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Borehole (Slurry) Mining of Coal, Uraniferous Sandstone, Oil Sands, and Phosphate Ore

By George A. Savanick

UNITED STATES DEPARTMENT OF THE INTERIOR

Report of Investigations 9101

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

acre/yr	acre per year
bbl/st	barrel per short ton
cm	centimeter
deg	degree
$/bbl	dollar per barrel
$/ft	dollar per foot
ft	foot
gal	gallon
gpm	gallon per minute
h	hour
hp	horsepower
in	inch
in/s	inch per second
lbf/ft^3	pound (force) per cubic foot
lbf/in^2	pound (force) per square inch
mg/L	milligram per liter
µg/L	microgram per liter
µm/L	micrometer per liter
µS/cm	microsiemens per centimeter
pCi/L	picocurie per liter
pct	percent
pct/yr	percent per year
rpm	revolution per minute
st	short ton
std ft^3/min	standard cubic foot per minute
st/d	short ton per day
st/h	short ton per hour
st/yr	short ton per year
10^3bbl	thousand barrels
$10^3$$	thousand dollars
10^3st	thousand short tons
10^3st/yr	thousand short tons per year
vol pct	volume percent
wt pct	weight percent
yd^3/min	cubic yard per minute
yr	year

BOREHOLE (SLURRY) MINING OF COAL, URANIFEROUS SANDSTONE, OIL SANDS, AND PHOSPHATE ORE

By George A. Savanick[1]

ABSTRACT

This paper reviews advances in the art of borehole (slurry) mining made by the Bureau of Mines from 1974 to 1980. The design of a prototype borehole-mining tool (BMT) developed by the Bureau of Mines is presented along with production data, reclamation data, and an application of the BMT to the mining of coal, uraniferous sandstone, oil sands, and phosphate ore.

The BMT was first used near Wilkeson, WA, where steeply pitching metallurgical coal was mined at 8 st/h from a depth of 25 to 75 ft. Next, 940 st of uraniferous sandstone was mined at 8 st/h from a depth of 75 to 100 ft in Natrona County, WY. One thousand short tons of oil sands was mined in Kern County, CA, at the rate of 14 st/h from a depth of 110 to 150 ft in 1979. Most recently, 1,700 st of phosphate ore was produced at 25 st/h from deep (230- to 250-ft) deposits in St. Johns County, FL.

Progressive improvements were made in the borehole mining technique. These include the use of the hydrostatic head of a water-filled borehole for roof support, and the development of methods to survey and backfill mined-out cavities.

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INTRODUCTION

Borehole mining, also known as slurry mining, is a process in which a tool incorporating a water-jet cutting system and a downhole slurry pumping system are used to mine minerals through a single borehole drilled from the surface to the buried mineralized rock. Water jets from the mining tool erode the ore to form a slurry. The slurry flows into the inlet of a pump at the base of the tool. The material is lifted to the surface in a form suitable for pipeline transfer to a mill or processing plant.

Borehole mining, as defined by this paper, appears to be a likely prospect for the near future. It offers a number of important advantages over conventional open pit and underground mining methods, and it can access mineral deposits that presently are not mined because of technical or economic difficulties. This method can achieve essentially immediate production because there is no need to drive openings to and in a proved ore body to prepare it for mining; in contrast, conventional mining methods require from 3 to 5 yr before production and return on investment can be expected. The fragmentation and transportation systems are incorporated into a single machine that is remotely operated from the surface by a two- or three-person crew, thus eliminating health and safety problems inherent to underground mining. The environmental disturbance is minimal and short term; no overburden is removed, an subsidence can be avoided. Ore fragmented by the water jet is brought to the surface in slurry form and thus is ideally suited for low-cost pipeline transport. Borehole mining is selective and can extract deposits that are small or erratically mineralized, thereby broadening the resource base. This selectivity allows the ore to be extracted without disturbing the country rock, thereby avoiding dilution and yielding a clean product. Crushing and grinding costs would be minimal since the ore is reduced to grain size by the jet stream. The slurries would be an ideal feed for onsite milling operations. Tailings from the processing plant operations could be pumped into the mined-out caverns to control subsidence and reduce waste disposal problems.

This report presents the results of the Bureau of Mines borehole mining research conducted from 1974 to 1980. The report first discusses BMT's developed and tested prior to the development of the Bureau of Mines BMT. Then the design of the Bureau of Mines BMT is described. Results of field experiments follow with separate sections on the mining of coal, uraniferous sandstone, oil sands, and phosphate ore. The report presents a discussion of reclamation of borehole-mined land, including a description of cavity surveying and backfilling methods. The report concludes with a discussion of the economics of borehole mining of phosphate, uranium ore and oil sands.

BOREHOLE-MINING TOOLS

The earliest patent for a tool that used a water jet to fragment rock adjacent to a borehole and a downhole slurry pump to lift the broken ore to the surface was issued to Clayton in 1932 (1).[2] Patents on similar BMT's were issued to Aston in 1950 (2), Quick in 1955 (3), Fly in 1964 (4), Pfefferle in 1969 (5), Wennenborg in 1973 (6), Archibald in 1974 (7), and Brunelle in 1977 (8). Fly's apparatus (9) was built and used to excavate sandstones, limestones, and shales to a maximum depth of 350 ft. Mining rates of 1 yd^3/min were achieved,

[2]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

and cavities were excavated to a lateral distance of 30 ft from the borehole. The apparatus had two sidewall nozzles operated at 800 lbf/in^2 and 400 gpm to form the water jets. The slurry was caused to flow into the intake of a downhole jet pump which hoisted it to the surface. The jet pump was operated at about 800 lbf/in^2 and 500 gpm. Jets were also formed by forcing water through the water courses of a tricone rock bit attached to the base of the tool. These jets kept the slurry in suspension so that it could be taken into the downhole slurry pump. This tool used a single, pressurized water supply to operate the sidewall jets, the pump, and the tricone jets.

The apparatus described in the Wennenborg patent was built by FMC Corp. and tested in phosphate ore in eastern North Carolina. This device uses a high-volume, low-pressure water jet to slurrify the ore and an eductor to lift the slurry to the surface. Its most novel aspect is that it provides a method for drilling into, as well as mining, a deposit of granular ore. All previous BMT's required a predrilled, cased borehole. The Wennenborg device is designed for mining unconsolidated, easily drilled sediments, such as North Carolina phosphates.

The apparatus described in the Archibald patent was built by Marconaflo, Inc. (10), and used to mine uraniferous sandstones and tar sands on an experimental basis. The jet-cutting unit consists of a single nozzle and high-pressure piping that rides on a vertical rail attached to the main body of the device. This rail allows the nozzle to move independently of the slurry pump; the nozzle could be slid up and down as well as rotated 180° about a vertical axis. The vertical motion allows cutting to occur at various horizons without lifting or dropping the entire device, and it lets the intake of the slurry pump to be cleared of blockages by the cutting jet. The cutting jet is operated at 400 to 500 lbf/in^2 and 150 to 170 gpm.

