Disposal of Uranium-Mill Effluent by Well Injection in the Grants Area, Valencia County, New Mexico

GEOLOGICAL SURVEY PROFESSIONAL PAPER 386-D

Prepared in cooperation with the
New Mexico State Engineer Office
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By S. W. WEST

CONTRIBUTIONS TO PROBLEMS OF RADIOACTIVE WASTE DISPOSAL

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DISPOSAL OF URANIUM-MILL EFFLUENT BY WELL INJECTION IN THE GRANTS AREA, VALENCIA COUNTY, NEW MEXICO

By S. W. WEST

ABSTRACT

The geologic and hydrologic environment in the vicinity of the Bluewater uranium mill of The Anaconda Co. seems favorable for disposal of mill effluent into a deep well. Beds of sandstone in the Yeso Formation of Permian age, at depths of 950 to 1,423 feet, accept 200 to 400 gallons per minute of water under gravity flow. Water in the injection interval contained 3,900 parts per million of dissolved solids, of which 2,200 was sulfate. A thick interval of siltstone, anhydrite, and gypsum of low permeability in the upper part of the Yeso Formation separates the injection interval from the principal fresh-water aquifer in the Glorieta Sandstone and the San Andres Limestone of Permian age.

The disposal well was tested thoroughly during and following drilling, core samples were analyzed for porosity and permeability, and a set of geophysical logs was made to supplement other data. The well was completed by installing plastic-lined casing, cementing the annulus outside the casing, and gun perforating selected intervals of the casing.

After the well had been completed, it was tested by pumping water out at a rate of 100 gallons per minute for 18 hours. The specific capacity of the well was 0.119 gallons per minute per foot of drawdown. After the pumping tests, additional intervals were perforated, and all the rock intervals were fractured hydraulically. A 90-day injection test followed. Injection was intermittent at rates of 380 to 1,300 gallons per minute. The specific capacity of the well during injection was 3.6 to 3.8 gallons per minute per foot of drawdown.

Operational injection began in December 1960. The injection rate has varied considerably but has ranged generally from 200 to 400 gallons per minute. Water levels in the disposal well during injection ranged to within 10 feet of land surface from a static level about 250 feet below the surface. By the end of 1965, 500 million gallons of water had been injected into the Yeso Formation. The injected water contained an average of 13,200 parts per million of dissolved solids. Between January 1960 and December 1965, a total of 13.89 curies of uranium, 312.6 curies of thorium-230, and 0.612 curie of radium-226 were injected with the water.

The Anaconda Co. has monitored water levels in the disposal well and in seven nearby wells and has monitored chemical and radiochemical quality of water from another 27 wells and springs in the general area of the disposal well since 1959. Seasonal water-level fluctuations of 5 to 10 feet, in response to pumping for irrigation, were typical through 1961. Since the autumn of 1961, water levels have risen almost continuously, largely owing to reductions in pumping. Concentrations of sodium, sulfate, chloride, and nitrate increased from 1956 to 1962 in water from wells that tap the San Andres Limestone in the vicinity of the tailings pond, because of leakage from the pond before the disposal well was constructed. This contamination will mask any contamination from the disposal well (including contamination by radiochemical substances), even if water leaks from the disposal aquifer into the San Andres.

Injection data were used to determine the nature of the aquifer and to compute the transmissivity of the injection interval. Transmissivity values obtained from many test periods of different lengths ranged from 5,100 to 9,400 gallons per day per foot. The most reasonable value seems to be about 5,500 gallons per day per foot. The storage coefficient was computed to be 6.2×10^{-4}. Computed using these values and the average injection rate of 190 gallons per minute, the pressure increase in the disposal well should have been 88 feet at the end of 5 years. However, the actual increase was only about 5 feet. The small pressure increase indicates that the hydraulic characteristics of the aquifer were not evaluated correctly or that water is leaking to other formations. The data do not clearly indicate which interpretation is correct.

When all the data are considered, well injection of the mill effluent appears to be the most satisfactory method of effluent disposal that is economically feasible.

INTRODUCTION

Disposal of uranium-mill effluent (tailing water) of the Bluewater uranium mill of The Anaconda Co. became a problem soon after operation of the mill began in 1953. Initially, the company utilized a natural depression formed by basalt flows and floored with silt and clay for storage and evaporation of the effluent. The silt and clay contained much calcium carbonate, and as this was dissolved by the acid effluent, the permeability of the soil increased greatly.

The Anaconda Co. maintained a weather station near the tailings pond to compute evaporation from the pond, measured the amount of effluent discharged to the pond, and computed the volume of water in storage periodically. The water budget thus obtained did not balance, which indicated a significant amount of leakage from the tailings pond. Chemical analyses of water from nearby wells indicated that water in the principal aquifer (San Andres Limestone) beneath the pond was becoming contaminated by leakage from the pond.

Much research was done by The Anaconda Co. to find a satisfactory method for year-round disposal of an expected 400 gpm (gallons per minute) of effluent. The possibility of lining the existing pond with an impervious material was explored, but the cost was prohibitive. Construction of a new pond on a thick section of relatively impermeable shale of the Chinle Formation was considered, but the expense of constructing a pipeline and of pumping the effluent to a suitable site was excessive. Use of spray nozzles to increase evaporation was considered, but the cost of pumping under adequate pressure was high, and soluble salt residues from the effluent would be freely transported by the strong prevailing winds of the region. Disposal of the effluent by well injection into an unused aquifer containing nonpotable water and lying isolated stratigraphically from the principal sources of ground water in the area was considered by the company as a possible solution to the problem.

The Anaconda Co. decided, after preliminary field studies, to drill a disposal test well. The company invited the U.S. Geological Survey and the New Mexico State Engineer Office to observe the drilling, testing, and the subsequent disposal operations, if the test results were favorable. These agencies accepted the invitation because the thorough geologic and hydrologic testing offered a unique opportunity to gain much new information at the test site, to compare different methods of geologic and hydrologic analysis, and to evaluate the physical feasibility of well disposal of the mill effluent.

The site for the disposal test well was selected by The Anaconda Co. in the SE¼NE¼SW¼ sec. 8, T. 12 N., R. 10 W., about 9 miles northwest of Grants, Valencia County, N. Mex. The site is a little more than a mile northeast of the mill tailings pond and is down gradient on the potentiometric surface from the pond. Drilling was started in January 1959. The drilling, coring, casing, and preliminary testing were completed in May 1960. This well is identified in this report as The Anaconda Co. disposal well 1, or simply the disposal well, or well 12.10.8.314.

Some of the chemical analyses presented in this report were made by The Anaconda Co. and reported in parts per million, and some were made by the U.S. Geological Survey and reported in milligrams per liter. The two systems are equivalent for waters that have a density no greater than 1.000. In waters having a density greater than 1.000, the numerical value of a constituent is smaller when reported in parts per million than when reported in milligrams per liter. The conversion of values reported in parts per million to equivalent values in milligrams per liter requires multiplication of the value by the density of the water. The units originally reported by each organization have been retained to assure consistency with the intent of the respective laboratories.

ACKNOWLEDGMENTS

The author gratefully acknowledges The Anaconda Co., New Mexico Operations, personnel for cooperating during drilling and testing of the disposal well and during 5 years of operational injection and for granting permission to publish data obtained from their tests. Special thanks are given A. J. Fitch, Manager; E. C. Peterson, Assistant Manager; R. D. Lynn, Z. E. Arlin, and Dale Kittel of The Anaconda Co. geological staff; W. J. Roberts and I. R. Beck, Mill Superintendents; and R. M. Wilde, Radiological Safety Director.

Division of Reactor Development, Atomic Energy Commission, provided additional financial support for the completion of this report.

Personnel of the State Engineer Office who participated in the study were James Williams, Glenn Hammock, and Eugene Chavez. Principal participants of the U.S. Geological Survey were S. W. West, Sidney Ash, and R. L. Cushman. Several other U.S. Geological Survey personnel made minor contributions to the study.

The disposal test well was drilled under contract by Aspen Drilling Co. Earlougher Engineering Co. was employed by The Anaconda Co. as consultant during drilling and testing of the well. Earlougher Engineering Co. also made laboratory determinations of porosity and permeability of core samples; R. W. Amstutz, Engineer, did the fieldwork. Drillstem testing was under contract with Welex Co. Geophysical logging was done by the Schlumberger Well Surveying Corp. Chemical analyses of water from the test well were made by National Aluminate Co. and by the U.S. Geological Survey during drilling. Radiochemical analyses were made by Tracer Laboratory. John Dolan of the Petroleum Research Corp. analyzed the hydrologic data from preliminary pumping and injection tests.

Two reports on the disposal well have been published previously: one by West (1961) and one by Lynn and Arlin (1962). Gordon (1961) described the geology and hydrology in the vicinity of the disposal well. Extensive information was drawn from these publications in the preparation of this report.

WELL-NUMBERING SYSTEM

All wells referred to in this report are identified by a location number used by the U.S. Geological Survey and the State Engineer for numbering water wells in New Mexico. The location number is based on the system of public land surveys. It indicates the geographic location of the well to the nearest 10-acre tract when the well can be located that accurately. The location number consists of a series of numbers corresponding to the township, range, section, and tract within a section, in that order, as illustrated in figure 1 for well 12.10.8.332.

GEOLOGIC AND HYDROLOGIC SETTING

The stratigraphic units underlying the tailings pond are, in descending order, alluvium and basalt of Quaternary age; part of the Chinle Formation of Late Triassic age; the San Andres Limestone, the Glorieta Sandstone, the Yeso Formation, and the Abo Formation of Permian age; the Madera(?) Limestone of Pennsylvanian age (mapped with Abo Formation on pl. 1); and crystalline rocks of Precambrian age (Gordon, 1961). The same stratigraphic units are present at the disposal well, except for the alluvium and the basalt. The San Andres Limestone is the principal aquifer in the area; the alluvium and basalt form an excellent aquifer locally. The other formations generally have a much smaller water supply, or they have saline water; commonly, both conditions prevail.

The geologic and hydrologic conditions in the vicinity of the disposal well and the tailings pond are summarized in this report in order to brief the reader on the general environment that affects well disposal or that is affected by well disposal. Thickness, physical characteristics, and water-bearing characteristics of the stratigraphic units are summarized in table 1. The outcrop pattern of units is shown on plate 1. The principal aquifers are described in more detail on the following pages.

SAN ANDRES LIMESTONE

The San Andres Limestone crops out on dip slopes along the flanks of the Zuni Mountains (pl. 1) and underlies all the area except the higher parts of the Zuni Mountains. Gordon (1961) divided the formation into three units. The lower unit consists of massive bluish-gray dolomitic limestone that is sandy in the lower part. Locally, the lower part of this unit consists of interbedded sandstone and limestone. The unit ranges in thickness from 20 to 40 feet. The middle unit consists of light-gray to yellowish-buff medium-grained sandstone, which ranges in thickness from 15 to 30 feet. The upper unit consists of massive gray limestone, which ranges in thickness from 60 to 100 feet. The limestone beds grade northward into limy sandstone.

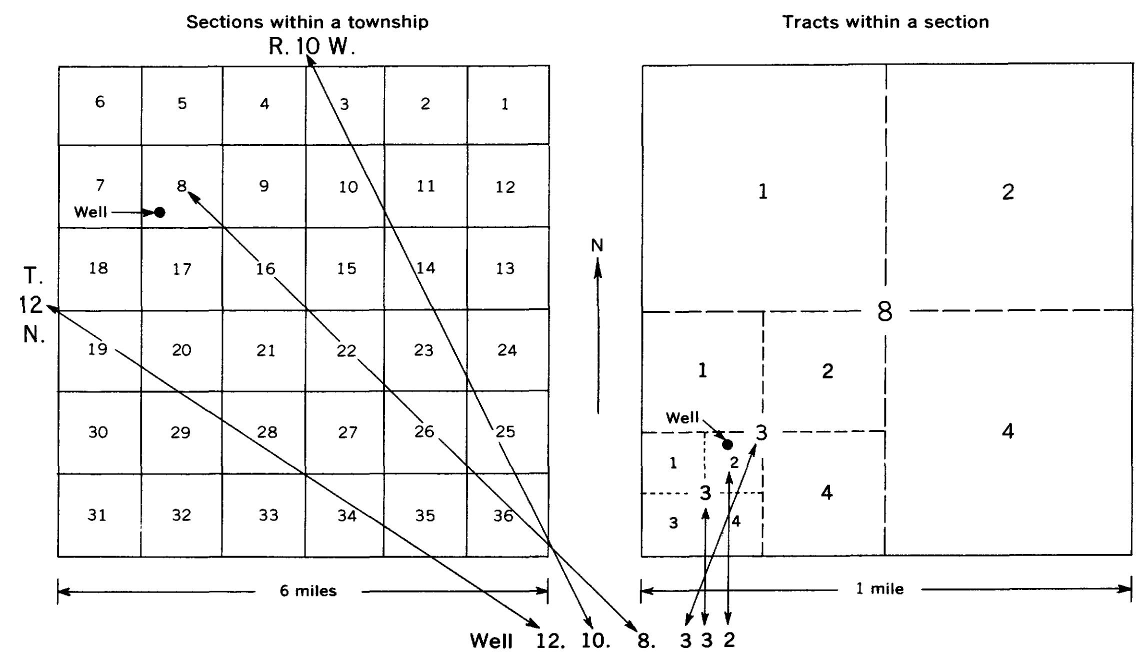

FIGURE 1.— Well-numbering system.

TABLE 1. — *Generalized stratigraphic section and water-bearing characteristics of geologic formations in the vicinity of The Anaconda Co. disposal well 1*

[Adapted from Gordon (1961, p. 87–88)]

System	Series	Subdivision	Thickness (ft)	Physical characteristics	Water-supply characteristics
Quaternary	Holocene	Alluvium	0–50	Valley-fill deposits of unconsolidated silt, clay, sand, and gravel.	Yields adequate quantities of water for shallow stock and domestic supplies at many places and for irrigation locally.
	Pleistocene and Holocene	Basalt	0–200	Dense to vesicular black basalt, extruded as lava flows of varying thickness and extent.	Yields adequate quantities of water for shallow stock and domestic supplies at many places.
	Pleistocene	Alluvium	0–100	Valley-fill deposits of sand, gravel, silt, and clay.	Yields adequate quantities of water for shallow stock and domestic supplies at many places and for irrigation in favorable localities in valley.
Triassic	Upper Triassic	Chinle Formation	1,400–1,600	Variegated siltstone and mudstone, with interbedded silty sandstone and some conglomeratic sandstone. Only lower part is present at site of disposal well.	Sandstone yields adequate quantities of water for stock and domestic supplies and for irrigation in some localities in valley.
Permian		San Andres Limestone	95–170	Thick-bedded to massive light-gray limestone, sandy limestone, and limy sandstone. The limestone strata are cavernous in many localities.	Yields adequate quantities of water for irrigation and for industrial and municipal supplies.
		Glorieta Sandstone	125–300	Thick-bedded to massive well-sorted medium-grained white to yellowish-gray sandstone with limonitic flecks. Some interbedded siltstone in basal part.	Yield generally not separated from that of overlying San Andres.
		Yeso Formation, undivided	350–875	Orange to red siltstone and fine-grained silty sandstone, with a few thin-bedded limestones in lower middle part and a thick-bedded to massive crossbedded fine-grained silty sandstone in basal part of formation. Some of the siltstone is gypsiferous; some beds of mudstone, anhydrite, and gypsum.	Yields adequate quantities of water for domestic and stock supplies in and near outcrop areas and for irrigation at a few places.
		Abo Formation	500–800	Dark-brick-red to reddish-brown arkosic sandstone and siltstone, with numerous layers of conglomerate in lower part.	Not utilized for water supply in the Grants-Bluewater area, as the formation is deeply buried except in Zuni Mountains.
Pennsylvanian		Madera(?) Limestone	0–480	Limestone, arkose, conglomerate, and shale.	Not known.
Precambrian				Granite, gneiss, metarhyolite, schist, and greenstone.	Not known.

