysis. No attempts were made at correlating the general spoil-material mineralogy with the leachate radiochemistry.

Chemical data from the leachate analyses indicate significant radionuclide dissolution from spoil material during laboratory-batch tests. Radionuclide activities in the leachate samples generally correlate with the field gamma measurements made for locating spoil-sample sites (tables 5, 7, and 8). Physical and chemical characteristics of the water were determined before mixing with spoil materials, and physical and chemical characteristics of the water-spoil material mixtures were determined after completion of batch tests (table 7). Leachate from spoil sample MVS-3 contained the largest uranium concentration (7,700 μg/L), and leachate from MVS-2 contained the largest radium-226 and radium-228 activities (34 and 2.7 pCi/L, respectively; table 8).

Radionuclide activities in leachate samples showed significant variation between mines and between spoil piles sampled at each mine. Smaller activities were found in samples from spoil piles known to consist primarily of overburden sediments from the mine pits. Leachate from spoil sample MVS-1 contained the smallest uranium concentration (20 μg/L) but contained the second largest radium-228 activity (2.1 pCi/L). Radionuclide activities in leachate from the JS-1 and JS-3 spoil samples also were significantly lower than in leachate from other samples. Leachate from sample JS-1 contained 38 μg/L of uranium and had a radium-226 activity of 0.95 pCi/L. Leachate from spoil samples collected at the Jack Daniels mine contained large uranium concentrations and radium-226 activities, although gamma measurements at sample sites JDS-3 and JDS-4 indicated material of lower radionuclide activity than samples JDS-1 and JDS-2.

CONSIDERATIONS FOR FURTHER STUDY

Collection and analysis of additional hydrologic data would be necessary to determine shallow ground-water flow characteristics and thus the implications of radionuclide mobilization near mines in the Monument Valley and Cameron mining districts. Information from additional wells installed at the mines would provide data on the lateral and vertical extent of the shallow ground-water system and its relation to units that supply water to nearby existing wells and springs. Background levels of radionuclides also could be determined from water-chemistry data collected from the additional wells. Dissolved-oxygen concentration and redox measurements in water from the wells could be used to relate radionuclide concentrations to chemical reactions in the shallow ground water. Stable-isotope data from pit water and shallow ground water could indicate whether water at mine sites is from rainfall, ground water, or a mixture of both. Further monitoring of water levels could provide information on the hydraulic relations between mines and the few existing wells and the response of the ground-water system to seasonal variations in rainfall. Geophysical methods could provide information on the thickness and configuration

Table 7. Laboratory measurements from batch tests of spoil material, Monument Valley and Cameron mining districts

[°C, degrees Celsius; µS/cm, microsiemens per centimeter; mg/L, milligrams per liter; dashes indicate no data]

Sample identification	Temperature water (°C)	Specific conductance (µS/cm)	pH (standard units)	Carbonate, total (mg/L)	Bicarbonate, total (mg/L)
Water from study area wells before batch tests					
8T-525[1]	23.0	600	7.9	-----	315
Arizona Inspection Station well[2]	23.0	1,000	9.0	10	216
Water and spoil-material mixtures after batch tests					
Monument Valley mining district					
MVS-1	20.0	600	8.3	6.9	275
MVS-2	20.0	600	8.0	-----	152
MVS-3	20.0	600	7.8	-----	275
MVS-4	20.0	600	8.2	6.9	313
RHS-1	20.0	2,850	6.5	-----	311
Cameron mining district					
JS-1	23.0	2,900	8.5	6.9	214
JS-2	23.0	3,000	7.7	-----	280
JS-3	23.0	3,600	8.0	-----	250
JS-4	23.0	2,000	8.5	7.5	245
JDS-1	22.0	2,600	8.5	8.8	214
JDS-2	22.0	2,400	8.3	6.3	216
JDS-3	22.0	3,500	8.0	-----	237
JDS-4	22.0	5,000	7.9	-----	229

[1]Used in tests with spoil material from the Monument Valley mining district.
[2]Used in tests with spoil material from the Cameron mining district.

Table 8. Leachate radiochemistry from batch test of spoil material, Monument Valley and Cameron mining districts

[µg/L, micrograms per liter; pCi/L, picocuries per liter; <, value is known to be less than the value shown]

Sample identification	Uranium natural, dis-solved (µg/L as U)	Gross alpha, dis-solved (µg/L as U-nat)	Gross beta, dis-solved (pCi/L as Cs-137)	Gross beta, dis-solved (pCi/L as Sr/Yt-90)	Radium 226, dis-solved, radon method (pCi/L)	Radium 228, dis-solved (pCi/L as Ra-228)
Monument Valley mining district						
MVS-1	20	32	20	15	1.0	2.1
MVS-2	3,500	3,400	1,600	1,200	34	2.7
MVS-3	7,700	8,200	3,200	2,400	17	1.6
MVS-4	1,600	1,700	960	720	4.0	1.6
RHS-1	2,500	2,700	1,100	820	6.5	<1.0
Cameron mining district						
JS-1	38	76	50	37	.95	<1.0
JS-2	2,700	3,600	1,700	1,300	8.2	<1.0
JS-3	94	140	83	62	1.3	1.3
JS-4	1,100	1,300	800	600	21	1.2
JDS-1	2,200	2,500	1,400	1,100	9.7	<1.0
JDS-2	3,800	4,700	2,300	1,800	10	<1.0
JDS-3	2,400	3,400	1,600	1,200	3.9	<1.0
JDS-4	2,700	3,700	1,800	1,400	4.3	<1.0

of water-bearing alluvial units associated with springs.