The slurry-pumping system contains a pump mechanically driven from the surface and 20-ft-long sections containing a drive shaft and slurry conduits. The device operated in a 30-in-diam borehole and produced 30- to 45-pct solids in the slurry. It was tested successfully by mining a uraniferous sandstone from a roll-front deposit in the Gas Hills of Wyoming from a depth of 180 ft and by mining tar sands from a depth of 350 ft in the McKittrick oilfield near Bakersfield, CA.

BUREAU OF MINES BOREHOLE-MINING SYSTEM

The Bureau of Mines contracted with Flow Industries, Inc., to design, fabricate, and test a new and unique BMT in 1974 (12). The Bureau of Mines BMT has an eductor for a downhole slurry pump, whereas mechanically driven slurry pumps were used in the Marconaflo equipment. It contained separate conduits for the eductor drive water and the cutting jet water, whereas the FMC and the Fly systems used a single conduit.

The Bureau's system, shown schematically in figure 1, is composed of the BMT suspended from a crane in a 16-in-diam cased borehole. The BMT generates a high-velocity water jet that erodes and slurrifies ores. The slurry is drawn into the inlet of an eductor and lifted to the surface where it is metered and deposited into a slurry discharge tank (fig. 2). The ore settles in the tank while the water overflows into a pond, which is the source of water for pumps that supply the cutting jet and the eductor.

The BMT, which is operated while suspended from a crane (fig. 3), is in the form of a 12-in-diam cylinder capped with a three-passage swivel. The cylinder is composed of a kelly section, a series of standard sections, and a mining section.

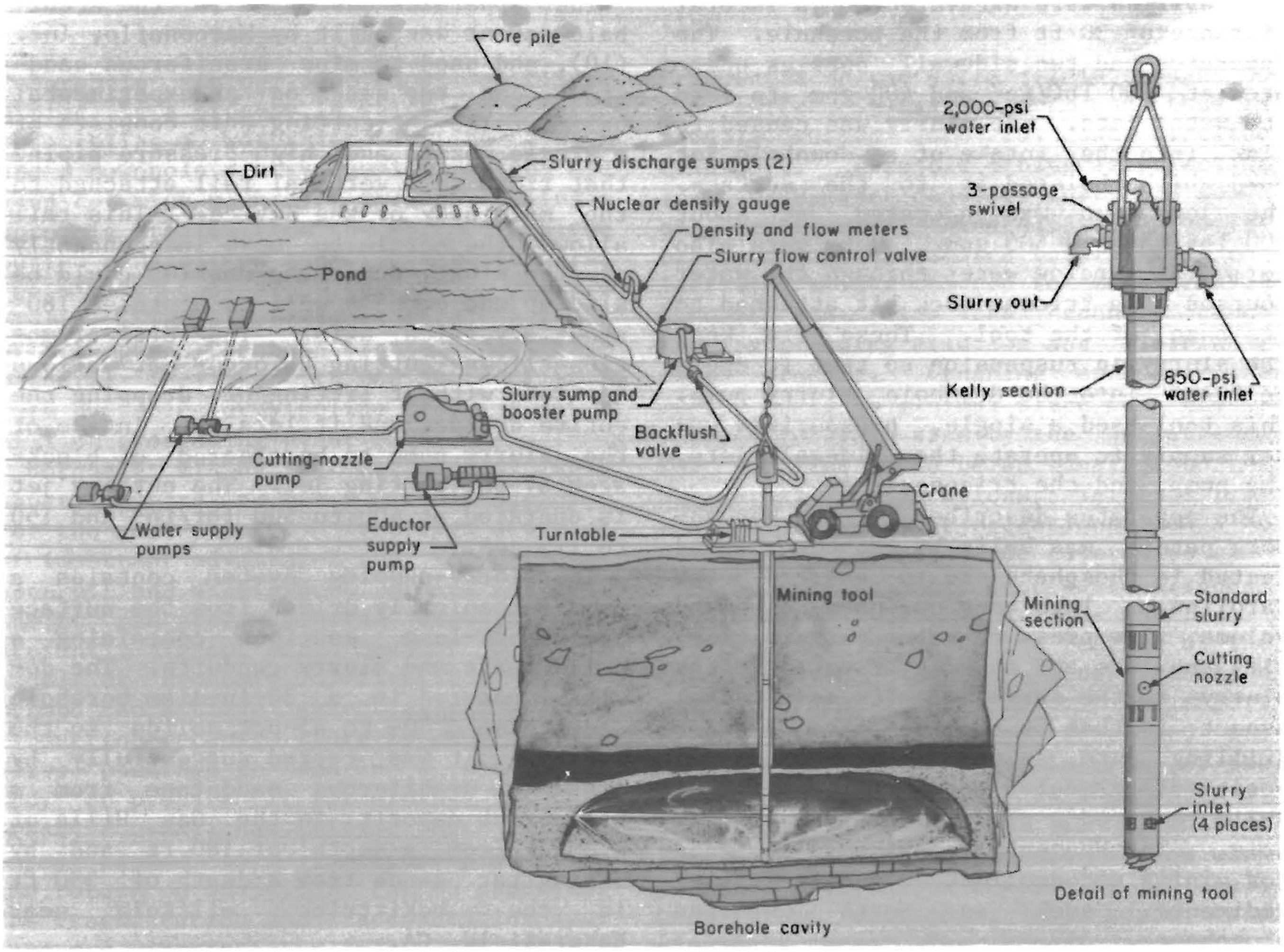

FIGURE 1.—Bureau of Mines borehole-mining system.

The cutaway view of the three-passage swivel is shown in figure 4. The outer part is stationary and is supported by a crane. The swivel core rotates relative to the exterior while simultaneously passing the three pressurized streams: the water supply to the cutting nozzle, the drive water to the eductor pump, and the slurry output. The swivel is connected to a kelly section by eight bolts. The kelly section is a cylinder 22 ft long and 12-in in diameter with two 0.75-in webs welded along its length. The webs key into a rotary turntable, thereby transmitting torque to the BMT. This turntable is driven by hydraulic motor and governed by a hydraulic controls and limit switches, which allows for rotary speeds of 0 to 20 rpm and for automatic oscillation for any interval from 0° to 360°.

FIGURE 2.—Slurry discharge.