The San Andres was exposed to erosion after deposition, and a karst topography having a relief of as much as 100 feet was developed on the limestone before the overlying Chinle Formation of Late Triassic age was deposited. An extensive network of solution channels was dissolved throughout the limestone during the long period of surface erosion, and a very high permeability was thereby imparted to the formation. Clastic sediments of the Chinle Formation were then deposited in the sinkholes in the limestone and locally were washed downward into the solution channels. However, apparently the clastic sediments do not greatly inhibit the circulation of water through the San Andres.

The yields of wells that tap the San Andres range from 500 to 2,800 gpm. Specific capacities range from 10 to 1,100 gpm per foot of drawdown; the average specific capacity is about 200 gpm per foot of drawdown.

The Glorieta Sandstone, which directly underlies the San Andres, contributes water to the San Andres by vertical migration. Although the rate of vertical movement is slow, the contribution probably is large because the contact is extensive.

The salinity of water in the San Andres varies widely. The principal solutes are calcium, magnesium, and bicarbonate ions; some of the water also has high concentrations of sodium and sulfate ions, especially where the limestone is overlain by clay of the Chinle Formation. The water of best quality is near the outcrop area, southwest of the disposal well and the tailings pond, in a narrow belt between Bluewater and Milan. The concentrations of dissolved solids in this belt generally range from 350 to 750 mg/l (milligrams per liter). In other parts of the aquifer, the concentrations of dissolved solids are as much as 2,200 mg/l.

The general direction of ground-water movement is southeast, parallel to the course of the Rio San Jose (pl. 1). The gradient of the potentiometric surface of the San Andres aquifer ranges from about 1 to 10 feet per mile. Local irregularities in the potentiometric surface probably exist, but they do not show on plate 1. The potentiometric surface of the San Andres aquifer is lower than that of the alluvium and basalt aquifer in part of the Grants-Bluewater area; thus, some water probably leaks downward from the alluvium and basalt through rocks of the Chinle Formation into the San Andres. Elsewhere in the area, the alluvium and basalt directly overlie the San Andres, and at these localities water can circulate freely from one to the other.

From Grants southeastward a few miles, the relative positions of the potentiometric surfaces are reversed, and water probably leaks upward from the San Andres into the alluvium and basalt. This part of the Rio San Jose valley probably was the principal natural discharge area for the San Andres in the Grants-Bluewater area before the construction of large-capacity wells.

ALLUVIUM AND BASALT

Alluvium and basalt underlie the valleys of Rio San Jose and its tributaries (pl. 1). The stream courses in the main valleys were eroded to depths of 150 to 200 feet below the present land surface. Alluvium was then deposited along the stream courses. When these deposits had accumulated to a maximum thickness of about 30 feet and had covered most of the valley floor, basaltic lava erupted and flowed down several of the valleys. Alluvium continued to accumulate adjacent to the flows and eventually covered part of the flows. The accumulation has continued to the present.

The lower part of the alluvium generally contains a high proportion of sand and gravel; the upper part is predominantly clay and silt. The basalt texture ranges from dense to vesicular; cooling fractures are common to abundant. The Bluewater Basalt Flow originated at El Tintero crater, 4 to 5 miles north of the disposal well and the tailings pond. The basalt is exposed as far south as Toltec Siding, and it has been traced in the subsurface to the vicinity of Grants. It is at a shallow depth at the tailings pond, but it is not present at the disposal well.

The alluvium and basalt yield as much as 1,000 gpm of water to wells. The specific capacity of only one well (31 gpm per foot of drawdown) was determined. The largest yields are obtained in the vicinity of Bluewater Station, west of the tailings pond and the disposal well, and in the vicinity of Milan, several miles down the valley from the tailings pond and the disposal well (pl. 1). The water of best chemical quality is found in a narrow band extending from Bluewater Station to Milan.

The direction of ground water movement in the alluvium and basalt is generally downslope, parallel to the Rio San Jose valley and its principal tributaries. The gradient of the water table is 20 feet or more per mile (pl. 1). In much of the area the water table in the alluvium and basalt is higher than the potentiometric surface in the San Andres Limestone; therefore, in these areas water probably leaks downward from the alluvium and basalt through rocks of the Chinle Formation and into the San Andres.

The principal discharge area for the alluvium and basalt aquifer is in the Rio San Jose valley from Grants southeastward. Part of the water moves slowly to the surface and evaporates on salt flats, and part discharges from large springs (Horace Springs) 8 miles southeast of Grants.

CONSTRUCTION AND PRELIMINARY TESTING

DRILLING, CORING, AND CORE ANALYSIS

The disposal well was drilled with a rotary drill using a bentonite-base fresh-water mud as the circulating fluid. A 7⅞-inch-diameter hole was drilled to a depth of 445 feet with a rock bit. The hole was then reamed to 12¼ inches in diameter to a depth of 85 feet, and a 9⅝-inch-diameter conductor pipe was installed to that depth. All depths in this report are referred to zero datum, which is the top of the kelly bushing at an altitude of 6,690 feet, 8 feet above land surface.

Coring was started at a depth of 445 feet, and a continuous 3½-inch core was cut to a depth of 2,511 feet. The overall core recovery for that interval was 96.6 percent (Lynn and Arlin, 1962).

A lithologic log of the core was made in the field, and representative samples of the core were obtained for microscopic study in the laboratory. The field and office logs were combined, and the information is presented in detail in table 2 and is summarized, in part, graphically, on plate 2.

TABLE 2.—*Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)*

[Depth is referred to an altitude of 6,689.75 feet, 8 feet above land surface]

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Triassic System:		
Chinle Formation:		
Conglomerate, grayish-red, poorly sorted, calcareous; grains range from silt to rounded pebbles as much as ½ in. in diameter and consist of quartz and limestone; contains some calcite crystals and thin fragments of claystone and siltstone	40	40
Sandstone, grayish-red, very fine to very coarse grained and silty, poorly sorted, weakly to firmly cemented, calcareous; consists mainly of quartz, and partly of rounded limestone	5	45
Conglomerate, grayish-red; poorly sorted, calcareous; grains range from silt to rounded pebbles as much as ¼ in. in diameter and consist of quartz and limestone;		

TABLE 2.—*Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)*—Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Triassic System—Continued		
Chinle Formation—Continued		
contains some fragments of siltstone and limestone	5	50
Shale, silty, grayish-red, friable, slightly calcareous, and some light-brownish-gray amorphous, dense limestone	5	55
Shale, grayish-red, friable, slightly calcareous	10	65
Shale, grayish-red, friable, slightly calcareous, and some light-greenish-gray friable micaceous, slightly calcareous siltstone	5	70
Siltstone, shaly, grayish-red and light-greenish-gray, friable, micaceous, slightly calcareous	5	75
Shale, slightly silty, grayish-red, friable, micaceous, slightly calcareous; some iron stains	5	80
Shale, grayish-red, friable, slightly calcareous	5	85
Shale, slightly silty, light-greenish-gray and grayish-red, friable, slightly calcareous	10	95
Shale, grayish-red, friable, slightly calcareous	30	125
Sandstone, pale-reddish-brown, fine- to medium-grained, fairly well sorted, weakly cemented, calcareous; consists mainly of quartz; sample also contains some grayish-red friable shale	10	135
Shale and siltstone, light-greenish-gray to grayish-red, calcareous; siltstone is firmly cemented; shale is friable	5	140
No sample	5	145
Shale, grayish-red, friable, slightly calcareous, and some light-greenish-gray firmly cemented, calcareous siltstone	45	190
Shale, grayish-red and light-greenish-gray, slightly silty, friable, micaceous, calcareous	5	195
Shale, grayish-red, friable, calcareous, and some pale-red, fine-grained well-sorted, weakly cemented calcareous sandstone	15	210
Shale, sandy, grayish-red, friable, calcareous, and some light-greenish-gray well-indurated calcareous siltstone	10	220
Sandstone, shaly, grayish-red, very fine- to fine-grained, well-sorted, weakly cemented, calcareous, and some light-greenish-gray well-indurated calcareous siltstone	10	230
Sandstone, shaly, pale-reddish-brown, very fine grained, well-sorted, weakly cemented, calcareous, and some shaly light-greenish-gray moderately well indurated calcareous siltstone	10	240
Shale, sandy, grayish-red, friable, calcareous	10	250
Shale, grayish-red, calcareous, and some medium-gray well-indurated calcareous siltstone	10	260
Shale, slightly silty, grayish-red and light-greenish-gray, calcareous	10	270
Shale, slightly silty, grayish-red, friable, calcareous, and some medium-light-gray moderately cemented calcareous siltstone	20	290
Shale, grayish-red and light-greenish-gray, friable, calcareous, and some medium-light-gray moderately firmly cemented calcareous siltstone; contains some calcite crystals	20	310
Shale, grayish-red and light-greenish-gray, friable, calcareous, and some greenish-gray amorphous, dense limestone	10	320
Shale, grayish-red, friable, calcareous, and some medium-light-gray firmly cemented calcareous siltstone	10	330
Sandstone, pale-reddish-brown, very fine to fine-grained, well-sorted, weakly cemented, calcareous, and some medium-light-gray well-indurated calcareous siltstone	10	340
Shale, grayish-red, friable, calcareous, and some medium-light-gray well-indurated calcareous siltstone and light-olive-gray amorphous, dense limestone	10	350
Sandstone, shaly, slightly conglomeratic, grayish-red to pale-reddish-brown, weakly cemented, calcareous; contains some rounded pebbles of quartzite	10	360
Permian System:		
San Andres Limestone and Glorieta Sandstone (undivided):		
Sandstone, slightly shaly, pale-red to pale-reddish-brown, very fine to fine-grained, well-sorted, weakly cemented, calcareous	10	370
Shale, sandy, grayish-red, friable, calcareous; sand is very fine to medium, moderately well sorted, quartzitic	10	380
Sandstone, light-brown, fine-grained,		

TABLE 2.—*Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)*—Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Permian System—Continued		
San Andres Limestone and Glorieta Sandstone—Continued		
well-sorted, weakly cemented, calcareous; consists of subangular to subrounded quartz, some calcite, and a few pyrite crystals	20	400
No sample	5	405
Sandstone, shaly, light-brown, fine-grained, well-sorted, weakly cemented, calcareous; consists mainly of quartz, some calcite, a few pyrite crystals, and some dolomite	40	445
Sandstone, light-gray, fine-grained, well-sorted, subangular to subrounded, fairly firmly cemented, slightly friable; mainly siliceous, partly calcareous cement, and some thin bedding traces of light-green claystone and fine-grained disseminated pyrite; some closed, irregular fractures	5.0	450.0
Sandstone, light-gray, fine-grained, well-sorted; contains brecciated fragments 1 in. or more in width in a matrix of crushed sandstone; moderately siliceous cement; disseminated fine-grained pyrite; some calcite on slippage planes and in small, short vertical seams	12.0	462.0
Limestone, medium-gray, massive, amorphous, dense; siliceous in upper 1 ft, decreasing downward; irregular vertical fractures filled with white calcite	2.9	464.9
Sandstone, light-gray, fine-grained, well-sorted, firmly cemented, siliceous and calcareous; some fine-grained pyrite; many closed, irregular vertical fractures	5.3	470.2
Limestone, light-brownish-green, massive; many vertical fractures as much as 2 mm wide filled with calcite	5.8	476.0
Sandstone, light-gray, fine-grained, well-sorted, firmly cemented, calcareous; abundant disseminated pyrite	9.7	485.7
Sandstone, light-gray, medium-grained, calcareous; a few vertical fractures as much as 2 mm wide filled with calcite; some disseminated pyrite	40.4	526.1
Sandstone, light-gray, very fine to fine-grained, well-sorted, calcareous, and some thin beds of medium-green claystone; some disseminated pyrite; a few fractures filled with quartz or calcite	70.3	596.4

TABLE 2.—*Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)*—Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Permian System—Continued		
Yeso Formation:		
San Ysidro Member:		
Sandstone, pale-yellowish-brown, fine-grained, well-sorted, subangular to subrounded; siliceous and calcareous cement	3.6	600.0
Sandstone, light-gray and grayish-brown, very fine to fine-grained, well-sorted, subangular; intermixed and interbedded with thin beds of light-green and grayish-red claystone; some disseminated pyrite; some closed fractures	25.4	625.4
Claystone, grayish-red	.6	626.0
Sandstone, grayish-brown, fine-grained; siliceous and calcareous cement	1.0	627.0
Claystone, sandy, grayish-red	1.0	628.0
Sandstone, light-gray and grayish-brown, very fine to fine-grained, well-sorted, and some thin beds of grayish-red claystone	6.0	634.0
Sandstone, light-brown to light-gray, very fine to medium-grained, subrounded to rounded, firmly cemented, slightly calcareous; minor fractures; grayish-red mudstone from 634.4 to 634.5 ft	14.9	648.9
Sandstone, pale-reddish-brown, very fine to fine-grained and silty, rounded, firmly cemented, gypsiferous; dark-reddish-brown mudstone from 648.3 to 648.9 ft	2.1	651.0
Siltstone, sandy, pale- to dark-reddish-brown (partly mottled with light-gray), dense; abundant clay in lower part	3.5	654.5
Sandstone, very pale orange, very fine grained, well-sorted, subrounded to rounded, firmly cemented, calcareous, and some thin zones of siltstone and mudstone; minor fractures partly filled with calcite; pale-reddish-brown and mottled in lower part	12.3	666.8
Siltstone and mudstone, dark-reddish-brown, compact	1.0	667.8
Sandstone, grayish-orange-pink to dark-reddish-brown, very fine to fine-grained, well-sorted, subrounded to rounded, firmly cemented, gypsiferous, and some thin zones of siltstone and mudstone	18.9	686.7
Mudstone, dark-reddish-brown, compact	.6	687.3
Sandstone, very pale orange, very fine to fine-grained, rounded, firmly cemented	.3	687.6