SUMMARY

Hydrologic data were collected from abandoned uranium mines and from wells and springs in the Monument Valley and Cameron mining districts to provide information for reclamation plans developed by the NAMLRD. Several open pits, shafts, and drill holes have partially filled with water, presenting potential pathways of radiation exposure to animals and humans that come into contact with the water. This report describes the chemical characteristics and hydraulic interaction of shallow ground water and pit water and the

possible chemical interactions between the shallow ground water and the spoil material that will be used in reclamation.

The mining districts lie in the Colorado Plateau region of northeastern Arizona and part of southeastern Utah. Seventy-three mined sites existed in the Monument Valley area after mining ceased in 1969, and ninety-eight mined sites existed in the Cameron area after mining ceased in 1963. Most of the uranium was mined from mineralized deposits in sandstones, siltstones, mudstones, and conglomerates of the Chinle and Moenkopi Formations of Triassic age. Uranium mines in the Monument Valley area were established mainly in channel-fill deposits within the Shinarump Member of the Chinle Formation. In the study area near Cameron, uranium was mined from channel-fill deposits within the Petrified Forest Member of the Chinle Formation. Field investigation involved two mines, one drill hole, and four wells in the Monument Valley area and six mines, three wells, and three springs in the Cameron area. Data collected from one mine, one well, and four springs before the study also were used.

In the Monument Valley mining district, water in the open pit at the Moonlight mine and in the drill hole at the Radium Hill mine may occur from ground-water flow from the Shinarump Member of the Chinle Formation. Ground water in the Shinarump Member also flows to several wells near the two mines. Ground water was 86.8 ft below land surface in a drill hole at one of the mines and flowed at land surface from a well completed in the De Chelly Sandstone. Local ground-water flow near the Moonlight and Radium Hill mines is from the southeast to the northwest along the trend of Oljeto Wash. Regional ground-water flow in the Cameron area is toward the Little Colorado River. The definition of ground-water relations in the area of the mines is restricted by the sparsity of existing wells. Depth to ground water measured in the Cameron area ranged from 3.5 ft below the pit bottom at the Jeepster No. 1 mine to 24.1 ft below land surface at well 3T-539. In the Cameron mining district, rainfall runoff contributes water to several of the pits and drill holes. Ground water in the Shinarump Member and sandstone and siltstone member may flow into open pits and mine drill holes through fractures or along faults in the lower part of the overlying Petrified Forest Member.

Significant differences in ground-water and pit-water chemistry were determined between the two mining districts and between sample sites within each district. Although the fate of pit water and shallow ground water near the mines is unknown, chemical analyses of water were compared to USEPA and State of Arizona water-quality standards. In the Monument Valley area, water from the two mines contained larger radionuclide activities and generally larger concentrations of other dissolved constituents than ground water from well 8T-525, which is about 1.8 mi west of the Moonlight mine. Shallow ground water from the Moonlight mine contained the largest uranium-238 and radium-226 activities, 14,000 and 110 pCi/L, respectively, and the largest radon-222 activity, 250,000 pCi/L. Water from well 8T-525 also contained significant radon-222 activity (590 pCi/L). Radionuclide activities generally were smaller in water from the Cameron area than in water from the Monument Valley area. Shallow ground water from the Jack Daniels and Manuel Denetsone No. 2 mines contained 150 and 180 pCi/L of uranium-238 and 0.10 and 0.52 pCi/L of radium-226, respectively. Pit water and water from wells and springs in the Cameron area, however, contained radionuclide activities that may reflect background levels for the area. Uranium-238 activities in pit water from the Cameron area ranged from 11 to 22 pCi/L; water from Clay Well spring, about 1.9 mi from the nearest mine, contained 27 pCi/L, which was the third largest uranium-238 activity among the samples.

Significant amounts of radionuclides were leached from spoil materials during laboratory-batch tests. Spoil materials from each of the two mining districts were combined with water from a well that was assumed to have limited chemical influences from mining disturbances. Uranium concentrations and radium activities generally correlate with field gamma measurements made on spoil piles at each site. Smaller radionuclide activities were found in overburden material from the Moonlight and Jeepster No. 1 mines. Uranium concentrations in leachate samples ranged from 20 to 7,700 μg/L, and radium-226 activities ranged from 0.95 to 34 pCi/L. The batch tests were completed using the portion of spoil material that was 2.00 mm in diameter and smaller to maximize surface areas and increase chemical interactions. Particle-size data indicate that the spoil material is predominantly gravel and coarser sediments (larger than 2.00 mm in diameter) at three of the four mines and is predominantly sand at the remaining mine. The character of radionuclide leachate and mobilization of radionuclides from the larger material cannot be determined from the batch-test data, and actual leaching rates and movement of radionuclides would depend on site-specific conditions that include the amount of oxygen and organic material present, temperature, spoil mineralogy, and local ground-water composition.

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