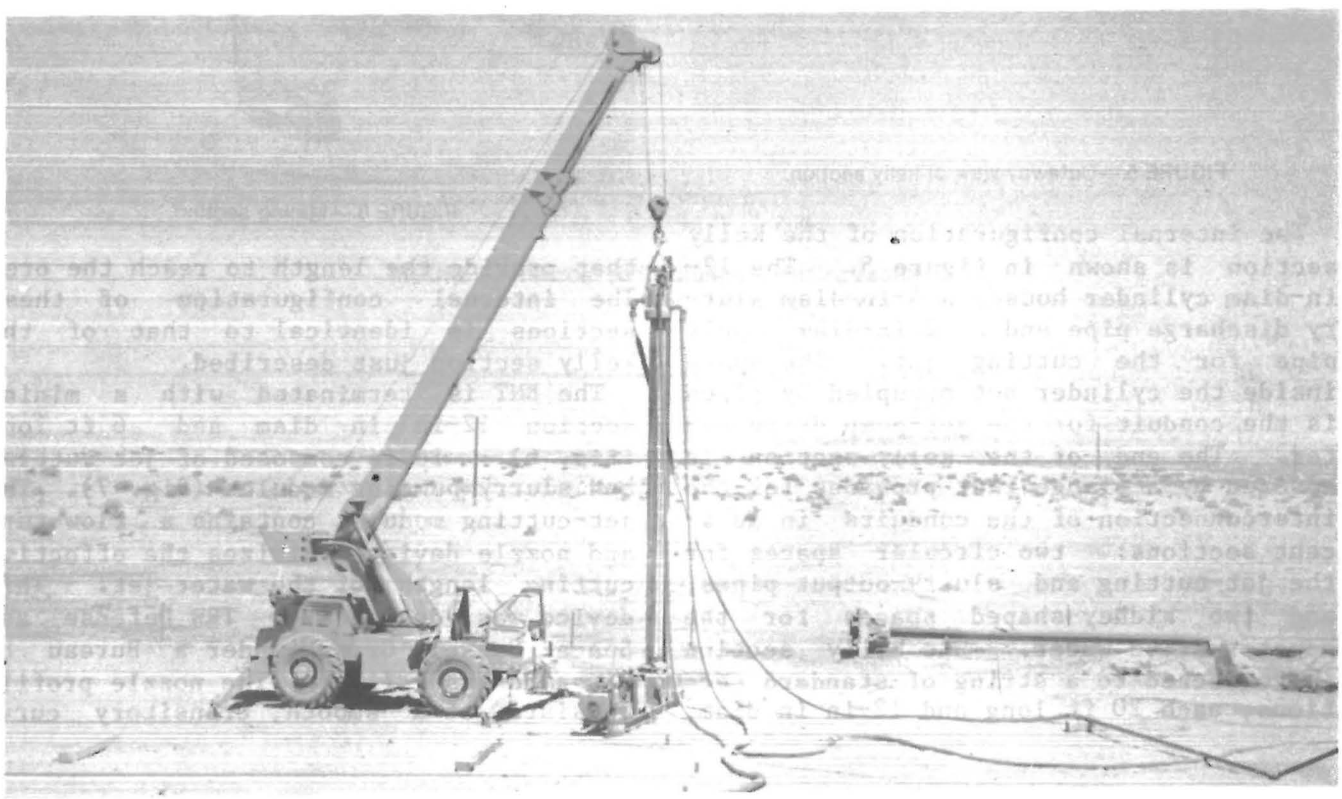

FIGURE 3.—Borehole mining tool suspended from crane.

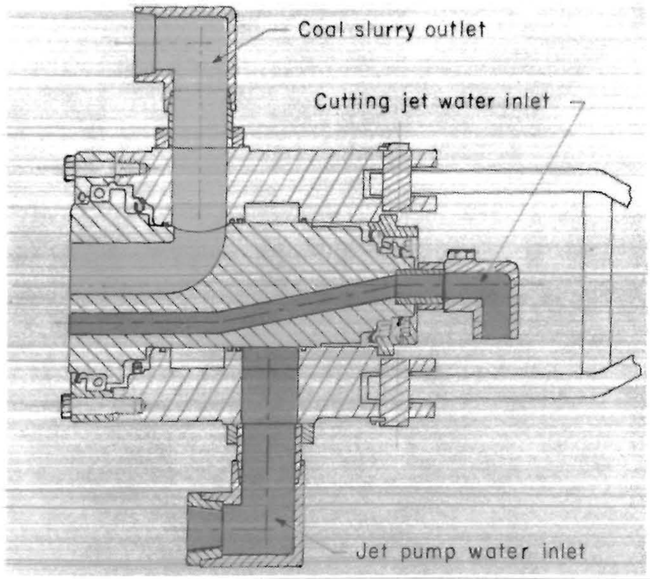

FIGURE 4.—Cutaway view of three-passage swivel.

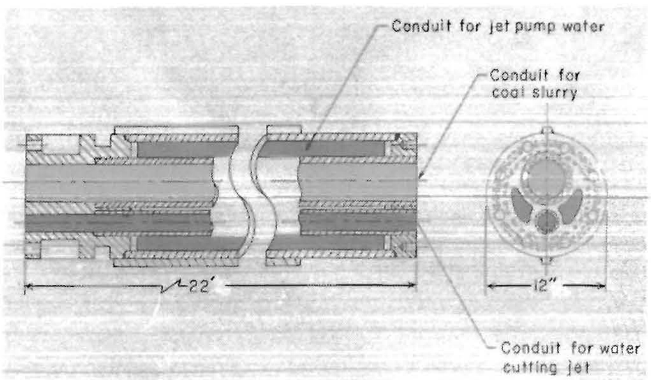

FIGURE 5.—Cutaway view of kelly section.

The internal configuration of the kelly section is shown in figure 5. The 12-in-diam cylinder houses a 4-in-diam slurry discharge pipe and a 2-in-diam supply pipe for the cutting jet. The space inside the cylinder not occupied by pipes is the conduit for the jet-pump drive water. The end of the kelly section is covered by a flange that provides for the interconnection of the conduits in adjacent sections: two circular spaces for the jet-cutting and slurry-output pipes, and two kidney-shaped spaces for the eductor drive water. The kelly section is connected to a string of standard sections, each 20 ft long and 12-in in diam,

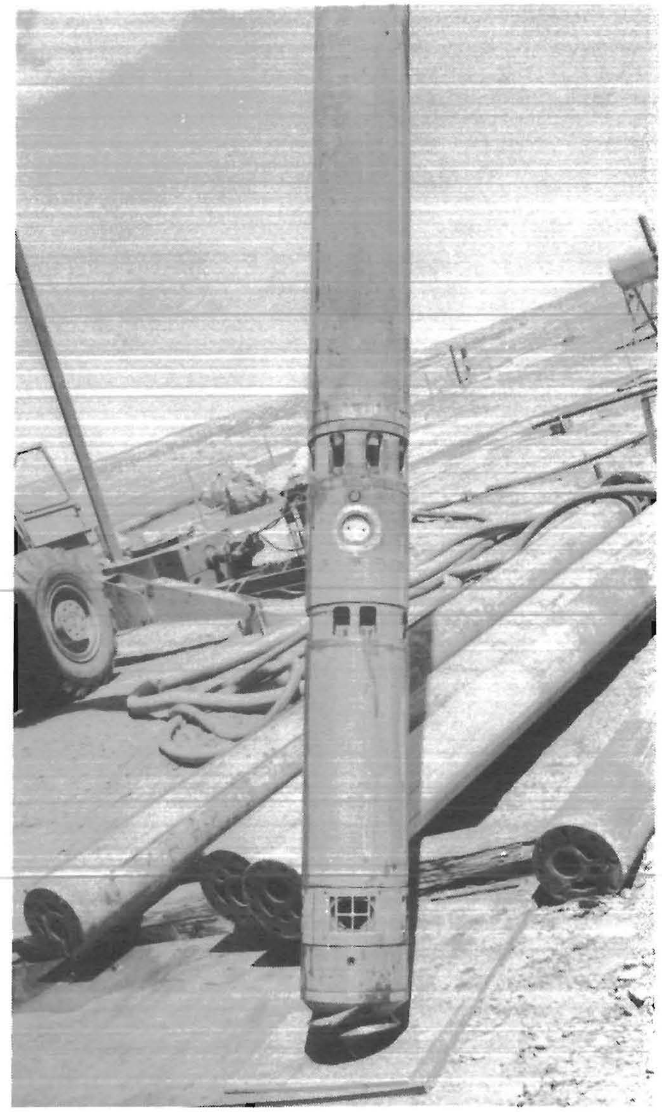

FIGURE 6.—Mining section.

that provide the length to reach the ore. The internal configuration of these sections is identical to that of the kelly section just described.