TABLE 2. — *Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)* — Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Permian System — Continued		
Yeso Formation — Continued		
San Ysidro Member — Continued		
Mudstone and siltstone, dark-reddish-brown, compact	0.6	688.2
Sandstone, very pale to dark-reddish-brown, partly mottled, very fine to fine-grained, rounded, firmly cemented	4.5	692.7
Mudstone and siltstone, dark-reddish-brown, compact, calcareous, and some thin layers of very fine to fine-grained firmly cemented sandstone	11.8	704.5
Sandstone, pale-reddish-brown, very fine grained and silty, firmly cemented, calcareous; numerous horizontal and steeply dipping fractures as much as ½-in. wide filled with gypsum	8.2	712.7
Gypsum and anhydrite, white to dark-gray	2.4	715.1
Anhydrite, dark-gray; fractures filled with gypsum common	7.2	722.3
Gypsum and anhydrite, dark-gray	.9	723.2
Mudstone, light- to medium-gray grading downward into dark-reddish-brown, compact	.3	723.5
Sandstone, pinkish-gray and pale- to dark-reddish-brown, very fine to fine-grained and silty (medium grains rare to common), subrounded to rounded, firmly cemented, gypsiferous, and some thin beds of siltstone and mudstone; fractures in lower part filled with gypsum	31.8	755.3
Siltstone and mudstone, sandy, dark-reddish-brown, compact; fractures filled with gypsum common	3.0	758.3
Sandstone, light-gray and pale- to dark-reddish-brown, very fine to fine-grained, rounded, firmly cemented; fractures filled with gypsum abundant	2.0	760.3
Mudstone, dark-reddish-brown, compact to friable	7.0	767.3
Sandstone, silty, banded light- and medium-gray to dark-reddish-brown, very fine to medium-grained, rounded, firmly cemented; some fractures filled with gypsum	5.3	772.6
Siltstone, pale-reddish-brown (partly banded with dark-reddish brown), firmly cemented; minor fractures	1.0	773.6
Sandstone, very pale orange to dark-reddish-brown, very fine to medium-grained, poorly sorted, firmly cemented, and some thin beds of mudstone and siltstone; fractures filled with gypsum common; a bed of limestone from 775.0 to 775.2 ft; a bed of anhydrite from 788.4 to 788.7 ft	16.4	790.0
Siltstone and mudstone, pale- to dark-reddish-brown, firmly cemented; fractures filled with gypsum common	2.5	792.5
Sandstone, pale- to dark-reddish-brown, very fine to medium-grained (some silt and clay), poorly sorted, firmly cemented; fractures filled with gypsum common	1.0	793.5
Mudstone, dark-reddish-brown (partly mottled with light gray), compact; some gypsum	.5	794.0
Anhydrite, light- to medium-gray, dense	.9	794.9
Siltstone, pale- to dark-reddish-brown, firmly cemented; fractures filled with gypsum abundant	.6	795.5
Anhydrite, light- to medium-gray, dense; abundant euhedral crystals of gypsum as much as ¼-in. long imbedded in upper 0.7 ft and lower 1.4 ft	3.6	799.1
Mudstone and siltstone, slightly sandy, medium- to dark-gray	4.0	803.1
Anhydrite, light- to medium-gray, dense	.7	803.8
Shale, carbonaceous, light- to dark-gray, partly mottled and banded, partly gypsiferous and partly calcareous; fractures as much as ½-in. wide filled with gypsum common	12.4	816.2
Siltstone, light- to dark-gray, partly mottled, partly carbonaceous, and partly sandy in upper part; firmly cemented fractures filled with gypsum rare to common	6.3	822.5
Sandstone, silty, medium-gray, very fine to medium-grained, poorly sorted; some minute fractures filled with gypsum	1.3	823.8
Mudstone, medium-gray, compact, partly carbonaceous; fractures filled with gypsum abundant	7.1	830.9
Siltstone, slightly sandy, medium-gray, firmly cemented; fractures filled with gypsum common	1.2	832.1
Mudstone, partly sandy, light- to medium-gray and pale-reddish-brown, partly carbonaceous; some fractures filled with gypsum	6.1	838.2

TABLE 2.—*Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)* — Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Permian System — Continued		
Yeso Formation — Continued		
San Ysidro Member — Continued		
Anhydrite, light-gray, dense	3.4	841.6
Sandstone, silty, pale-reddish-brown and light-gray, very fine to medium-grained, and some thin layers of gypsum	10.4	852.0
Mudstone, dark-gray, and some thin layers of gypsum in lower 2 ft	1.6	853.6
Anhydrite, light-gray to black, dense	2.6	856.2
Mudstone, slightly sandy, grayish-brown to black, slightly calcareous; horizontal veins of gypsum abundant	9.6	865.8
Anhydrite, light-gray to black, dense	1.4	867.2
Mudstone, light- to dark-gray, and horizontal layers of gypsum	1.2	868.4
Sandstone, silty, light-gray to pale-red, very fine to medium-grained; horizontal veins of gypsum	7.6	876.0
Anhydrite, medium-gray; dense veins of gypsum common	1.6	877.6
Sandstone, light-gray to pale-red, very fine to coarse-grained, poorly sorted; vertical and horizontal fractures filled with gypsum common	32.4	910.0
Anhydrite, light- to medium-gray, dense	1.0	911.0
Mudstone, grayish-black, carbonaceous	7.0	918.0
Sandstone, silty, medium-light-gray to pale-red, very fine grained, and thin black mudstone partings; zone of high porosity from 921.7 to 922.0 ft	9.0	927.0
Sandstone, grayish-orange-pink, fine- to coarse-grained, well-rounded; gypsum cement; some thin layers of mudstone; high porosity from 926.5 to 930.0 ft	5.8	932.8
Mudstone and siltstone, pale-brown, mottled; thin bed of firmly cemented sandstone from 936.4 to 936.7 ft	15.1	947.9
Sandstone, very light gray and light-brown, very fine to fine-grained; upper part firmly cemented; lower part friable	15.7	963.6
Mudstone, partly silty and sandy, very dusky red, mottled	12.2	975.8
Sandstone, partly silty, grayish-orange to very dusky red, very fine to fine-grained, rounded to subrounded, slightly porous, and some thin beds of dark-brown mudstone	22.2	998.0
Sandstone, partly silty, grayish-orange, pale-reddish-brown and very dusky red, very fine grained (some fine and medium grains), weakly to firmly cemented; porous in some zones; some thin beds of brown mudstone	112.4	1,110.4
Sandstone, pale-reddish-brown, very fine to coarse-grained, fairly well sorted, fairly porous; coarse material well rounded; gypsiferous	5.6	1,116.0
Sandstone, silty, light-brown, very fine grained, firmly cemented, fairly porous; some vugs filled with gypsum	5.4	1,121.4
Sandstone, gypsiferous, pale-reddish-brown, very fine to medium-grained, fairly well sorted, fairly porous	2.3	1,123.7
Sandstone, partly gypsiferous, pale-reddish-brown, very fine to coarse-grained, fairly well sorted, porous; coarse material well rounded	7.8	1,131.5
Sandstone, silty, very dusky red, very fine grained, firmly cemented, and many brown (some gray) mudstone partings	14.8	1,146.4
Sandstone, pale-red, fine- to medium-grained	1.4	1,147.8
Sandstone, silty, grayish-red and very dusky red, very fine grained, and some fine- to medium-grained sandstone containing abundant interstitial gypsum; many mudstone partings	27.6	1,175.4
Sandstone, moderate-reddish-orange, fine- to medium-grained, well-sorted, fairly porous; interstitial gypsum abundant	2.5	1,177.9
Sandstone, silty, pale-reddish-brown and light-gray, very fine to fine-grained; firmly cemented with gypsum; many very dusky red mudstone partings	16.6	1,194.5
Sandstone, silty, pale-reddish-brown, very fine grained, well-sorted, firmly cemented, and some brown mudstone partings	2.7	1,197.2
Sandstone, light-gray and pale-red, fine- to medium-grained, well-sorted, firmly cemented	2.2	1,199.4
Sandstone, pale-reddish-brown, very fine to fine-grained, well-sorted; firmly cemented with gypsum	7.8	1,207.2
Sandstone, partly silty, pale-reddish-brown, fine- to medium-grained; firmly cemented with gypsum	2.4	1,209.6
Sandstone, silty, pale-reddish-brown,		

TABLE 2.—*Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)*—Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Permian System—Continued		
Yeso Formation—Continued		
San Ysidro Member—Continued		
very fine grained, well-sorted; firmly cemented with gypsum	5.2	1,214.8
Mudstone, medium-bluish-gray and pale-reddish-brown, calcareous	1.1	1,215.9
Sandstone, silty, pale-reddish-brown and light-gray, very fine-grained; firmly cemented with gypsum; low porosity; some thin beds of moderate-reddish-brown mudstone	16.9	1,232.8
Sandstone, silty, moderate-reddish-brown and light-gray, very fine grained, well-sorted; firmly cemented with gypsum; some thin beds of brown shale	11.2	1,244.0
Sandstone, pale-reddish-brown to very dusky red, very fine to fine-grained, well-sorted, firmly cemented	10.2	1,254.2
Sandstone, pale-reddish-brown, fine- to medium-grained, fairly well sorted, firmly to weakly cemented	6.6	1,260.8
Sandstone, pale-reddish-brown to very dusky red, very fine to fine-grained, well-sorted, firmly cemented	7.5	1,268.3
Sandstone and siltstone, light-gray and pale-reddish-brown to very dusky red; sandstone very fine grained; firmly cemented with gypsum	35.3	1,303.6
Meseta Blanca Sandstone Member:		
Sandstone, partly silty, pale-reddish-brown and grayish-red, very fine to fine-grained, well-sorted, rounded; firmly to weakly cemented with gypsum; low porosity	170.1	1,473.7
Abo Formation:		
Siltstone, moderate-reddish-brown; contains some very fine sand in lower part; firmly cemented	3.4	1,477.1
Sandstone, pale-reddish-brown, very fine grained, firmly cemented	2.3	1,479.4
Siltstone, light-gray to pale-brown, firmly cemented; contains some very fine sand	4.5	1,483.9
Sandstone, partly silty, pale- to moderate-reddish-brown, very fine to fine-grained, firmly cemented	31.1	1,515.0
Sandstone, partly silty, pale- to medium-reddish-brown, very fine to fine-grained, firmly cemented, and some thin layers of brown, red, and green mudstone	14.2	1,529.2
Mudstone, sandy, pale- to medium-reddish-brown and greenish-gray (in alternating layers), very		

TABLE 2.—*Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)*—Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Permian System—Continued		
Abo Formation—Continued		
dense, firmly cemented, and some thin layers of green siltstone and very fine grained sandstone; a few vertical and horizontal fractures	30.5	1,559.7
Sandstone, dark-reddish-brown, very fine to fine-grained, well-sorted; firmly cemented with gypsum; some green and brown mudstone partings	1.3	1,561.0
Mudstone, grayish-red, and some thin sandy layers	1.7	1,562.7
Sandstone, silty, dark-reddish-brown, very fine grained, poorly sorted, firmly cemented with gypsum, and thin mudstone	2.6	1,565.3
Mudstone, sandy, brown, green, light-gray; sand grains are very fine	3.2	1,568.5
Mudstone, dark-reddish-brown and grayish-green, dense, firmly cemented, and thin interbeds of very fine grained silty sandstone	4.5	1,573.0
Mudstone, moderate- to dark-reddish-brown, dense, firmly cemented	6.2	1,579.2
Mudstone, partly sandy, dark-reddish-brown, dense	14.6	1,593.8
Mudstone, dark-reddish-brown and light-greenish-gray, dense	8.0	1,601.8
Mudstone, slightly sandy, moderate-reddish-brown, dense	1.8	1,603.6
Mudstone, moderate-reddish-brown, dense	1.6	1,605.2
Mudstone, slightly sandy, moderate-reddish-brown and greenish-gray, dense	11.7	1,616.9
Mudstone, dark-reddish-brown and greenish-gray	4.1	1,621.0
Sandstone, grayish-orange-pink, fine- to medium-grained; firmly cemented with quartz	1.3	1,622.3
Mudstone, dark-greenish-gray and moderate-reddish-brown, dense	5.9	1,628.2
Mudstone, partly sandy, light-gray and moderate-reddish-brown, dense	8.8	1,637.0
Mudstone, pale- to dark-reddish-brown and dark-greenish gray	12.2	1,649.2
Siltstone, sandy, pale- to moderate-reddish-brown; sand grains very fine to fine; firmly cemented with gypsum; some very thin beds of clay	8.1	1,657.3
Sandstone, silty, pale- to dark-reddish-brown, very fine to fine-grained, well-sorted; firmly cemented with gypsum	5.1	1,662.4
Sandstone, moderate-orange-pink, very fine to medium-grained;		

TABLE 2.—*Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)* — Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Permian System — Continued		
Abo Formation — Continued		
poorly sorted and well-sorted in alternating layers; mud balls abundant; firmly cemented with gypsum and calcite	3.5	1,665.9
Mudstone, dark-reddish-brown, compact, and some thin layers of siltstone	1.7	1,667.6
Siltstone, light-gray and pale-reddish-brown (in thin alternating layers), and some thin layers of clay	1.0	1,668.6
Sandstone, silty, pale-reddish-brown, very fine to fine-grained, well-sorted, firmly cemented	1.1	1,669.7
Mudstone, dark-reddish-brown, compact, and some grayish-green stringers of clay	3.2	1,672.9
Sandstone, moderate-reddish-brown, very fine grained, and some nodules and thin layers of grayish-green mudstone	16.4	1,689.3
Mudstone, dark-reddish-brown; very low porosity; fractured and recemented	4.7	1,694.0
Siltstone, slightly sandy, pale-reddish-brown	1.3	1,695.3
Sandstone, dark-reddish-brown, very fine grained (fine and medium grains rare), firmly cemented; some fractures; a thin bed of conglomerate from 1,701.4 to 1,701.9 ft	10.1	1,705.4
Mudstone, moderate- to dark-reddish-brown	9.6	1,715.0
Sandstone, light-greenish-gray and grayish-red, very fine to medium-grained, subangular to subrounded, weakly to firmly cemented, partly friable, porous; fractures common	25.7	1,740.7
Mudstone, partly silty and sandy, pale- to dark-reddish-brown	2.1	1,742.8
Sandstone, silty, pale-reddish-brown and greenish-gray, very fine grained	1.8	1,744.6
Mudstone, pale-reddish-brown and greenish-gray	2.9	1,747.5
Sandstone, partly silty, dark-reddish-brown and greenish-gray, very fine to fine-grained (medium grains rare), and some thin beds of mudstone	40.0	1,787.5
Siltstone and mudstone, grayish-red, grayish-purple, grayish-green, firmly cemented, gypsiferous	9.9	1,797.4
Sandstone, dark-reddish-brown and grayish-orange-pink, very fine to fine-grained, gypsiferous	19.5	1,816.9
Siltstone, partly sandy, moderate- to dark-reddish-brown; some fractures	22.6	1,839.5
Sandstone, partly silty, dark-reddish-brown, very fine to fine-grained, gypsiferous	2.5	1,842.0
Mudstone and siltstone, partly silty, grayish-red to dark-reddish-brown (broken by greenish-gray in a few zones), dense, calcareous and slightly gypsiferous; sand grains rare; some fractures; some limestone pebbles from 2,019.7 to 2,025.0 ft	269.0	2,111.0
Mudstone, grayish-red to dark-reddish-brown, calcareous; subangular to subrounded particles of limestone common to abundant; anhydrite inclusions rare; some shear planes	127.2	2,238.2
Conglomerate, dusky red; consists of subangular to subrounded limestone fragments in a matrix of mudstone	5.3	2,243.5
Pennsylvanian System:		
Madera(?) Limestone:		
Limestone, medium-gray, fossiliferous, and some thin beds of blackish-red calcareous siltstone	19.5	2,263.0
Mudstone, dusky-red and medium-dark-gray, and a few thin layers of silty and sandy limestone	19.0	2,282.0
Limestone, light-gray, medium-light-gray, light-olive-gray, fossiliferous, and some irregular masses of dark-gray mudstone	8.3	2,290.3
Mudstone, dark-gray, calcareous, and some irregular masses of gray limestone	4.4	2,294.7
Limestone, medium-dark-gray, fossiliferous, and some irregular masses of dark-gray mudstone	1.3	2,296.0
Mudstone, dark-gray, calcareous, and some irregular masses of gray limestone	54.8	2,350.8
Sandstone, white and greenish-black, very fine to coarse-grained, poorly sorted, weakly to firmly cemented, calcareous; sand grains consist of orthoclase feldspar and quartz	6.7	2,357.5
Limestone, medium-dark-gray, very finely crystalline, and some thin beds of black calcareous mudstone; vertical fractures common	17.4	2,374.9
Sandstone, moderate-orange-pink, medium- to coarse-grained, firmly cemented, calcareous; sand grains consist of quartz, orthoclase feld-		

TABLE 2. — *Lithologic log of The Anaconda Co. disposal well 1 (12.10.8.314)* — Continued

Stratigraphic unit and material	*Thickness (feet)*	*Depth (feet)*
Pennsylvanian System — Continued		
Madera (?) Limestone — Continued		
spar, limestone, and black mudstone	2.3	2,377.2
Mudstone, partly sandy, blackish-red, dense, slightly calcareous	1.5	2,378.7
Sandstone, light-gray, medium-grained, firmly cemented, calcareous; sand grains consist of quartz, orthoclase feldspar, limestone, and black mudstone	2.2	2,380.9
Mudstone, partly sandy, blackish-red, very dusky red, green, dense, slightly calcareous	5.2	2,386.1
Sandstone, moderate-orange-pink, medium- to coarse-grained, firmly cemented, calcareous; sand grains consist of quartz and feldspar	1.9	2,388.0
Mudstone, medium-gray to blackish-red, dense, calcareous, and some thin zones of fossiliferous limestone	4.0	2,392.0
Limestone, olive-gray, fossiliferous, and some interbedded black mudstone	2.5	2,394.5
Mudstone, medium-dark-gray and grayish-purple, dense, calcareous	19.1	2,413.6
Limestone, medium-gray, dense, fossiliferous, and some irregular mudstone partings	2.8	2,416.4
Mudstone, medium-gray, blackish-red, light-green, dense, calcareous and gypsiferous	4.8	2,421.2
Limestone, medium-light-gray, dense, fossiliferous	1.8	2,423.0
Mudstone, grayish-purple, grayish-red, greenish-gray, slightly calcareous, partly carbonaceous, and some thin-bedded limestone and numerous nodules of light-gray limestone; some slickensided fracture planes	15.8	2,438.8
Sandstone, dark-greenish-gray, fine- to coarse-grained, angular to subangular; fragments consist of quartz, feldspar, and granite gneiss; some fragments as much as 1½ in. across	1.2	2,440.0
Precambrian System:		
Schist and gneiss; predominant minerals are quartz, orthoclase feldspar, biotite, and muscovite; fractures common to abundant; some fractures contain calcareous material	71.0	2,511.0

Sections of core were taken at 2-foot intervals by The Anaconda Co., covered to preserve their moisture content, and shipped to the Earlougher Engineering Co. for determination of porosity and permeability. A graph of porosity and permeability is shown on plate 2, and average values for several sandstone units are given in table 3. Porosity and permeability of most of the rock were low. However, a few beds of sandstone had as much as 30 percent porosity and averaged about 17 percent through a long interval of the Yeso and Abo Formations. The horizontal permeability ranged from less than 0.01 to 1,088 millidarcys; the average for sandstone beds in a long interval of the Yeso and Abo Formations was 108 millidarcys (pl. 2 and table 3). The average horizontal permeability and the cumulative thickness of sandstone units between the depths of 926 and 1,818 feet indicate that the transmissivity of this interval should be about 1,100 gpd per foot (gallons per day per foot).