The BMT is terminated with a mining section 12-in in diam and 6 ft long (fig. 6). It is composed of jet-cutting and slurry-pumping modules (fig. 7). The jet-cutting module contains a flow-turn and nozzle device maximizes the effective cutting length of the water jet. This device was designed by TRW Defense and Space System Group under a Bureau of Mines contract (11). The nozzle profile consists of a smooth, transitory curve

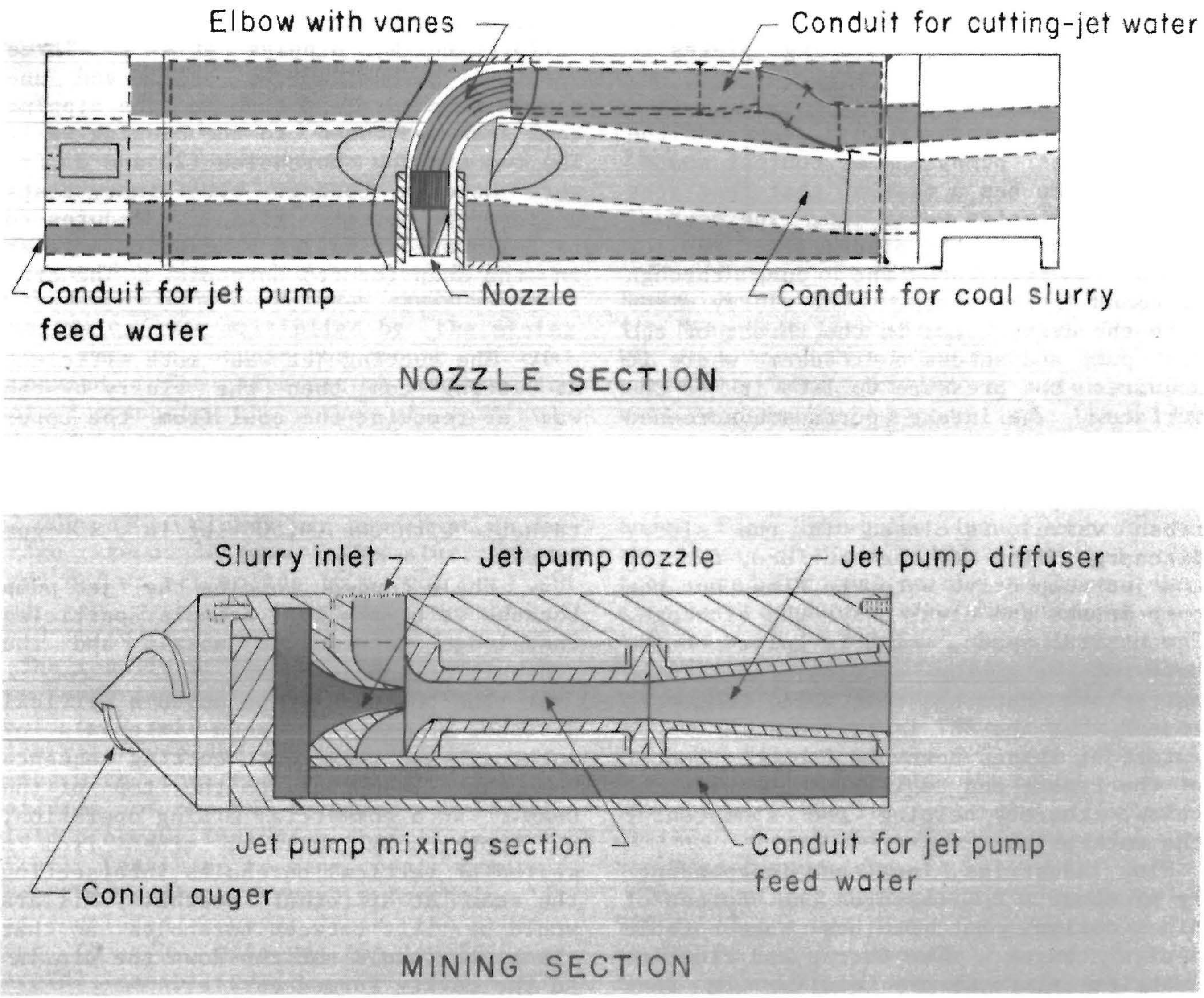

FIGURE 7.—Internal configuration of mining section.

from nozzle entrance to the outlet orifice. Upstream of the nozzle is a short-turn elbow with flow-splitting plates to guide the flow around the elbow with reduced flow disturbances.

The slurry-pumping module contains the eductor (jet pump) and a conical spade. The jet pump has a nozzle that generates the high-velocity water jet. The venturi effect caused by the discharge of the jet draws slurry into the pump through screened intake ports. The slurry mixes with the drive water in the throat of the jet pump and enters a diffuser where it acquires the pressure to lift it to the surface. The intake ports are screened to prevent oversize material from blocking the pump. Should the material block the inlet, a fast-acting valve ("backflush" valve), is closed in the slurry discharge line at the surface, forcing the jet-pump drive water to flow out the pump intake and clear away the blockage. The conical spade, which is bolted to the base of the mining section, facilitates entry into cuttings that fill the void caused when the BMT is raised. A 50-gpm water jet issues downward from the center of the spade and agitates the cuttings below, thereby helping the spade enter the muck pile.

Flow Industries, Inc., had independently produced a BMT based on the Bureau of Mines design, but it has some notable design changes. The Bureau and Flow Industries products are similar in that both are composed of 20-ft lengths of 12.75-in-diam cylinders connected by flanges, and the slurry pumps have the same design. They differ in that the cutting nozzle of the Flow Industries product is controlled independently from the remainder of the tool, similar to the Marconaflo BMT. This permits water-jet cutting to be performed anywhere along the length of the borehole while the pump is low in the sump, where the slurry density is highest.

COAL MINING

Flow Industries, under a Bureau of Mines contract (12), conducted borehole mining operations in 1975-76 at a site 3 miles south of Wilkeson, WA. This site contained a seam of bituminous coal 17.75-ft thick, dipping at 42°. Three vertical boreholes (two shallow and one deep) were drilled through the dipping coal seam and cased to the hanging wall. The two shallow boreholes (25 and 35 ft) were used to conduct preliminary tests designed to optimize mining procedures to be followed during a 4-h production test in the deep (88 ft) borehole. The preliminary tests results were as follows:

1. The cutting jet was more efficient at cutting coal then the slurry system was at removing the coal from the borehole. Thus, the maximum mining rate was limited by the slurry-pumping rate.
2. A cutting radius of 10 ft was attainable with the 4,500-lbf/in^2, 100-gpm jets.
3. Shale tended to clog the jet pump because it breaks into acicular particles that lodge between the nozzle and the sidewall of the jet pump.
4. The tool had to be moved a vertical distance of 1 ft between intervals of cutting, and the best cutting sequence was from the bottom to the top of the seam. In a commercial mining operation, a dipping seam would be mined from a series of vertical boreholes intersecting the seam at different depths. Pillars would be left between boreholes so that the slurry would not run down the dip into the cavity formed earlier.
5. The best traverse rate of the water jet across the coal face was 4 to 6 in/s.

A production rate test was conducted in the deep borehole, which was lined with 16-in steel casing. The parameters of the cutting jet were similar to those used in the preliminary test except that a single, high-discharge jet (4,500 lbf/in^2, 200 gpm) was used to increase the effective cutting range to 15 ft. Two methods of measuring the production were employed. In one, a density meter was placed in the slurry output line in series with a flow meter, and the output of the two was recorded electronically. The mining rate was obtained by

TABLE 1. - Summary of 4-h coal mining test with 520-hp water jet

Measurement	Quantity, st	Average rate, st/h
Slurry density meter......	33.2	8.3
Volume collected:		
Intermediate pools......	25.2	6.4
Settling pond...........	6.3	1.6
Total................	31.5	8.0

integrating the product of the flow rate and the slurry density measurements. That value was multiplied by the mining time rate to obtain the amount of coal produced. The alternative method involved measuring the volume of coal collected in two portable swimming pools and in a settling pond into which the slurry was discharged. During this test, 92,600 gal of slurry was pumped at an average rate of 386 gpm. The slurry averaged 8.7 wt pct solids (6.4 vol pct) and had an average specific weight of 64.0 lb/ft^3.

The results of the 4-h production test are summarized in table 1, which shows that both methods of estimating production rate yielded 8 st/h. This rate, along with the fact that no mechanical failures of the BMT occurred during the field program, indicates that it is technically feasible to mine coal remotely from the surface through a borehole. It was concluded, however, that the production (8 st/h) rate was too low for commercial feasibility.

URANIUM MINING

The successful coal mining experience led to the application of borehole technology to mining uraniferous sandstones. Uranium sands are considered to be a likely prospect for borehole mining because (1) the ore has a high unit value, (2) the sandstones can be cut by low-pressure (1,000- to 3,000-lbf/in^2) water jets, and (3) many deposits are shallow, small, irregularly shaped, and isolated; these deposits cannot be mined by conventional methods, but are amenable to the selective capabilities of the borehole system.

The Bureau of Mines cooperated with Rocky Mountain Energy Corp. (RME), at its Nine-Mile Lake site, Natrona County, WY, in a borehole-mining test. RME prepared the site, drilled a water supply well, constructed a pond and lined it with polyethylene, and drilled three 16-in-ID cased boreholes to a depth of 100 ft into the Teapot sandstone ore body. Flow Industries, under contract to the Bureau of Mines (13), modified the tool used for coal at the Wilkeson, WA, site and conducted the sandstone mining operations. A shallow deposit at Nine-Mile Lake was chosen for the test because the slurry pump is limited to differential lifts of 200 ft. The modifications included fitting of the BMT with a turning vane-nozzle ensemble designed to pass 300 gpm at 2,000 lbf/in^2, the flow conditions chosen for efficient erosion of the Teapot sandstone.

During mining operations, approximately 940 st of ore was mined from depths of 75 to 100 ft at an average rate of 8 st/h from standoff distances as great as 25 ft. Slurry densities ranged from 0 to 46 wt pct with an average of 700 determinations being 7.2 wt pct. The tests also showed the following:

1. The average jet-cutting rate was about 16 st/h at 520 hp. The slurry pump normally works at a lower rate because the tool moves vertically as one piece, thereby lifting the pump out of the slurry sump during part of the mining cycle. The mining rate could be made equal to the jet cutting rate if the cutting jet could be moved independently from the slurry pump.

2. The optimum jet-cutting traverse rate across the sandstone was between 40 and 80 in/s.

3. The jet-cutting rate was proportional to the horsepower of the cutting jet.

A photographic survey of the borehole cavities created in the Teapot sandstone ore body was taken using equipment developed for the purpose by the Bureau of Mines. Figure 8 shows the cavity created in one of the boreholes at Nine-Mile Lake. The white, 2-in-diam PVC pipes in the foreground are placed in monitor holes drilled 10 and 20 ft from the center of the borehole. A 1-in-diam steel pipe 25 ft from the borehole is shown in the background. This photographic survey showed that roof failure was confined to a 7-ft radius from the center of the borehole. Presumably, this indicates that the rock within this radius was damaged during drilling.

FIGURE 8.—Cavity produced during borehole mining.

OIL-SAND MINING

The possibility of mining oil in the 383 known shallow oilfields (14) in the United States has become a matter of interest because of the energy crisis of the 1970's. Oil could be produced from these shallow fields by surface mining methods. However, open pit mining of oil sands could be expected to meet with environmental objections including the following: (1) disruption of the surface, (2) increased air pollution from volatile hydrocarbons uncovered in the open pit, (3) accumulation of waste rock piles, (4) accumulation of tailings, (5) damage to groundwater quality, and (6) surface water pollution.

Borehole mining offers an alternative method for mining the oil sands with minimal disturbance to the environment because no overburden is removed, no waste rock piles are generated, tailings can be backfilled into the borehole cavity, no surface streams are polluted because a closed-loop water system is employed, and surface subsidence can be avoided by backfilling the mined cavities. Borehole mining appears to be more acceptable on an environmental basis than does surface mining.

In 1979, the Bureau of Mines and Flow Industries demonstrated the technical, economic, and environmental feasibility of hydraulic bore-hole mining of shallow oil sands (15). Flow Industries performed this work on a site in Kern County, near Taft, CA, in the Midway Sunset Oil Field. This test demonstrated that the borehole mining technique was an environmentally compatible method for mining oil sands. The experiment measured production rate along with the environmental impacts.

Mining was conducted from July 25 to August 24, 1979. During the operation, 994 st of oil sands was extracted from two holes. The mining rate ranged from 0 to 45 st/h (table 2) with an overall average 14 st/h. Typical operating parameters are listed in table 3. A range of values is given when the parameter varied significantly.