Other core studies included determinations of water content, ion exchange, and neutralization capacities.

DRILL-STEM TESTS

Thirteen drill-stem tests were attempted under contract with Welex Co. at various intervals as the drilling progressed. Nine were completed successfully. All the drill-stem tests were double shut-in tests with three low-range Bourdon Tube recording pressure gages (Lynn and Arlin, 1962). These tests gave nonsteady formation fluid pressures of each interval tested.

Water samples were collected from 13 intervals of the well by swabbing through the drill stem after packers had been set at selected points. As each interval was swabbed, water samples were analyzed in the field for conductivity, chloride, alkalinity, and pH. A sample was not collected from the test interval in the well for laboratory analysis until the field analyses had remained constant for several hours; thus, the sample was ensured to be true formation water. The laboratory chemical analyses of water from six successful swabbing tests and one pumping test are given in table 4. Some intervals did not yield enough formation water in the time of the test to ensure a good analysis. All the water samples from below the Glorieta Sandstone contained more than 3,000 mg/l of dissolved solids, including more than 1,400 mg/l of sulfate. None of this water is considered to be potable.

After the water sample was collected for chemical analysis, the water level was measured in the drill stem to determine the rate of water-level rise after swabbing. These measurements were to be used for computation of the transmissivity, but most tests were too short to be definitive.

TABLE 3. — *Porosity and permeability of sandstone cores from The Anaconda Co. disposal well 1*

[Laboratory analyses by Earlougher Engineering Co., Tulsa, Okla.]

Interval	Stratigraphic unit	Depth (feet)	Thickness (feet)	Average porosity (percent)	Average permeability (millidarcys) Vertical	Average permeability (millidarcys) Horizontal	Horizontal capacity (feet × millidarcys)
1	Primarily Glorieta Sandstone	445–613	[1]150	15.3	335	271	40,700
2	Yeso Formation:						
	San Ysidro Member	613–773	160	11.3	6.90	13.54	2,170
3	do	773–926	153	5.4	.095	.096	15
4	do	926–1,130	154	14.9	9.18	34.57	5,324
5	do	1,130–1,165	35	7.8	.245	.109	3.8
6	do	1,165–1,253	74	11.3	.388	2.044	151
7	Primarily Meseta Blanca Sandstone Member	1,253–1,490	234	22.2	184	230	53,820
8	Abo Formation	1,490–1,818	107	14.1	....	17.71	1,895
9	Abo Formation and Madera(?) Limestone	1,880–2,440	[2]622	2.8	....	.253	....
10	Precambrian	2,440–2,511	[3]71	2.0	....	.029	....
4,6,7,and 8		926–1,130 1,165–1,818	569	17.3	....	108	[4]61,190

[1]Only 10 samples from this interval analyzed.
[2]Only 29 samples from this interval analyzed.
[3]Only 3 samples from this interval analyzed.
[4]Approximately the same as a transmissivity of 1,100 gpd per ft.

TABLE 4. — *Chemical analyses of water collected from The Anaconda Co. disposal well 1 by swabbing through tubing during drilling and during a pumping test*

[Analyses by U.S. Geological Survey. Chemical constituents are in milligrams per liter. Dissolved solids are sum of analyzed constituents. Pg, Glorieta Sandstone; Pys, San Ysidro Member of Yeso Formation; Pym, Meseta Blanca Sandstone Member of Yeso Formation; Pa, Abo Formation]

Date	Interval (feet)	Depth of well (feet)	Stratigraphic unit	Temperature (°C)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Potassium (K)	Bicarbonate (HCO_3)	Sulfate (SO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)	pH
1-17-59	490–576	576	Pg	....	210	53	202		572	536	108	0.4	0.2	1,410	742	273	2,290	7.4
1-21-59	633–688	769	Pys	6	468	121	359		598	1,420	338	.4	.7	3,010	1,660	1,180	3,810	7.5
1-28-59	916–970	1,094	Pys	19	592	137	433		260	2,260	295	.1	.3	3,860	2,040	1,830	4,370	7.4
2- 5 -59	990–1,200	....	Pys	24	574	140	451		272	2,260	292	.0	.3	3,870	2,010	1,780	4,450	7.6
4-22-59	1,300–1,475	1,830	Pym	24	600	137	432		288	2,240	205	.0	.7	3,880	2,060	1,820	4,360	7.2
2- 3 -59	1,305–1,450	1,513	Pym	19	576	141	400	7.5	250	2,170	300	.2	.0	3,740	2,020	1,810	4,460	7.6
2-18-59	1,520–1,922	1,922	Pa	16	304	72	2,800		175	6,150	409	3.8	2.2	9,830	1,053	913	11,100	7.9

GEOPHYSICAL LOGGING

Geophysical logs — consisting of spontaneous-potential logs, induction-electrical logs, caliper logs, micrologs, gamma-ray logs, and sonic logs — were made by the Schlumberger Well Surveying Corp. (pl. 2). Qualitative interpretations of the logs were made immediately by The Anaconda Co. for use in planning the well completion. In general, the logs gave good resolution of lithologic changes.

A few computations of porosity were made by the U.S. Geological Survey from the microlog and the sonic log for comparison with each other and with the laboratory determinations of porosity. In general, the correlation was good. However, the values obtained by the different methods were somewhat different in some intervals (pl. 2). The deviation was not consistent from one method to another. The generally good correlation shows that geophysical-log interpretation can be a useful tool for estimating porosity of water-bearing rocks in this type of geologic environment when core analysis is not feasible.

CASING

Several zones of sandstone in the lower part of the San Ysidro Member and the Meseta Blanca Sandstone Member of the Yeso Formation and in the upper part of the Abo Formation were selected by The Anaconda Co. for injection development on the basis of core analyses, drill-stem and swabbing tests, and geophysical logs. Dense beds of mudstone, siltstone, and anhydrite above and between the beds of sandstone selected for injection had very low permeabilities, and these dense beds were expected to permit only an insignificant amount of leakage of injected fluids upward into the fresh-water aquifer. The casing program was planned accordingly. The following description of the casing program was extracted from the report by Lynn and Arlin (1962).

Surface conductor pipe was removed, and the well was reamed to 17¼-inch diameter to a depth of 730 feet (pl. 2). This interval was cased with seamless stainless steel pipe having a grade of H–40, a weight of 48 pounds per foot, and an outside diameter of

$13\frac{3}{8}$ inches. Casing collars were spot welded, and the casing was installed with mud scratchers and centralizers. Portland cement was circulated to the land surface in the annulus between the casing and the walls of the hole. The casing was then pressure tested to assure a tight seal. The hole below 730 feet was then reamed to a diameter of 11 inches, and the injection casing, consisting of seamless steel pipe having a grade of J–55, a weight of 32 pounds per foot, and an outside diameter of $8\frac{5}{8}$ inches, was installed to a depth of 1,830 feet. It was installed with centralizers and a collar baffle that permitted the lower 32 feet to remain filled with cement to seal off the lower part of the hole.

The injection casing was treated before installation with a baked-on internal coating of plastic 7 to 8 mils thick to prevent corrosion by the acid injection fluid.

The annulus between the injection casing and the walls of the hole was filled with a sulfate-resistant cement consisting of equal parts of Type V portland cement and inert pozzolan (Lynn and Arlin, 1962). The cement was circulated to the land surface in two stages. The first attempt at circulation failed because the cement was lost into fractures at and below a depth of 900 feet. The casing was gun perforated just above the top of the cement, and the second stage of cement was pumped through the perforations and circulated to the land surface. The perforations were sealed, and the casing was tested for leaks by applying air pressure of several hundred pounds per square inch. The test showed that the casing was adequately sealed.

Selected intervals of the casing were gun perforated between 1,254 and 1,480 feet below zero datum, primarily opposite the Meseta Blanca Sandstone Member, with 108 bullets designed to make holes nine-sixteenths of an inch in diameter (pl. 2). The perforations were washed out by injecting clear water under high pressure. This prepared the well for the first test of well performance and aquifer characteristics.

PUMPING TESTS

A submersible pump was installed, using drill pipe for the discharge column, and a separate pipe was strapped to the outside of the column for easy access in measuring water levels. The prepumping water level was 237 feet below the measuring point (top of the kelly bushing at an altitude of 6,690 ft) on April 14, 1959, just before a 1-hour preliminary pumping test was started. The pumping rate varied slightly during the test but was nearly constant at 100 gpm. The maximum depth to water during the test was 1,010 feet below the measuring point. After pumping, the water level recovered to 237 feet. The data from the preliminary test were used to plan a longer test.

The water level in the well was allowed to stabilize after the preliminary pumping test, and a longer drawdown and recovery test was made April 15–16, 1959. The pumping rate was nearly constant at 100 gpm for 18 hours. The maximum depth to water during the test was 1,024 feet — a drawdown during pumping of 787 feet. The specific capacity of the well during the test was 0.13 gpm per foot of drawdown. The water had fully recovered to the prepumping level within 12 hours after pumping was stopped.

The specific capacity of the well was so low that minute changes in pumping rate were reflected in large changes in water level. The resulting erratic water levels were unsuitable for use in computing the transmissivity of the aquifer. The water-level recovery was more uniform, and measurements made during recovery were plotted on semilog graph paper for computation of transmissivity by the straight-line method (fig. 2). The slope of the curve during the early part of recovery indicated a very low apparent transmissivity (1,000 gpd per ft or less), approximately the same as that estimated from the core analysis. (See table 3.) The apparent low transmissivity during the early part of recovery was thought to be the result of one or more of the following factors: (1) Blocking of fractures in the aquifer with drilling mud and cement during well construction, (2) convergence of ground water flow from an extensive fracture system in the aquifer into a few fractures intercepted by the well bore, or (3) wide variation in permeability of individual beds of sandstone. The slope of the curve during the late part of recovery indicated a much higher apparent transmissivity — 8,500 gpd per ft — than the early part. Presumably the difference could be the result of vertical leakage from another aquifer or leakage from some other type of recharge boundary, but the difference in apparent transmissivity was much greater than should be expected from a recharge boundary. More logically, water levels during the late part of recovery more nearly represent conditions in the formation beyond the zone of construction damage to the aquifer and beyond the zone of flow convergence in fractures intercepted by the well bore.

A much longer drawdown and recovery test was started April 16, 1959, after the water level had recovered from the preceding test, and was com-

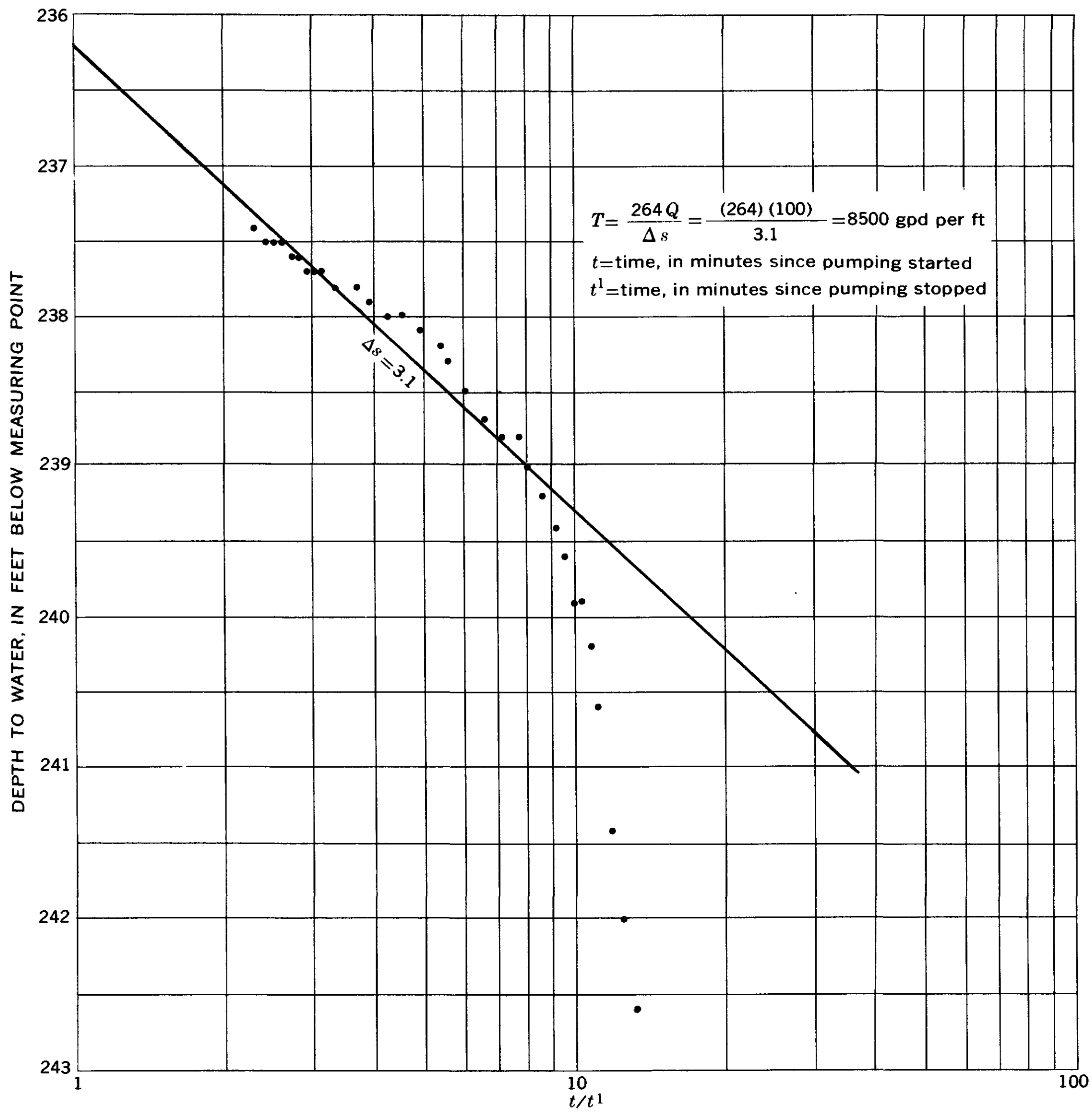

FIGURE 2. — Curve of water-level rise after pumping stopped, April 15–16, 1959. *T*, transmissivity, in gallons per day per foot; Δ*s*, change in water level over one log cycle, in feet; *Q*, pumping rate, in gallons per minute.

pleted April 24. The pumping rate was nearly constant at 100 gpm for 148.5 hours. The water level at the end of the pumping period was 1,081 feet. The drawdown during the test was 844 feet, and the specific capacity of the well was 0.12 gpm per foot of drawdown. Data from the late part of the recovery period was used to compute the apparent transmissivity, 6,400 gpd per ft (fig. 3).