One major complication was encountered during the operation. The borehole became filled with rocks that accumulated at the base of the mining tool because they were prevented from entering the slurry pump by a screen over the inlet. The BMT was unable to penetrate this pile of rocks. Mining had to be terminated in each borehole when the pile got so high that the jet could not be lowered below the casing (110 ft). The addition of a crusher to the mining tool would prevent the rocks from obstructing the BMT.

The water used was sampled before mining began and on seven occasions while it was in progress. Table 4 summarizes these analyses. It appears that no significant chemical changes occurred, but the data are inconclusive.

It is difficult to draw any conclusions regarding the dissolution of solids because of chemical variations introduced by adding makeup water during the mining process. The incoming source water was waste brine from nearby oil wells and could be expected to vary with the number and type of oil recovery operation occurring.

In order to monitor the possible escape of water from the mining operation, two monitoring wells were drilled 50 ft in the direction of groundwater flow (southeast) of the boreholes. These wells were drilled to intersect potential aquifer sands at depths of 150 and 550 ft. Both sands were above the local groundwater level. Periodic sampling of these dry wells indicated that no water entered these sands during the mining process. From this, it is inferred that no mining water escaped radially from the mining cavity; although it may have percolated vertically beneath the cavity. Vertical percolation is definitely possible because the mining cavity, although 110 to 150-ft deep, was above the water table. Percolation could have been checked by drilling monitoring wells which were deviated under the cavity, but the equipment for such drilling was not available.

Ground subsidence is possible in borehole mining operations. To evaluate it, a series of surveys collected information on changes in ground elevation at the site. Surveys were performed to obtain baseline elevations before mining, weekly during the project, and 30 days after the mining stopped.

Table 2. - Summary of oil-sand mining operations, Kern County, CA

(Duration: 70.05 h; production: 993.50 st; average mining rate: 14.2 st/h)

Date,	1979	Time, h	Sand in tank, st	Tank	Mining rate, st/h	Depth, ft	Date,	1979	Time, h	Sand in tank, st	Tank	Mining rate, st/h	Depth, ft
July	24[1,5]	3.0	0	1	0	NAp	Aug.	17[2]..	1.0	37.71	13	26.9	125-135
July	25[1]..	1.25	26.24	1	21.0	150	Aug.	17[2]..	1.25	36.00	14	28.8	135
July	26[1]..	2.35	40.95	2	17.4	123-135	Aug.	17[2]..	1.25	34.92	15	27.9	130
July	26[1]..	2.75	34.97	3	12.7	121-122	Aug.	17[2]..	1.25	32.76	16	26.2	130
July	27[1]..	2.5	40.58	4	16.2	118-121	Aug.	17[2]..	1.1	38.10	17	34.6	124
July	27[1]..	2.0	46.50	5	23.2	117-119	Aug.	17[2,3]	1.2	NA	NA	NA	132
July	27[1,3]	1.25	NA	NA	NA	118	Aug.	18[2]..	.75	41.83	18	21.5	126
July	27[1]..	1.5	44.00	6	16.0	114	Aug.	18[2]..	2.25	41.39	19	18.4	129
July	27[1]..	1.5	NA	NA	NA	113	Aug.	18[2,3]	2.25	NA	NA	NA	124-126
Aug.	13[2]..	2.1	34.37	7	9.5	110-145	Aug.	22[2,3]	3.5	NA	NA	NA	106-120
Aug.	13[2]..	2.2	NA	NA	NA	126-145	Aug.	23[1]..	1.0	48.25	20	6.3	105-112
Aug.	14[2]..	3.0	39.90	8	7.7	130-140	Aug.	23[1]..	1.0	44.64	21	44.6	116
Aug.	14[2,3]	4.3	39.84	9	9.3	138-140	Aug.	23[1]..	1.25	44.54	22	35.6	110-115
Aug.	14[2]..	2.2	NA	NA	NA	122-132	Aug.	23[1]..	1.5	38.41	23	25.6	114
Aug.	15[2]..	6.75	42.16	10	4.7	108-140	Aug.	23[1,3]	1.0	NA	NA	NA	112
Aug.	15[2]..	1.7	NA	NA	NA	135-136	Aug.	24[1]..	1.5	40.35	24	16.1	112-113
Aug.	16[2]..	1.0	39.10	11	14.5	140	Aug.	24[1]..	2.5	34.38	25	13.8	112-115
Aug.	16[2]..	2.75	42.00	12	15.3	135-140	Sept.	5[1,4]	Pond	7.00	NAp	NA	NAp
Aug.	16[2,3]	.40	NA	NA	NA	140	Sept.	5[2]..	Pond	8.00	NAp	NA	NAp

NA Not available. NAp Not applicable.
[1]Borehole 1. [2]Borehole 2.
[3]Production data not given because tanks were measured only when full.
[4]Sand in pond estimated by measuring deltas after water removed.
[5]Equipment malfunction.

TABLE 3. - Operating parameters for oil-sand mining, Kern County, CA

	Typical value	Range
Cutting jet:		
Pressure............................lbf/in^2..	400	100-2,500
Flow rate................................gpm..	300	100-500
Hydraulic power...........................hp..	50	10-700
Nozzle diameter...........................in..	0.62	0.62-0.75
Line diameter.............................in..	1.70	NAp
Rotation rate............................rpm..	10	4-15
Traverse rate...........................in/s..	60	2-120
Vertical cutting increment................in..	2	NAp
Angle of cutting arc.....................deg..	180	0-360
Depth.....................................ft..	130	110-150
Jet pump:		
Pressure............................lbf/in^2..	1,000	450-1,500
Flow rate................................gpm..	500	350-650
Agitation jet flow rate..................gpm..	90	60-110
Hydraulic power...........................hp..	300	100-600
Nozzle diameter...........................in..	0.70	NAp
Agitation jet diameter....................in..	188	NAp
Throat diameter...........................in..	2.50	2.5-2.9
Nozzle line diameter, effective...........in..	2.5	NAp
Secondary flow:		
Rate.....................................gpm..	400	300-600
Solids................................wt pct..	15	0-35
Specific gravity............................	1.1	1.0-1.3
Slurry flow:		
Rate.....................................gpm..	800	600-1,100
Line diameter.............................in..	3.75	NAp
Solids ....wt pct..	7	0-18
Specific gravity............................	1.05	1.0-1.15
Mining rate ....st/h..	15	0-45

NAp Not applicable.