About 1 million gallons of water were pumped from the aquifer during the three pumping tests. The water was stored for later use in two earthen tanks lined with large sheets of polyethylene.

Although apparent transmissivities indicated that the aquifer should be capable of accepting water at a rate of a few hundred gallons per minute by injection, The Anaconda Co. decided to perforate the casing adjacent to several thin beds of sandstone both above and below the Meseta Blanca Sandstone Member and to fracture the rock opposite the perforated intervals hydraulically to permit injection at a rate higher than that indicated as possible by preliminary testing.

HYDRAULIC FRACTURING

Perforating and fracturing were done in two stages. Thirty-eight openings were made with a gun perforator in the casing opposite thin beds of sandstone in the upper part of the Abo Formation (pl. 2).

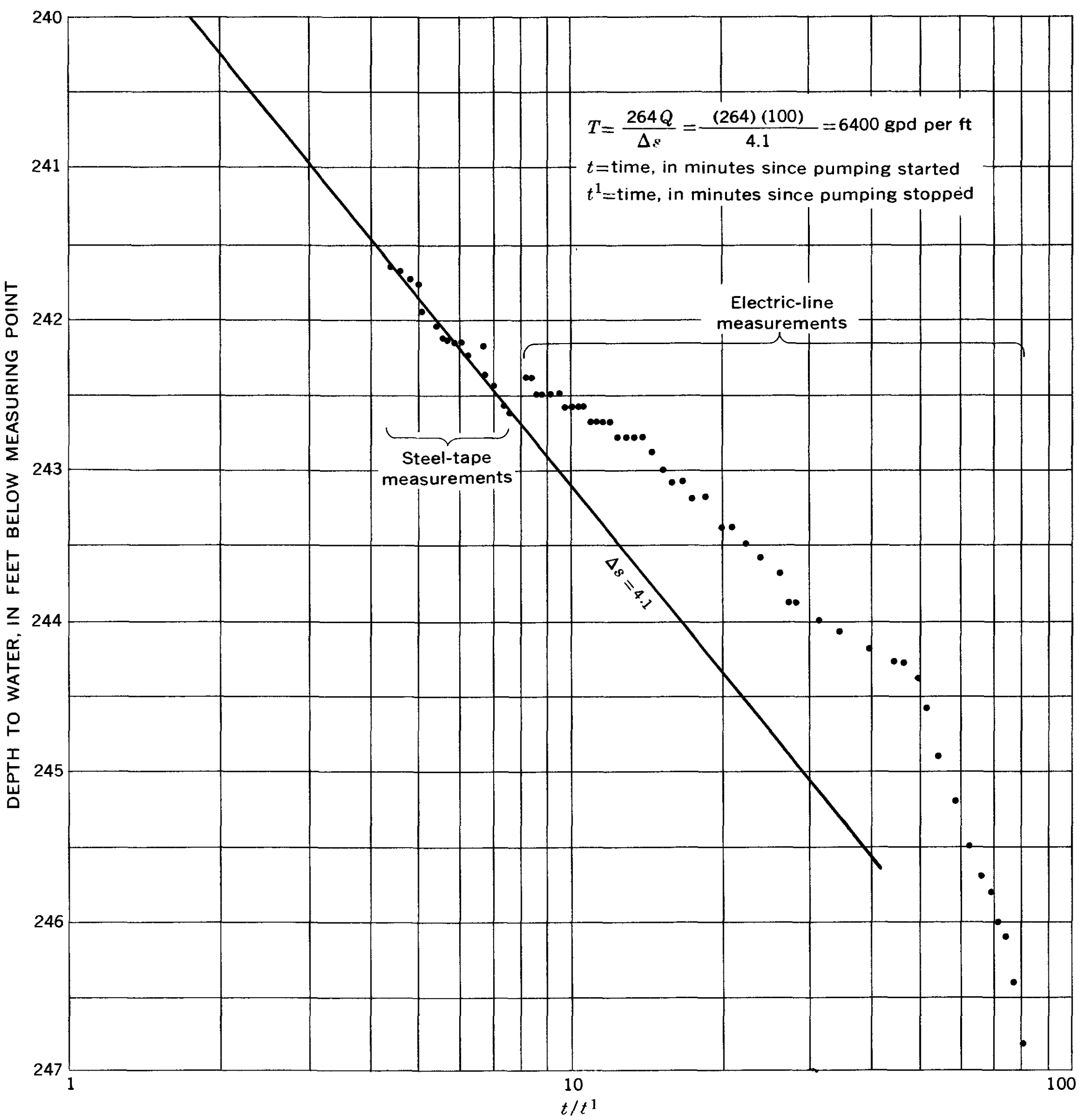

FIGURE 3. — Curve of water-level rise after pumping stopped, April 22–23, 1959. *T*, transmissivity, in gallons per day per foot; Δs, change in water level over one log cycle, in feet; *Q*, pumping rate, in gallons per minute.

These beds and the Meseta Blanca Sandstone Member were fractured in the first stage. The second stage consisted of gun perforating the casing with 101 shots opposite beds of sandstone in the lower part of the San Ysidro Member, setting a drillable plug at a depth of 1,220 feet, and fracturing these beds (Lynn and Arlin, 1962).

The "Riverfrac" process of Dowell, Inc., was used in both stages of fracturing. Fracturing was accomplished with 94,000 pounds of 20/40-mesh fracturing sand and 212,000 gallons of water. Two hundred and fifteen round balls were added to seal each of the perforations as fracturing was accomplished and as the velocity of water through the perforation became sufficient to move a ball to the perforation (Lynn and Arlin, 1962).

The average pumping rate during the first stage of fracturing was 3,360 gpm, and the breakdown pressures ranged from 600 to 1,200 pounds per square inch. The average pumping rate during the second stage was 2,100 gpm, and the breakdown pressures ranged from 600 to 3,800 pounds per square inch. After the second stage of fracturing, the fractured interval was treated with 1,000 gallons of mud acid and detergent in an attempt to establish better communication between the well bore and the natural fractures in the formation (Lynn and Arlin, 1962).

The temporary plug was drilled out, and the well was cleaned to the completion depth of 1,796 feet. Several short-term injection tests were made with the drill-rig pumps. These tests indicated that the potential injection rate had been greatly increased by the hydraulic fracturing.

Well construction and preliminary testing were completed May 1, 1959. The Anaconda Co. submitted all the construction and test data to the New Mexico State Department of Health and to the U.S. Atomic Energy Commission with a request for permission to inject mill effluent into the well during a 90-day test period. The request was approved, and the company proceeded with construction of necessary surface facilities.

SURFACE INSTALLATIONS

Surface installations constructed before injection began included a decanter in the tailings pond at the point of feed-water pickup, a filter plant nearby, and a pipeline to the well (Lynn and Arlin, 1962). The decanter is a 4- by 120-foot wooden box erected on foundations in the tailings pond. The top of the decanter can be raised as the fluid level in the pond is raised by displacement owing to the addition of mill tailings. The decanted water is lifted from a sump with a turbine pump and forced alternately through one of two circular leaf filters. The filtrate then passes through a surge tank, from which a centrifugal pump forces it through a metering manifold and through 1.4 miles of pipeline to the well head. The pipeline is 12 inches in diameter and is lined with rubber to prevent corrosion. The lift between the tailings pond and the well head is 90 feet. The water enters the well by gravity through a sealed pipeline–well-head connection to prevent entrance of air. All equipment from the sump pump to the lower end of the injection pipe are either rubber lined or stainless steel.

The well bore and the initial injection fluid were treated with 9,000 pounds of citric acid crystals to prevent precipitation of iron in the mill effluent in the vicinity of the well bore, where the effluent comes in contact with the formation water. Equipment was installed for continuous treatment of the feed water to 4 ppm (parts per million) of copper sulfate for control of bacteria and fungi and to 20 ppm of sodium polyphosphate for retardation of calcium sulfate precipitation (Lynn and Arlin, 1962).

Filters reduce the turbidity of the injection fluid to about 0.1 ppm of suspended solids. Flood tests of core samples from the injection interval indicated that as much as 0.4 ppm of suspended matter could be tolerated (Lynn and Arlin, 1962).

CONSTRUCTION OF MONITOR WELL 1

The Anaconda Co. drilled a monitor well 300 feet southeast of the disposal well. It was drilled to a depth of 628 feet and fully penetrated the San Andres Limestone–Glorieta Sandstone fresh-water aquifer. Perforated casing was installed through this aquifer so the well could be used for monitoring water levels and chemical quality of water. Such monitoring might provide evidence of interformational leakage of water upward from the injection interval in the Yeso Formation to the San Andres–Glorieta aquifer.

The water level in monitor well 1 on March 19, 1960, was at an altitude of 6,452 feet, 224 feet below the top of the casing. This level was 1 foot lower than the initial water level in the disposal well.

Concentrations of selected ions in the water in March 1960 were reported by The Anaconda Co. as follows: Sodium, 235 ppm; sulfate, 660 ppm; chloride, 142 ppm; and nitrate, 10 ppm.

NINETY-DAY INJECTION TEST

The 90-day injection test was started January 20, 1960. The test was designed to evaluate both the well performance and the aquifer characteristics. Injection rates and water levels in the injection well were monitored closely throughout the test. Several injection rates were tried so that a range of potential rates for future injection could be established.

A velocity-meter survey of the well was made to determine the percentage of injected water that left the well through each of the perforated intervals. The injection rate was 1,336 gpm during the survey. The survey showed that 74 percent of the water entered the formation between the depths of 1,232 and 1,484 feet, primarily in the Meseta Blanca Sandstone Member interval (table 5).

TABLE 5. — *Summary of velocity-meter survey of The Anaconda Co. disposal well 1 during injection*

Depth interval (feet)	Percent of perforations in interval	Water loss from well in interval (gpm)	Cumulative water loss from well (gpm)
900–1,050	19.50	121.9	121.9
1,050–1,078	2.44	36.1	158.0
1,078–1,150	9.32	168.5	326.5
1,150–1,232	9.70	24.4	350.9
1,232–1,374	23.10	640.0	990.9
1,374–1,484	20.60	345.0	1,335.9
1,484–1,505	1.21	0	....
1,505–1,540	2.03	0	....
1,540–1,587	2.44	0	....
1,587–1,628	2.84	0	....
1,628–1,679	2.03	0	....
1,679–1,749	2.84	0	....
1,749–1,782	2.03	0	....
Total	100.08	1,335.9	....

INJECTION RATES

When injection began on January 20, 1960, an initial injection rate of 480 gpm was maintained for 20 minutes. Then the rate was increased to 820 gpm and continued for 26 hours. After a 29-hour idle period due to mechanical reasons, injection began again. For the 16-day period ending February 8, which included several delays of 3 to 10 hours each, the injection rate ranged from 600 to 1,300 gpm and averaged about 1,000 gpm. On February 8, the injection rate was decreased to about 380 gpm and continued at that rate, except for three brief delays, until February 18. Injection operations were suspended for the next 10 days while a pump in the supply line was repaired. During this delay the well was cleaned of bits of rubber and plastic that entered it from the defective pump. Injection was resumed February 28; except for a 1-hour shutdown on February 29, injection was continuous at a rate of about 380 gpm until March 14, when another idle period of 17 hours was necessitated by high turbidity of water in the tailings pond. Injection was resumed on March 15 and continued at a rate of 380 gpm until March 28. Between March 28 and the end of the 90-day test period on May 8, the injection rate fluctuated between 380 and 900 gpm. The specific capacity of the well was 3.6 to 3.8 gpm per foot of water-level rise. Approximately 67 million gallons of liquid were injected during the test period. The well was idle between May 8 and December 14 except for a short time during cleaning and swabbing.

WATER LEVELS AND HEAD CHANGES IN THE AQUIFER

The head at a given depth in the injection aquifer could be monitored only by measuring water levels or pressure at a point in the injection well because it is the only well in the area that taps the aquifer. Measurements of the depth to water in the well were made with an electrical tape and a pressurized air line and were checked occasionally with a steel tape. The depth to water in the well immediately prior to the start of the 90-day test was 251 feet, at an altitude of 6,439 feet. NOTE. — The water level in the well was lowered about 14 feet from the original level by the addition of citric acid and mill effluent, which raised the specific gravity of the fluid column to about 1.01.

The head in the well during injection (fig. 4) was not a true measure of the head in the aquifer because of the energy loss due to friction from flow in the well bore and through the perforations in the well. Decline of the water level in the well when injection stopped was used to estimate the rise in head in the aquifer at the well-aquifer interface. The water level declined about 15 feet in the first minute after injection stopped on May 8, about 4 feet the second minute, and about 3 feet the third minute. The amount of head lost in overcoming fluid friction in the pipe and in the screen openings was less than 15 feet and probably was less than 10 feet when the injection rate was 600 gpm. Therefore, the buildup in head was about 205 feet inside the well and between 190 and 195 feet in the aquifer at the well face when 600 gpm was being injected. The head at a given level in the aquifer during injection decreased with distance from the well.

The well overflowed at least twice, once on February 4 when the injection rate was increased briefly to 1,200 gpm and once on April 17 when the rate was 900 gpm.

Change of the head within the well after injection was not observed in sufficient detail to determine how long measurable residual head increase remained. A measurement made on May 11, about 70 hours after injection ceased, showed the level to be at a depth of about 223 feet or about 28 feet higher than the preinjection level. No water-level measurements were made between mid-May and mid-October. On October 20 the water level in the well was at a depth of 250 feet, or approximately the depth prior to injection; thus, the pressure increase during the 90 days of injection had dissipated in a period of 5 months or less.

Data from the 90-day injection test indicated that disposal of the uranium-mill effluent by injection into the Yeso Formation probably was feasible and that an injection rate of about 400 gpm was possible. The Anaconda Co. applied to State and Federal agencies for permission to use the well for operational injection. Data from the 90-day test were presented to the agencies, and because the data did not show any indications of contamination of the potable water supplies of the area, permission for operational injection was granted, with the stipulation that the injection head must always be lower than the land surface; that is, injection must be by gravity flow only.

OPERATIONAL INJECTION

RATE AND VOLUME OF FLUID INJECTED

The injection well was made a part of the mill waste-disposal system, and routine injection was started December 14, 1960. Injection rates for January 1960 through December 1965 are shown graphically in figure 4. High turbidity in the supply pond was the most frequent reason for shutdowns. When the pond level was too low, fine-grained sediment

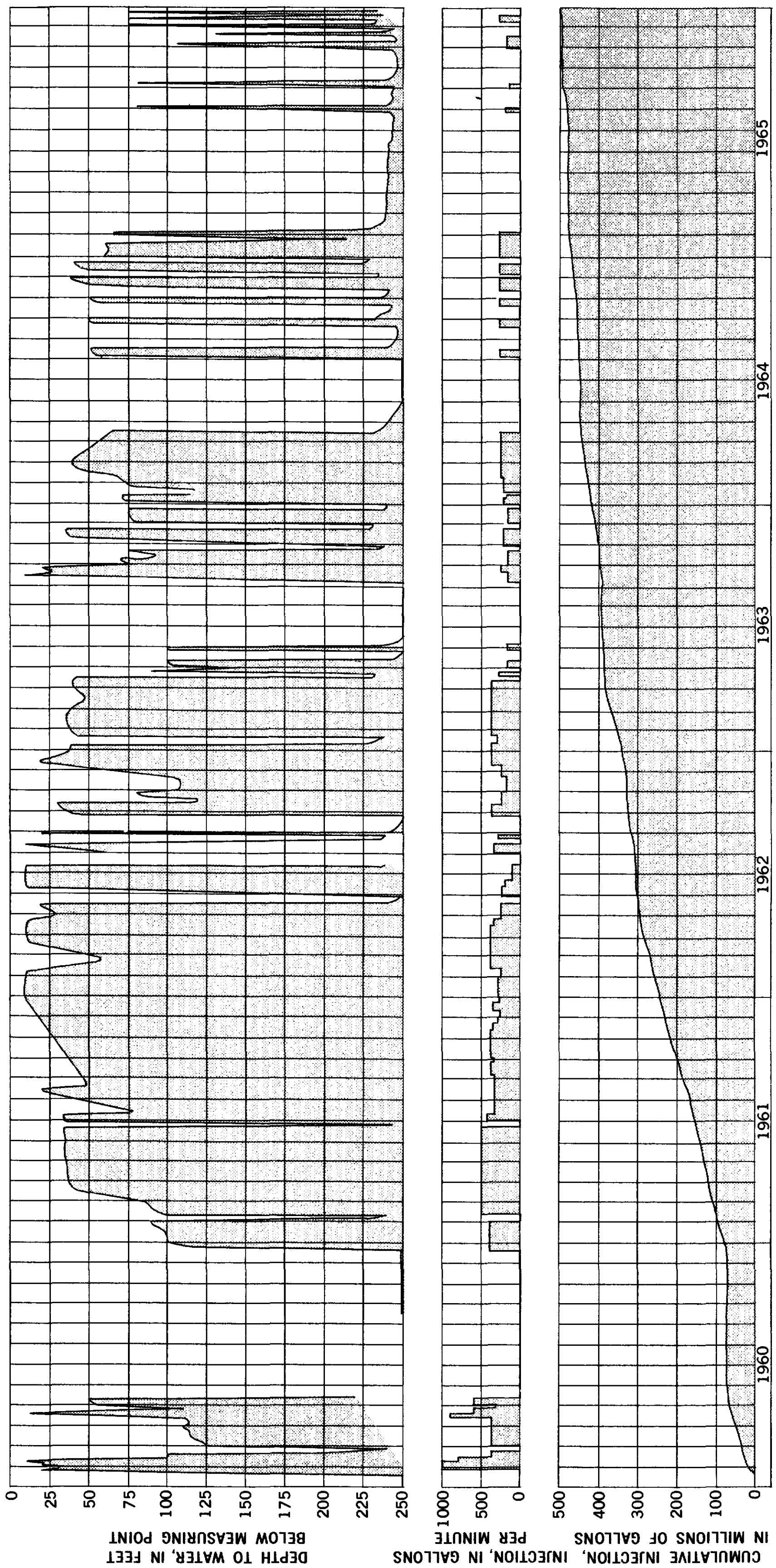

FIGURE 4. — Depth to water, injection rate, and cumulative quantity of fluid injected.

that had settled to the bottom of the pond was drawn into the decanter. Also, wind action when the pond level was low stirred up the fine sediment and caused high turbidity in the pond water.

The injection rate was regulated to ensure only gravity flow within the well. Even a low-pressure injection to the well could make the injection operation economically undesirable, assuming that permission to inject under any pressure at the well head could be obtained. On February 23, 1962, the supply line was treated with formaldehyde to inhibit growth of algae and bacteria. Some of the formaldehyde solution entered the well and seemed to improve the injection efficiency.

Injection was halted during July 11–30, 1962, to clean the well. Clogging of the screen was suspected because injection rates of only 125 to 250 gpm were possible; higher rates would cause the water level in the well to rise to the land surface. These rates were too low to keep up with the rate of waste discharge from the mill.

Injection was resumed on July 31 at a rate of 400 gpm. Because of the relatively rapid rise in water level in the well, there was doubt that cleaning the well had restored lost injection efficiency. Shutdowns and reductions of the injection rate because of high turbidity and low pond level curtailed injection. When the pond level had increased by December 1962, a rate of 400 gpm was attempted; injection efficiency had improved, and the 400-gpm rate could be maintained without raising the water level in the well to the land surface. Injection was stopped from May 11 to September 4, 1963, because the water level in the pond was low.

Injection efficiency was less after the long shutdown, and injection rates of more than 250 gpm caused an excessively high water level in the well. The efficiency improved during September and October, and by November the efficiency seemed to be comparable to that during the first part of 1963.

The maximum amount of water injected in 1 month was 19 million gallons in April 1960—equivalent to a steady rate of 440 gpm. The rate of injection during 1961 (320 gpm) was the highest average injection rate of any year. Through December 1965 a total of 501 million gallons of waste water had been injected. Cumulative monthly totals are shown graphically in figure 4.

WATER LEVELS AND HEAD CHANGES IN THE AQUIFER

Because of the stipulation in the permit granted to The Anaconda Co. that injection of mill effluent be by gravity flow only, negative drawdown (head increase) could not exceed 250 feet, the depth to static water level. The injection rate was regulated so that, in general, water level in the well would not rise higher than 10 feet below the land surface. The general trend of water level changes in the well during January 1960 through December 1965 is shown graphically in figure 4. Minor fluctuations of water level could not be shown at the time scale used.

Water level always returned to about 250 feet below land surface soon after injection was stopped and remained at that level until injection was resumed.

Water was not injected into the well from February through July 1965, and for the first time during a lengthy shutdown, the water did not return to the original level of 250 feet. Instead, the water level declined slowly to a level of about 245 feet. The difference between this noninjection water level and that during other shutdowns cannot be explained.

CHEMICAL AND RADIOCHEMICAL QUALITY OF INJECTED WATER

The chemical composition of water injected through the disposal well is a combination of the chemicals used in processing the uranium ore and the ions leached from the ore, less the ions purposely removed from the solutions or precipitated from solution by reactions in the tailings pond. During the first few years of mill operation, both limestone and sandstone ores were processed; only sandstone ore has been processed since mid-1959.

The sandstone ore is crushed and then leached with sulfuric acid to extract the uranium oxide. The resultant solution then goes into ion-exchange vats, where the uranium is adsorbed on resins and is thereby extracted from the acid. The acid and the leached sand ore are drained from the ion-exchange vats and flushed to the tailings pond. The uranium is extracted from the resins with sodium chloride in an acid solution. Lime is added to this solution to increase the pH sufficiently to precipitate some of the iron, manganese, and aluminum yet leave the uranium in solution. These impurities are filtered out and are discharged to the tailings pond. Then the uranium is precipitated from solution by further increase of the pH. After the uranium precipitate has been removed from the solution by filtration, the spent liquid is released to the tailings pond.

When the limestone mill was in operation, the uranium oxide was removed from the ore by water in a "pressure cooker." From that point on, the extraction process was the same as that for the sandstone ore. The leached limestone was flushed into the tailings pond. The chemical composition of water in the tailings pond was influenced significantly by the quantities of each type of ore being processed and the reactions between the limestone tailings and the strong acid solutions.

Chemical and radiochemical quality of water injected through the disposal well has varied slightly, showing highest concentrations of dissolved solids in summer because greater evaporation caused a concentration of solids in the tailings pond (tables 6 and 7). The water is acid, having a pH range of 2.3 to 2.8. The water is enriched in ions of iron, manganese, calcium, magnesium, sodium, sulphate, and chloride, owing to the process of extracting uranium from the sandstone ore. In the early operation of the mill, ammonium nitrate was used where sodium chloride is now used in the process, and during that time the waste water was high in nitrate but low in sodium and chloride. The water contains small amounts of radioactive uranium, thorium-230, and radium-226.

Densities for water samples analyzed by The Anaconda Co. have been estimated and are listed in table 6.

Concentrations of iron and manganese were persistently high in the injected fluid after 1960, relative to normal concentration in natural waters. (See table 6 and Gordon, 1961, table 10.) Such high concentrations of iron and manganese would probably have caused serious problems of formation plugging by precipitates had the formation not been fractured and conditioned with acid before the initial injection of mill effluent.

Concentrations of calcium and magnesium in the effluent are only slightly higher than those of some natural waters in the San Andres Limestone and the Yeso Formation. Concentration of sodium in the effluent is similar to that in some natural waters of the area but higher than that generally found in water in the San Andres Limestone and the Yeso Formation. Concentration of chloride was significantly higher than that generally found in natural waters of the San Andres and the Yeso but not higher than that in some natural water in the Chinle Formation.

Concentration of nitrate, the ion that caused the gravest problem of contamination during early operation of the evaporation pond, ranged from a high of 185 ppm during the second quarter of 1963 to a low of 67 ppm during the first quarter of 1965 (table 6) ; it averaged 105 ppm. Nitrate concentration has not decreased significantly as might be expected, since the use of ammonium nitrate in ore processing ceased. Continuous inflow of mill effluent to the tailings pond and continuous withdrawal for injection seemingly would have flushed all the nitrate from the pond in a relatively short time. The persistence of nitrate in such high concentrations is principally due to use of processing water from a previously contaminated well that still yields water containing about 100 ppm nitrate. In part, it may be caused by slow oxidation of ammonium that was adsorbed on the clay on the floor of the pond and on the tailings during the use of ammonium nitrate in the mill.

A trend in concentration of dissolved solids is not conspicuous.

Between January 1, 1960, and December 31, 1965, a total of 13.89 curies, or 35,210,000 grams, of uranium was injected into the Yeso Formation through the disposal well. During the same period, 312.6 curies, or 16,038 grams, of thorium-230 and 0.612 curie or 0.612 gram, of radium-226 were also injected (table 7).

HYDROLOGIC AND CHEMICAL MONITORING

The Anaconda Co. has monitored water levels in six wells near the mill and the tailings pond since mid-1956. A monitor well near the effluent disposal well was added to the network in early 1960.

Seasonal fluctuations of 5 to 10 feet in water levels were typical through 1961 in all the wells (fig 5). The highest levels were in early spring, and the lowest levels were in late summer or early fall. These fluctuations are readily correlated with ground-water irrigation pumping in the area. If leakage from the tailings pond affected water levels in the wells, these effects were masked by the stronger effects of pumping. Two of the wells had net declines in water level from 1956 to 1961; the others remained fairly constant except for the seasonal fluctuations.

Water levels rose almost continuously, with only slight seasonal fluctuations, in all the wells from the autumn of 1961 through 1965. These rises in water level coincided with a significant reduction in ground-water irrigation pumping in the area. These rises began 8 years after use of the tailings pond began.

In addition to monitoring the water level, The Anaconda Co. has monitored the chemical and radiochemical quality of water monthly in 20 wells, bimonthly in 25 wells and springs, and semiannually in two wells. Samples from the tailings pond, the power-house pond, and the laboratory pond were analyzed monthly. Sampling points were selected to provide good areal distribution. (See pl. 1.) Concentrations of sodium, sulfate, chloride, and nitrate ions

TABLE 6. — *Chemical analyses of water injected into The Anaconda Co. disposal well 1, January 1960 to December 1965*

[Analyses by The Anaconda Co.; values rounded in accordance with U.S. Geological Survey standards. Chemical constituents are in parts per million]

Date	Iron (Fe)	Manganese (Mn)	Calcium (Ca)	Magnesium (Mg)	Sodium (Na)	Sulfate (SO_4)	Chloride (Cl)	Nitrate (NO_3)	Dissolved solids	Specific conductance (micromhos at 25°C)	pH	Estimated density (grams per milliliter at 20°C)
1960												
Jan. 1 to Mar. 31	....	....	....	....	....	6,100	1,290	89	....	12,500	2.7	1.003
Apr. 1 to June 30	....	....	242	411	1,210	8,330	1,720	130	....	19,000	2.8	1.008
July 1 to Sept. 30	....	....	....	....	....	....	....	....	....	....	....	....
Oct. 1 to Dec. 31	....	....	....	....	1,110	7,490	1,580	80	....	18,000	2.3	1.008
1961												
Jan. 1 to Mar. 31	360	472	491	222	850	6,830	1,230	82	11,600	15,500	2.3	1.006
Apr. 1 to June 30	390	470	635	269	1,210	8,470	1,870	79	15,700	18,700	2.3	1.008
July 1 to Sept. 30	270	443	609	495	1,080	6,910	1,410	106	12,400	14,700	2.3	1.005
Oct. 1 to Dec. 31	220	457	564	439	1,030	6,180	1,340	85	11,500	14,700	2.4	1.005
1962												
Jan. 1 to Mar. 31	190	442	545	454	799	5,780	1,260	72	10,400	14,500	2.8	1.005
Apr. 1 to June 30	340	442	713	580	1,270	9,150	2,140	84	17,800	21,500	2.4	1.009
July 1 to Sept. 30	670	677	720	870	2,370	12,300	3,180	151	24,600	26,000	2.4	1.011
Oct. 1 to Dec. 31	300	422	561	198	1,330	5,800	1,980	86	11,300	18,200	2.3	1.008
1963												
Jan. 1 to Mar. 31	200	341	520	167	1,120	4,320	1,590	101	9,020	13,200	2.5	1.003
Apr. 1 to June 30	390	684	693	275	2,060	7,140	2,820	185	14,100	22,100	2.4	1.009
July 1 to Sept. 30	960	480	661	230	1,590	6,370	2,670	124	13,000	18,000	2.4	1.008
Oct. 1 to Dec. 31	250	362	582	155	1,290	5,050	1,880	118	10,200	16,300	2.5	1.006
1964												
Jan. 1 to Mar. 31	240	359	509	139	1,230	4,790	1,720	93	9,800	15,800	2.4	1.006
Apr. 1 to June 30	320	402	578	160	1,510	5,840	2,040	80	12,000	18,000	2.4	1.008
July 1 to Sept. 30	360	518	796	190	1,510	7,120	2,400	96	14,600	19,800	2.4	1.008
Oct. 1 to Dec. 31	290	419	546	168	1,480	5,930	1,960	92	11,800	17,400	2.4	1.008
1965												
Jan. 1 to Mar. 31	300	422	488	122	1,410	5,190	1,940	67	10,500	14,500	2.5	1.005
Apr. 1 to June 30	....	....	....	....	....	....	....	....	....	....	....	....
July 1 to Sept. 30	420	385	586	214	1,780	7,050	3,120	114	16,000	20,400	2.7	1.008
Oct. 1 to Dec. 31	430	516	532	206	1,960	6,600	3,130	88	14,800	21,600	2.4	1.009
Average	360	459	578	298	1,390	6,760	2,010	105	13,200	18,200	2.5	1.008

TABLE 7. — *Radiochemical analyses of water and quantities of radioactive nuclides injected into The Anaconda Co. disposal well 1, January 1960 to December 1965*

[Analyses and computations of quantities by The Anaconda Co. Concentrations are given in microcuries per milliliter]