TABLE 4. - Water sample analyses before and during oil-sand mining

Sample date, 1979	7/26	8/7	8/13	8/17	8/18	8/20	8/22	8/24
Cations, mg/L:								
Arsenic	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.01
Barium	<1.0	<1.0	3.6	<1.0	<1.0	<1.0	<1.0	<1.0
Cadmium	<0.01	0.02	ND	0.01	0.01	0.01	0.01	0.01
Calcium	42	2.8	1,740	35	35	39	57	56
Chromium	0.05	<0.01	0.05	0.01	0.01	0.01	<0.01	<0.01
Chromium, hexavalent	<0.01	ND	ND	<0.01	<0.01	<0.01	<0.01	<0.01
Copper	0.01	0.18	0.06	0.01	0.02	0.01	0.02	<0.01
Iron	0.06	0.58	0.27	0.16	0.16	0.12	0.15	0.16
Lead	<0.01	<0.01	ND	<0.01	<0.01	<0.01	<0.01	<0.01
Magnesium	18	2.4	0.03	22	25	25	42	73
Manganese	0.01	0.01	0.03	0.03	0.03	0.05	0.21	0.06
Mercury	0.0002	ND	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Potassium	55	147	101	62	62	66	64	62
Selenium	<0.01	ND	ND	<0.01	<0.01	<0.01	<0.01	<0.01
Silver	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	<0.01	<0.01
Sodium	1,590	3,250	350	1,750	1,750	1,790	1,750	1,685
Zinc	0.02	0.06	0.04	0.04	0.03	0.03	0.05	0.02
Anions, mg/L:								
Bicarbonate	1,088	925.1	0	876.6	913	1,124.3	1,008.0	984
Carbonate	0	644.1	54.5	139.7	124.4	0	0	0
Chloride	1,897.7	3,600.2	3,168.3	2,028.4	2,067.4	2,124.0	2,109.8	2,102.8
Floride	2.6	1.0	0.2	1.9	2.0	1.9	1.8	1.8
Phosphate	30.0	ND	ND	1.2	1.5	1.7	0.8	0.9
Sulfate	145	330	59	153	163	190	390	380
Color[1]	250	300	2	200	250	200	150	150
Electrical conductivity......mµS/cm..	6,820	11,780	9,890	6,590	5,650	7,540	7,772	7,540
Hardness[2]	179.2	16.9	<4,353.6	178.1	178.1	200.5	315.5	440.5
MBAS[3]	0.5	ND	ND	0.7	0.7	0.6	0.6	0.7
Odor threshold[4]	1	5	2	5	5	5	4	4
pH	8.0	9.4	11.6	8.3	8.2	8.1	8.1	8.1
Total dissolved solids..........mg/L..	4,315	8,449	5,534	4,711	4,683	4,851	4,906	4,861
Total organic carbon...........mg/L..	13.8	ND	ND	123.2	145.2	189.2	167.2	171.6
Turbidity[5]	8.4	1,000	3,000	700	700	600	2,400	2,100

ND Not determined, insufficient sample to conduct analysis.
[1]Color units. [2]Milligrams per liter of $CaCO_3$.
[3]Methylene blue active substance reported as milligrams per liter of linear alkylate sulfonate.
[4]Dilution to least perceptible odor.
[5]Nephelometric turbidity units (NTU).

The top of an oil well casing was used as a datum with an assumed elevation of 100 ft. The project site (fig. 9) was subdivided into a grid, and the relative elevation of each of the grid points was measured weekly. Table 5 shows that an average land subsidence of one-quarter to three-eighths of an inch occurred as a result of the mining. This subsidence increased with time and decreased with distance from the center of the boreholes.

TABLE 5. - Elevation surveys before, during, and after oil-sand mining, feet

(Bench mark: 100.00 ft)

Survey point	7/23/79[1]	7/30/79	8/6/79	8/13/79	8/20/79	8/26/79	9/24/79[2]	Elevation change
A5........	86.22	86.18	86.18	86.19	86.19	86.17	86.14	0.08
A10.......	86.28	86.23	86.22	86.23	86.22	86.20	86.18	.10
A15.......	86.38	86.35	86.35	86.35	86.37	86.35	86.32	.06
A20.......	86.40	86.39	86.39	86.39	86.41	86.40	86.37	.03
B5........	86.05	86.05	86.05	86.05	86.07	86.05	86.03	.02
B10.......	86.14	86.14	86.14	86.14	86.15	86.13	86.10	.04
B15.......	86.09	86.10	86.09	86.10	86.11	86.08	86.06	.03
B20.......	86.13	86.14	86.15	86.16	[3]85.94	85.91	85.90	.04
B25.......	85.88	[3]86.15	86.15	86.16	86.18	86.16	86.14	.01
B50.......	85.73	85.70	ND	[3]86.11	86.13	86.12	86.10	.01
B75.......	87.25	ND	ND	[3]87.50	87.51	87.50	87.48	.02
C5........	86.31	ND	86.30	86.25	86.27	86.25	86.23	.08
C10.......	86.27	86.26	86.27	86.28	86.30	86.27	86.25	.02
C15.......	86.32	86.31	86.33	86.34	86.36	86.33	86.32	.00
C20.......	86.30	86.30	86.32	86.32	86.34	86.32	86.30	.00
C25.......	86.44	86.44	86.45	86.46	86.48	86.47	86.45	[4].01
C50.......	86.76	86.76	86.76	86.77	86.80	86.77	86.76	.00
C75.......	88.18	88.18	88.19	86.20	88.22	88.20	88.19	[4].01
D5........	86.48	86.23	86.23	86.24	86.25	86.21	86.19	.29
D10.......	86.50	ND	86.49	86.49	86.51	86.49	86.47	.03
D15.......	86.58	86.57	86.57	86.58	86.60	86.58	86.56	.02
D20.......	86.54	86.54	86.54	86.55	86.57	86.55	86.53	.01
D25.......	86.56	86.55	86.55	86.56	86.58	86.56	86.54	.02
D50.......	86.63	86.62	86.62	86.63	86.66	ND	86.62	.01
D75.......	86.93	86.98	86.97	[3]86.89	86.92	86.91	86.89	.00
E5........	ND	ND	ND	[3]86.41	86.39	ND	86.34	.07
E10.......	ND	ND	ND	[3]86.59	86.59	ND	86.55	.04
E15.......	86.50	86.50	86.50	86.51	86.52	86.50	86.47	.03
E20.......	86.53	86.48	86.53	86.54	86.54	86.52	86.50	.03
E25.......	86.61	86.60	86.61	86.62	86.63	86.61	86.58	.03
E50.......	86.75	86.72	86.71	86.76	86.78	86.76	86.74	.01
E75.......	87.03	87.02	87.03	87.05	87.06	87.04	87.07	[4].04

See footnotes at end of table.

TABLE 5. - Elevation surveys before, during, and after oil-sand mining, feet--Con.