Date	Volume of water injected (millions of gallons)	Uranium (natural)			Thorium-230			Radium-226		
		Concentration (μc/ml)	Quantity		Concentration (μc/ml)	Quantity		Concentration (μc/ml)	Quantity	
			Curies	Grams		Curies	Grams		Curies	Grams
1960										
Jan. 1 to Mar. 31	43.07	13.5×10^{-6}	2.20	3,230,000	2.00×10^{-4}	32.6	1,670	6.56×10^{-7}	0.107	0.107
Apr. 1 to June 30	24.40	17.3×10^{-6}	1.60	2,350,000	2.57×10^{-4}	23.7	1,220	5.63×10^{-7}	.052	.052
July 1 to Sept. 30	0	....	0	0	....	0	0	....	0	0
Oct. 1 to Dec. 31	10.17	11.0×10^{-6}	.42	620,000	1.80×10^{-4}	6.9	354	2.00×10^{-7}	.008	.008
1961										
Jan. 1 to Mar. 31	42.19	5.33×10^{-6}	.85	2,550,000	1.57×10^{-4}	25.0	1,282	2.46×10^{-7}	.038	.038
Apr. 1 to June 30	38.63	7.70×10^{-6}	1.12	3,360,000	2.64×10^{-4}	38.7	1,986	3.86×10^{-7}	.056	.056
July 1 to Sept. 30	47.25	5.39×10^{-6}	.96	2,880,000	1.62×10^{-4}	29.0	1,488	3.57×10^{-7}	.064	.064
Oct. 1 to Dec. 31	41.33	5.33×10^{-6}	.81	2,430,000	1.12×10^{-4}	16.9	867	3.08×10^{-7}	.046	.046
1962										
Jan. 1 to Mar. 31	38.49	6.29×10^{-6}	.92	2,760,000	1.12×10^{-4}	16.3	836	2.91×10^{-7}	.042	.042
Apr. 1 to June 30	23.33	8.32×10^{-6}	.74	2,220,000	2.34×10^{-4}	20.2	1,036	3.77×10^{-7}	.033	.033
July 1 to Sept. 30	15.26	9.20×10^{-6}	.53	1,590,000	2.30×10^{-4}	13.3	682	4.69×10^{-7}	.027	.027
Oct. 1 to Dec. 31	26.81	5.45×10^{-6}	.55	1,650,000	1.19×10^{-4}	12.1	621	2.34×10^{-7}	.024	.024
1963										
Jan. 1 to Mar 31	34.46	4.93×10^{-6}	.64	1,920,000	1.09×10^{-4}	14.2	728	1.89×10^{-7}	.025	.025
Apr. 1 to June 30	6.39	7.89×10^{-6}	.19	570,000	1.96×10^{-4}	4.7	241	2.39×10^{-7}	.006	.006
July 1 to Sept. 30	8.47	8.06×10^{-6}	.25	750,000	1.58×10^{-4}	5.1	262	3.28×10^{-7}	.011	.011
Oct. 1 to Dec. 31	19.09	4.61×10^{-6}	.33	990,000	1.29×10^{-4}	9.4	482	3.05×10^{-7}	.022	.022
1964										
Jan. 1 to Mar. 31	29.00	5.56×10^{-6}	.61	1,830,000	1.16×10^{-4}	12.7	651	1.18×10^{-7}	.013	.013
Apr. 1 to June 30	3.48	6.58×10^{-6}	.09	270,000	1.34×10^{-4}	1.8	92	3.02×10^{-7}	.004	.004
July 1 to Sept. 30	8.08	7.41×10^{-6}	.22	660,000	1.66×10^{-4}	5.0	256	1.71×10^{-7}	.005	.005
Oct. 1 to Dec. 31	17.25	5.70×10^{-6}	.37	1,110,000	1.72×10^{-4}	11.2	575	2.61×10^{-7}	.017	.017
1965										
Jan. 1 to Mar. 31	14.09	5.75×10^{-6}	.31	930,000	1.43×10^{-4}	7.7	395	1.07×10^{-7}	.006	.006
Apr. 1 to June 30	0	....	0	0	....	0	0	....	0	0
July 1 to Sept. 30	3.58	5.69×10^{-6}	.07	210,000	1.32×10^{-4}	1.7	88	1.56×10^{-7}	.002	.002
Oct. 1 to Dec. 31	6.56	4.44×10^{-6}	.11	330,000	1.74×10^{-4}	4.4	226	1.65×10^{-7}	.004	.004
Total quantities	501.38	....	13.89	35,210,000	....	312.6	16,038	....	.612	.612
Average concentrations	....	7.34×10^{-6}	....	....	1.66×10^{-4}	....	....	2.92×10^{-7}	....	....

in water from eight wells that tap the San Andres Limestone in the vicinity of the tailings pond and the disposal well are shown graphically on plate 3. These ions were selected for analysis of the chemical monitoring program because they are most diagnostic of mill effluent.

One or more chemical analyses by the U.S. Geological Survey for four of the wells shown on plate 3 are available for 1956, for two of the wells in 1957, and for one of the wells in 1958. Sampling of the other wells was begun in late 1959 or early 1960 by The Anaconda Co.

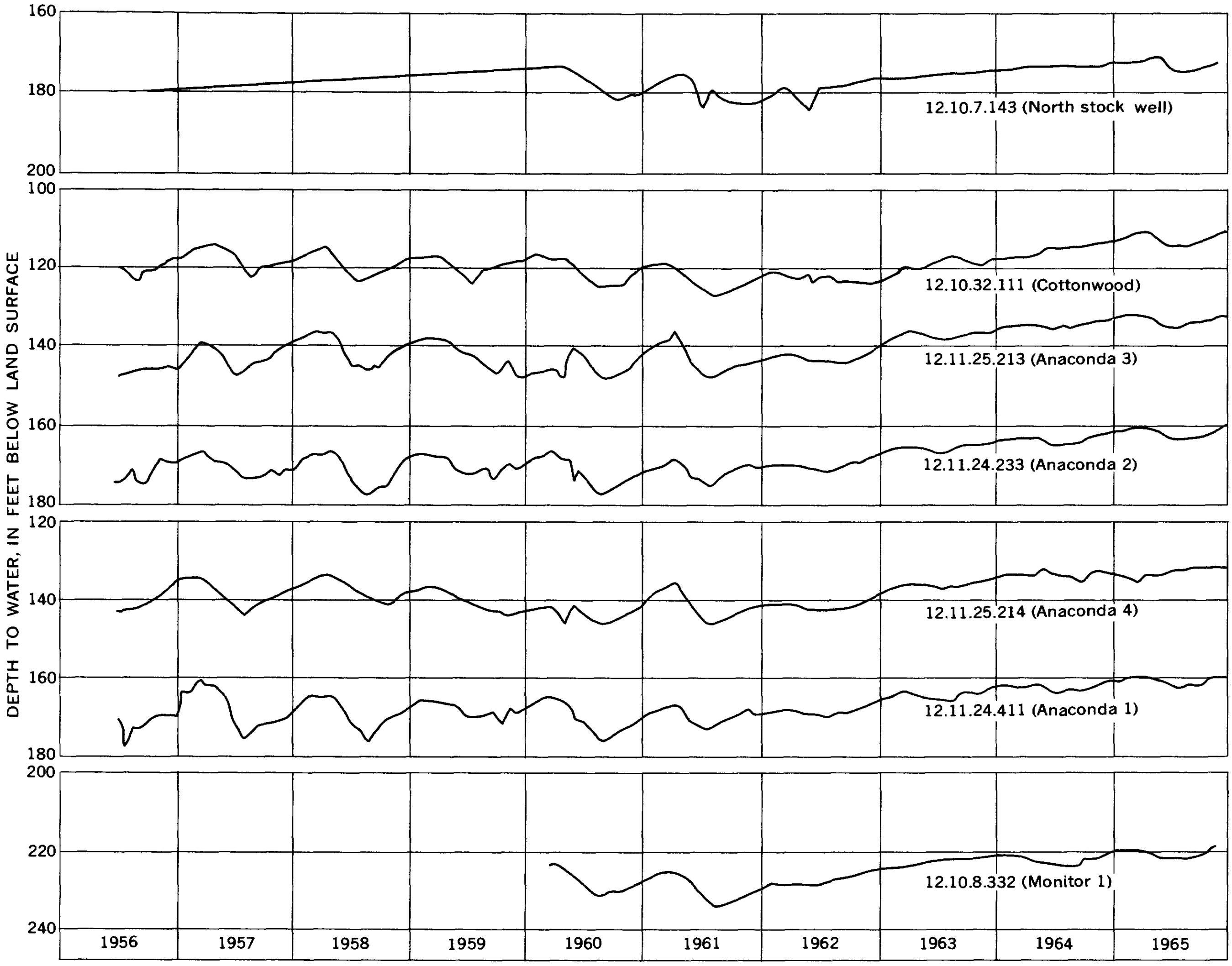

FIGURE 5. — Hydrograph of water levels in seven observation wells that tap the San Andres Limestone near The Anaconda Co. tailings pond and disposal well 1, 1956-65.

The changes in ion concentrations described above apparently are due to at least two factors. Kunkler (in Gordon, 1961, p. 63–74) stated that as a result of pumping in general, the quality of water from wells nearest the San Andres outcrop tends to improve, and the quality of water from wells farther from the outcrop tends to deteriorate. Sulfate is the ion that increases most as a result of pumping, and, in general, the concentration of sulfate in water in the San Andres Limestone is progressively higher away from the outcrops. Most of the wells described above are in the belt where pumping is expected to cause significant increases in sulfate and minor increases in sodium and chloride, such as in wells 12.10.27.431 and 12.10.35.322. Well 12.10.5.341a is about 3 miles from heavily pumped wells, and the quality of water in the well has not been affected by pumping. This well is in the belt of high-sulfate water, where the sulfate concentration ranges generally from a little less to a little more than 700 ppm. On the other hand, well 12.10.30.112 is nearer the outcrop, where the quality of water had remained consistently good even though pumping in the area has been heavy. Well 12.10.20.333a is in a marginal belt, where the concentration of sulfate in the water is affected significantly by pumping. The decrease in concentration of sulfate while sodium and chloride concentrations remained constant from 1962 to 1965 coincides with a decrease in pumping and a rise in ground-water levels. (See pl. 3.)

The increase in concentrations of all ions in water from wells 12.10.7.143 and 12.11.24.411 between 1956 and 1962 probably was caused by leakage from the tailings pond. The increase in sulfate may also have been affected by extensive pumping south and west of the tailings pond. The decrease in concentration of ions in water from well 12.11.24.411 from 1962 to 1965 coincided with decreased pumping and higher ground-water levels. Also, the level of water in the tailings pond was greatly reduced during this period.

The increase in concentrations of sodium, sulfate, and chloride in water from well 12.10.8.332 (monitor well 1) probably is related to mill effluent reaching the well either by downward leakage from the tailings pond or upward leakage from the Yeso Formation in the vicinity of the disposal well. The consistent upward trend in concentrations after the well was drilled (a little more than a month after the first injection test) suggests that leakage from the tailings pond had reached this site before well disposal of effluent began. The records indicate that pond leakage had reached other wells at nearly equal distances before 1960. Also, concentration of nitrate was 25 ppm before the 90-day injection test was completed.

HYDRAULIC CHARACTERISTICS OF THE AQUIFER AND PREDICTED PRESSURE INCREASES

Rates of injection, changes in rates of injection, and changes in water level in the injection well were analyzed to determine the hydraulic characteristics of the aquifer.

Owing to operational problems, hydrologic tests were made without having sufficient control for a constant injection rate and without allowing enough preinjection time for head to reach equilibrium in the aquifer. These test deficiencies resulted in data from which the apparent transmissivity of the aquifer could be computed only to the general magnitude of the true value. Evaluation of the storage coefficient is even less reliable than that of the transmissivity. Computing the storage coefficient by using data solely from the injection well could result in a large error. Data from an additional observation well would have been useful in computing this coefficient.

Apparent transmissivities during the pumping tests, during the 90-day injection test, and during subsequent operational injection are shown on plate 4. These data are summarized in table 8.

Data used to compute the apparent transmissivity were obtained during recovery of water levels after pumping tests, during injection, and during recovery after injection. The period of data varied widely — from a few hours to many days. Shorter periods were mostly in the early tests. In general, values obtained during early tests were higher than those obtained during later tests. These discrepancies may reflect existence of a hydraulic boundary, discontinuity of the aquifer, change in transmissivity and storage characteristics of the aquifer, or leakage to adjacent formations at a considerable distance from the injection well. However, boundary conditions are not readily apparent in the analysis of the hydraulic data. What might be interpreted in individual tests as boundary effects may be the residual effects of intermittent injection or of convergence of flow through fractures in the vicinity of the well.

The wide variation of transmissivities may be the result of improper evaluation and, in part, of insufficient data for the preinjection hydraulic conditions. The transmissivity probably is between 5,000 and 6,000 gpd per ft.

The storage coefficient of an aquifer generally cannot be determined accurately from a test of a single well. Because the disposal well is the only well in the area of injection influence that taps the Yeso aquifer, the storage coefficient (S) was estimated from data other than pumping or injection data. The following equation (Ferris and others, 1962, p. 88) and data were used:

$$S = \gamma_0 \, \theta m \left(\beta + \frac{\alpha}{\theta} \right)$$

where

γ_0 = specific weight of the water at a specified temperature (0.036 pounds per cubic inch),

θ = porosity of the aquifer (17 percent, from core analysis),

m = aquifer thickness, in inches (570 feet $\times$ 12 inches),

β = bulk modulus of compression of water (3.3×10^{-6} square inches per pound), and

α = bulk modulus of compression of the solid skeleton of the aquifer (assumed to be about 2.0×10^{-6} square inches per pound).

Thus,

$$S = (0.036)\,(0.17)\,(6{,}840)\left(3.3\times10^{-6} + \frac{2.0\times10^{-6}}{0.17}\right)$$
$$= 6.3\times10^{-4}.$$

The value of 2.0×10^{-6} square inches per pound for the compressibility of the aquifer skeleton could be in error, but the error would have to be large to change significantly the value for the storage coefficient.

Computations were made of the head increase, or negative drawdown, that should be expected at the aquifer face if the transmissivity (*T*) was 5,500 gpd per ft and the storage coefficient (*S*) was 6.3×10^{-4}. Figure 6 shows a graph of the predicted head increase for continuous 5-year injection at average rates of 100, 190, and 300 gpm at distances of 1 to 10,000 feet. The actual injection rate averaged 190 gpm, and for this injection rate, the head increase at a distance of 1 foot should have been 88 feet at the end of 5 years. Figure 4 shows that the predicted increase in pressure did not occur. The water surface in the well always declined to near the 250-foot level in a short time after injection, regardless of the length of the injection period. The fact that the head did not increase as predicted indicates that either the hydraulic characteristics of the aquifer were not evaluated correctly, water leaks to adjacent formations, the characteristics of the reservoir rock have been changed by solution, or aquifer damage near the well bore was not adequately evaluated.

TABLE 8.—*Summary of aquifer coefficients computed from pumping tests and injection data from The Anaconda Co. disposal well 1*

Period of data	Type of activity in period	Rate of pumping or injection applicable to computation (gpm)	Transmissivity (gpd per ft)
4-15 to 4-16-59	Recovery after pumping.	100	8,500
4-22 to 4-23-59	do	100	6,400
1-20 to 1-21-60	Injection	815	9,400
1-22 to 2-5-60	do	1,000	9,400
2-28 to 3-14-60	do	380	5,700
12-14-60 to 1-6-61	do	400	5,100
1-31 to 2-7-61	Recovery after injection.	400	5,400
6-18 to 6-27-61	do	400	5,400
5-15 to 5-27-62	do	225	5,700
1-23 to 2-9-63	Injection	390	7,600

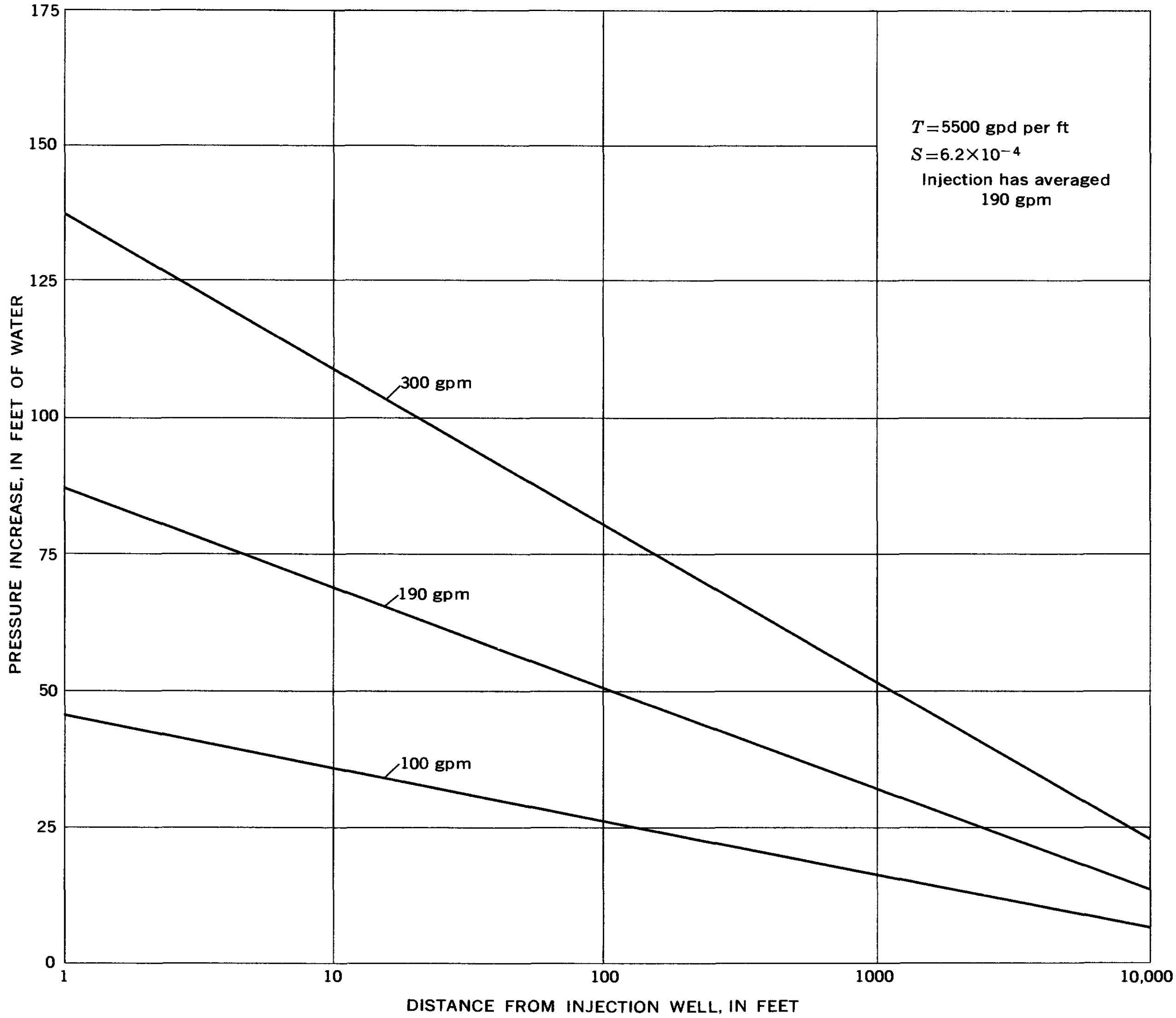

FIGURE 6.—Predicted increase in head within the disposal aquifer in the vicinity of The Anaconda Co. disposal well 1 at distances of 1 to 10,000 feet and at injection rates of 100, 190, and 300 gpm for 5 years.

Discrepancies in computed transmissivity show that the interpretation of hydraulic characteristics of the aquifer could easily be erroneous, but a fairly large increase in head should have been measured. Leakage of water upward to the Glorieta and the San Andres seemingly is not occurring in large quantities in the vicinity of the injection well. A well drilled into the Glorieta Sandstone and the San Andres Limestone 300 feet from the injection well shows no water-level fluctuations that can be attributed to leakage, large or small scale, of the fluids injected into the Yeso Formation. Because of prior contamination of the water by seepage from the tailings pond, chemical analyses of water from wells that tap the Glorieta and the San Andres cannot be used to determine the occurrence of leakage.

If water is leaking from the Yeso Formation into the Glorieta Sandstone and the San Andres Limestone, leakage may be moderately rapid through fracture systems a long distance from the injection well, or it may be very slow in a large area around the well and thus would not measurably affect water levels in the more permeable formations. No material is completely impermeable; therefore, an increase in head in the disposal aquifer has probably resulted in movement of some water from this aquifer into the overlying formations. The hydraulic gradient, prior to and during injection, was from the Yeso Formation toward the Glorieta and the San Andres. The altitude of the water level in a well tapping the Glorieta–San Andres aquifer (monitor well 1) at a point 300 feet from the injection well ranged seasonally from 6,445 to 6,452 feet as compared with the preinjection water level of 6,453 feet in the disposal well. However, addition of citric acid and injection water increased the specific gravity of the fluid column in the disposal well and lowered the water level 14 feet — 4 feet below the level in the nearby monitor well. Injection increased the head of the dense water in the Yeso above that in the San Andres, possibly causing upward leakage. After periods of injection, the residual head differential continued to favor upward leakage from the Yeso into the Glorieta and the San Andres.

The possibility that the acid injection fluid may have dissolved interstitial secondary minerals, thus changing the character of the reservoir rock, was investigated indirectly by Kim Ong of the U.S. Geological Survey, as described below. A synthetic test solution was prepared by dissolving salts of sulfate, chloride, and nitrate in the correct proportions to give concentrations of ions in the test solution within the range of those ionic concentrations in the injection water. (See table 6.) The pH of the synthetic solution was 2.4, and concentrations of principal ions, in milligrams per liter, were as follows:

Sodium	1,270	Potassium	76
Calcium	644	Chloride	1,749
Magnesium	563	Sulfate	7,900
Manganese	452	Nitrate	120
Iron	321		

Core samples from the Meseta Blanca Sandstone Member were pulverized, passed through a 125-micron screen, and uniformly mixed. The pulverized rock was dried at 180°C and divided into three test samples weighing about 5 grams each. Each sample was placed in 100 milliliters of the synthetic solution and allowed to stand for several days. The samples were stirred intermittently while in the solution. The undissolved rock material was separated from the solution by filtering through preweighed Gooch crucibles and was washed with demineralized water to remove all the synthetic solution containing the high concentration of salts. The undissolved rock samples were dried overnight at 180°C and then were weighed to determine the weight lost to the synthetic solution. Results of the experiment are summarized below; weights are given in grams.

Sample	1	2	3
Weight before treatment	3.0963	2.5775	3.0035
Weight after treatment	2.9369	2.4421	2.8463
Weight loss	.1594	.1354	.1572
Percent dissolved	5.15	5.25	5.23

The solubility experiment shows that a significant percentage of interstitial material in the sandstone aquifer could be dissolved by the injection water. However, the experiment does not show how much the porosity and permeability of the rock could be increased by such solution in the aquifer. Most of the sand grains in the aquifer are very fine to fine (table 2); thus, the interstitial openings would be small even without secondary minerals, and the permeability would not be greatly affected by solution of interstitial minerals. On the other hand, the porosity could be increased significantly by solution of interstitial minerals. If the specific gravity of the interstitial minerals (mostly calcite and gypsum) is near that of the quartz sand grains, the porosity of the rock possibly could be increased as much as 5 percent by solution.

If the porosity of the reservoir rock was increased by 5.2 percent of the rock volume, the coefficient of storage would be increased to 6.6×10^{-4}, in contrast to the 6.3×10^{-4} computed on the basis of a porosity of 17 percent. This change in the coefficient of storage would be effective only in the volume of rock invaded by the acid solutions, and it would have little effect on the computed head increase.

SUMMARY AND CONCLUSIONS

The geologic and hydrologic environment of The Anaconda Co. disposal well 1 is favorable for receipt of waste fluids. Several sandstone beds of variable thickness in the Yeso Formation of Permian age at depths of 950 to 1,423 feet have sufficient permeability to accept 200 to 400 gpm of water under gravity injection at the well head. The natural water in the injection interval contains about 3,900 ppm of dissolved solids, of which about 2,200 ppm is sulfate. The water is unsuitable for most uses without extensive demineralization. A thick interval of low-permeability siltstone, anhydrite, and gypsum in the upper part of the Yeso Formation separates the injection interval from the Glorieta Sandstone and San Andres Limestone of Permian age, the principal fresh-water aquifer in the vicinity of the tailings pond and the disposal well. Although the confining beds have been fractured by tectonic forces, most of the fractures have been sealed by deposition of gypsum.

Samples of cores from the disposal well were analyzed for porosity and permeability by Earlougher Engineering Co. A few computations of porosity were made from the micrology and the sonic log for comparison with each other and with the laboratory determinations of porosity. In general the correlation was good. The close correlation shows that geophysical-log interpretation can be a useful tool for estimating porosity in this type of geologic environment when core analysis is not feasible. The horizontal permeability and cumulative thickness of sandstone units between 926 and 1,818 feet indicate that the interstitial transmissivity of this interval should be about 1,100 gpd per ft.

The disposal well was completed by installing plastic-lined casing, cementing the annulus outside the casing, and gun perforating selected intervals primarily adjacent to the Meseta Blanca Sandstone Member of the Yeso Formation between 1,254 and 1,480 feet below zero datum. The prepumping water level was 237 feet below zero datum. After completion, the well was test pumped on April 15–16, 1959, at a rate of 100 gpm for 18 hours. Beginning April 16, the well was test pumped at a rate of 100 gpm for 148.5 hours. Apparent transmissivities (6,400–8,500 gpd per ft) computed from the drawdown and from recovery tests indicated that the formation should accept water at a rate of a few hundred gallons per minute. However, the test data indicated that the aquifer was damaged near the well bore by infiltration of drilling mud and cement and that the effects of this damage would be a greater limiting factor during injection then would the hydraulic properties of the aquifer. The casing was then perforated adjacent to several beds of sandstone above and below the Meseta Blanca Sandstone Member, and the rocks opposite all the perforated intervals were fractured hydraulically to establish better connection between the well bore and the natural fractures in the aquifer.

A 90-day injection test was started January 20, 1960. Injection was preceded by conditioning the well and the adjacent aquifer with 9,000 pounds of citric acid crystals to prevent precipitation of iron in the vicinity of the well bore. The higher density of the citric acid solution and mill effluent lowered the water level in the well bore to 251 feet below zero datum. Injection was intermittent, and injection rates ranged from 380 to 1,300 gpm. The specific capacity of the well during injection ranged from 3.6 to 3.8 gpm per foot of water-level rise. A few times the well overflowed. The large increase in specific capacity over the values obtained during pumping tests (from 0.12 to 3.6 or more gpm per foot of water-level change) indicates that hydraulic fracturing established much better connection between the well and natural fractures in the aquifer. The values for apparent transmissivity calculated from data collected during the test period ranged from 5,700 to 9.400 gpd per ft. Transmissivity computed from injection tests was higher than that computed from laboratory analyses of core samples. This fact and the close agreement of computed transmissivity before and after hydraulic fracturing indicate that permeability is controlled primarily by natural fractures in the aquifer.

Operational injection began December 14, 1960. The rate of injection varied considerably but ranged generally from 200 to 400 gpm. Water level in the disposal well during injection rose to within 10 feet of land surface. Injection had to be interrupted many times because of mechanical difficulties, necessity of cleaning the well, turbidity of water in the tailings pond, or too low a level of water in the pond. By the end of December 1965, 500 million gallons of water had been injected into the Yeso Formation. Each time injection was stopped for several days, the water level in the injection well returned to near the preinjection level.

The Anaconda Co. has monitored water levels in seven wells near the tailings pond and the disposal well. Seasonal fluctuations of 5 to 10 feet in response to irrigation pumping were typical through 1961. The water levels rose almost continuously, with only slight seasonal fluctuations, in all the wells from fall of 1961 through 1965, owing to a large reduction in irrigation pumpage.

The chemical and radiochemical quality of water has been monitored by The Anaconda Co. monthly in 20 wells, bimonthly in 25 wells and springs, and semiannually in two wells. Concentrations of sodium, sulfate, chloride, and nitrate have increased significantly in water from wells that tap the San Andres Limestone in the vicinity of the tailings pond and the disposal well. The upward trend in concentrations began before the disposal well was drilled, because of leakage from the tailings pond. This contamination of water in the San Andres probably will mask any contamination from the disposal well, even if water leaks from the disposal aquifer into the San Andres.

The transmissivity of the injection interval was computed for each long period of consistent injection or recovery after injection. The transmissivities obtained from all tests (including preinjection pumping tests) ranged from 5,100 to 9,400 gpd per ft. The transmissivity probably is between 5,000 and 6,000 gpd per ft. The coefficient of storage was computed to be 6.3×10^{-4}. Computations were made of theoretical head increase in the aquifer, assuming $T=5{,}500$ gpd per ft, $S=6.3\times10^{-4}$, and injection rate $Q=190$ gpm (the average rate for the entire period of injection). The head increase at a distance of 1 foot should have been 88 feet at the end of 5 years. The actual increase was about 5 feet following a short recovery period after injection ceased temporarily at the end of 5 years of operation. The fact that the head did not increase as predicted indicates that (1) the hydraulic characteristics of the aquifer were not evaluated correctly, (2) water leaks to other formations, (3) the characteristics of the reservoir rock have been changed by solution, or (4) aquifer damage near the well bore was not adequately evaluated.

Leakage of water upward into the Glorieta Sandstone and the San Andres Limestone has not been detected, but the effects of upward leakage could be masked by fluctuations of water levels caused by pumping in the general area of the disposal well and by prior contamination of water in the San Andres by leakage of mill effluent from the tailings pond. However, during periods of injection, the head differential has favored upward leakage of water from the Yeso into the Glorieta and the San Andres. Solubility experiments using cores from the injection interval and a synthetic solution comparable in composition to the mill effluent show that the porosity of the rock possibly could be increased as much as 5 percent by solution of interstitial minerals in the sandstone. However, this amount of solution would change only slightly the coefficient of storage and the predicted increase of head.

Data obtained so far do not show conclusively whether or not the injected effluent is being confined to the injection interval in the lower part of the Yeso Formation. The insignificant rise of water level in the injection well suggests that water is leaking from the Yeso Formation into the Glorieta and San Andres. However, the injected effluent is denser than the natural formation water, so the injected water would tend to displace the natural formation water upward, as well as laterally. If water is leaking from the Yeso into the Glorieta and the San Andres, it could be natural formation water leaking through fractures at considerable distances from the injection well.

Chemical analyses of water from wells near the tailings pond show a definite improvement in water quality since well disposal began to reduce the amount of effluent stored in the tailings pond. Even at monitor well 1, where the concentration of sulfate and chloride has continually increased, the rate of increase has declined since mid-1962.

When all the data are considered, well injection of the mill effluent appears to be the most satisfactory method of effluent disposal that is economically feasible. Ultimate effects are not predicted in this report.

SELECTED REFERENCES

Cooper, J. B., and John, E. C., 1968, Geology and ground-water occurrence in southeastern McKinley County, New Mexico: New Mexico State Engineer Tech. Rept. 35, 108 p.

Ferris, J. G., Knowles, D. B., Brown, R. H., and Stallman, R. W., 1962, Theory of aquifer tests: U.S. Geol. Survey Water-Supply Paper 1536–E, p. 69–174.

Gordon, E. D., 1961, Geology and ground-water resources of the Grants-Bluewater area, Valencia County, New Mexico, *with a section on* Aquifer characteristics, by H. L. Reeder, *and with a section on* Chemical quality of the ground water, by J. L. Kunkler: New Mexico State Engineer Tech. Rept. 20, 109 p.

Lynn, R. D., and Arlin, Z. E., 1962, Deep well construction for the disposal of uranium mill tailing water by The Anaconda Co. at Grants, N. Mex.: Am. Inst. Mining Metall. Petroleum Engineers Trans., Mining Engineers, v. 223, no. 3, p. 230–237.

West, S. W., 1961, Disposal of uranium mill effluent near Grants, New Mexico, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–D, p. 376–379.

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