(Bench mark: 100.00 ft)

Survey point	7/23/79[1]	7/30/79	8/6/79	8/13/79	8/20/79	8/26/79	9/24/79[2]	Elevation change
F5........	86.27	86.28	86.29	86.30	[3]85.73	85.70	85.69	0.04
F10.......	86.15	86.17	86.17	86.18	86.20	86.18	85.17	[4]4.02
F15.......	86.21	86.22	86.23	86.24	86.26	86.23	86.27	[4].06
F20.......	86.57	86.58	86.58	86.61	86.63	86.59	86.57	.00
F25.......	86.69	[3]86.49	86.48	86.49	86.51	86.49	86.48	.01
G5........	ND	86.16	86.17	86.18	[3]85.97	85.95	85.94	.03
G10.......	86.32	86.32	86.34	86.35	86.36	86.35	86.33	[4].01
G15.......	86.59	86.59	86.60	86.66	86.63	86.60	86.59	.00
G20.......	86.64	86.64	86.65	87.12	86.68	86.65	86.64	.00
G25.......	87.09	87.10	88.10	88.73	87.14	87.10	87.11	[4].02
G50.......	88.69	88.70	88.71	88.73	88.75	88.72	88.71	[4].02
G75.......	91.99	92.00	92.01	92.02	92.05	92.06	92.01	[4].02
H5........	ND	[3]86.20	86.20	86.20	86.24	86.21	86.20	.00
H10.......	86.26	[3]86.24	86.23	86.24	86.27	86.24	86.23	.01
H15.......	86.49	86.50	86.52	86.53	86.55	86.52	86.51	[4].02
H20.......	86.63	86.64	86.66	86.67	86.69	86.66	86.05	.58
H25.......	86.68	86.69	86.71	86.72	86.74	86.71	86.70	[4].02
H50.......	88.40	88.40	88.41	88.43	88.45	88.42	88.41	[4].01
H85.......	90.15	90.15	90.16	90.17	90.19	90.17	90.15	.00
I5........	ND	[3]86.04	86.04	86.05	86.07	86.04	86.03	.01
I10.......	ND	[3]85.89	85.09	85.89	85.92	85.88	85.88	.01
I15.......	86.34	86.30	86.29	86.30	86.32	86.30	86.28	.06
I20.......	86.35	86.36	86.36	86.36	86.39	86.36	86.35	.00
I25.......	86.40	86.41	86.41	86.41	86.44	86.41	86.40	.00
J5........	86.11	86.14	86.15	86.16	86.19	86.15	86.10	.01
J10.......	86.07	86.08	86.09	86.16	86.19	86.09	86.06	.01
J15.......	86.18	[3]86.11	86.13	86.16	86.19	86.11	86.10	.01
J20.......	86.20	86.23	86.23	86.16	86.19	ND	86.22	[4].02
J25.......	86.21	86.20	86.21	86.16	86.19	86.21	86.19	.02

ND Not determined.
[1]Baseline survey conducted prior to initiation of mining.
[2]Survey conducted 30 days after completion of mining.
[3]New hub set (station from which elevations taken).
[4]Net gain in elevation.

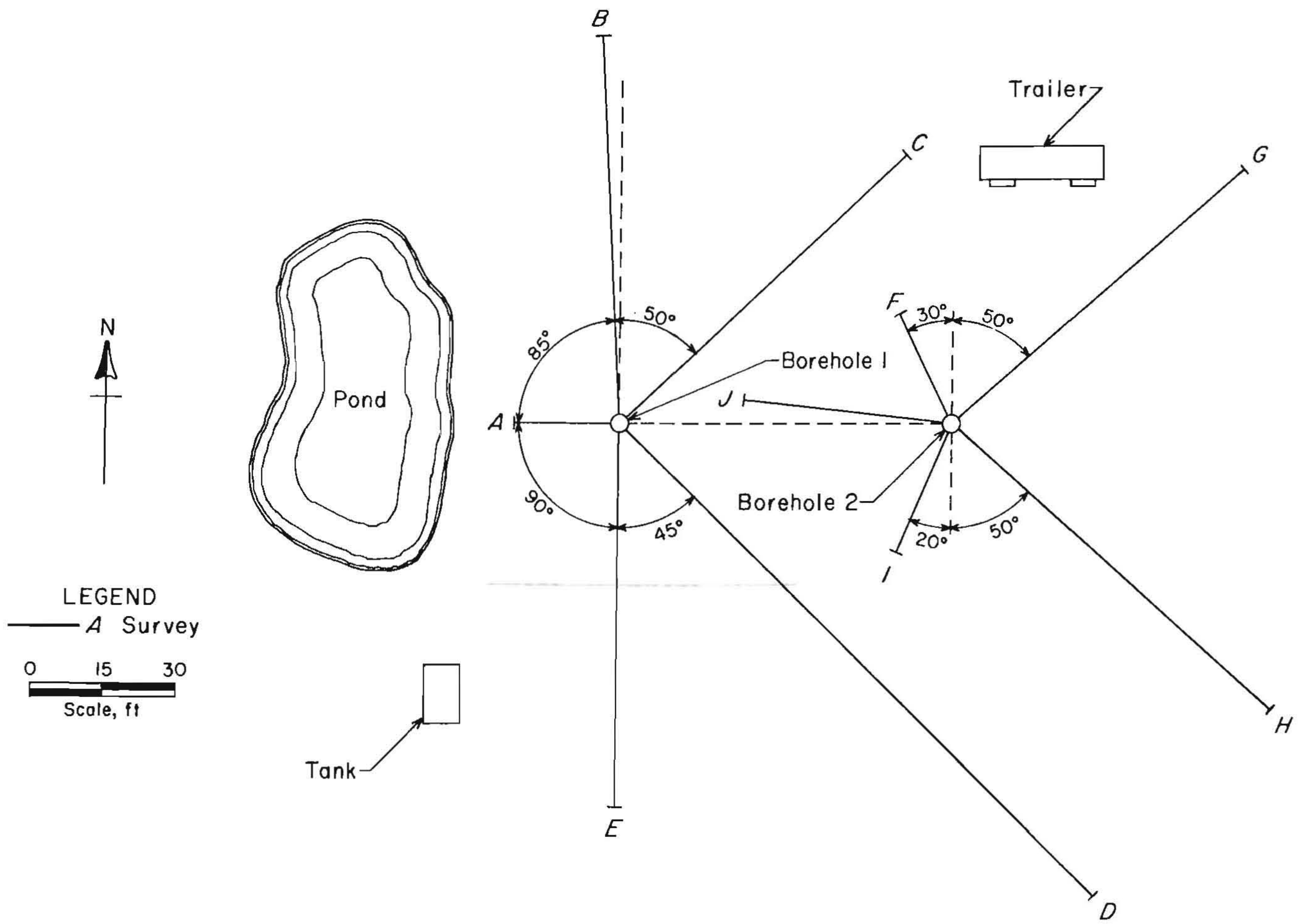

FIGURE 9.—Survey grid system.

Contour maps of the subsidence around the two boreholes are given in figures 10 and 11. The distinct depressions shown in the south portion of figure 10 are imprints of the outrigger of the crane that suspended the mining tool in the hole.

This field test showed that borehole oil-sand mining is technically feasible and that the environmental impacts are minimal.

PHOSPHATE MINING

St. Johns County in Northwest Florida contains vast untapped deposits of high-grade phosphate that are not amenable to conventional surface mining methods because the ore-bearing zone is deep (250 ft) and is in an environmentally sensitive setting. The Bureau of Mines and Flow Industries, in cooperation with the Agrico Mining Co., conducted borehole phosphate mining tests in St. Johns County, near St. Augustine, FL (16). Agrico provided the mining site and site services; the Bureau of Mines, through a contract with Flow Industries, provided the mining equipment and the field test crew. The purpose of the test was to determine if phosphate ore can be mined economically in an environmentally compatable manner with the Bureau of Mines borehole mining system.

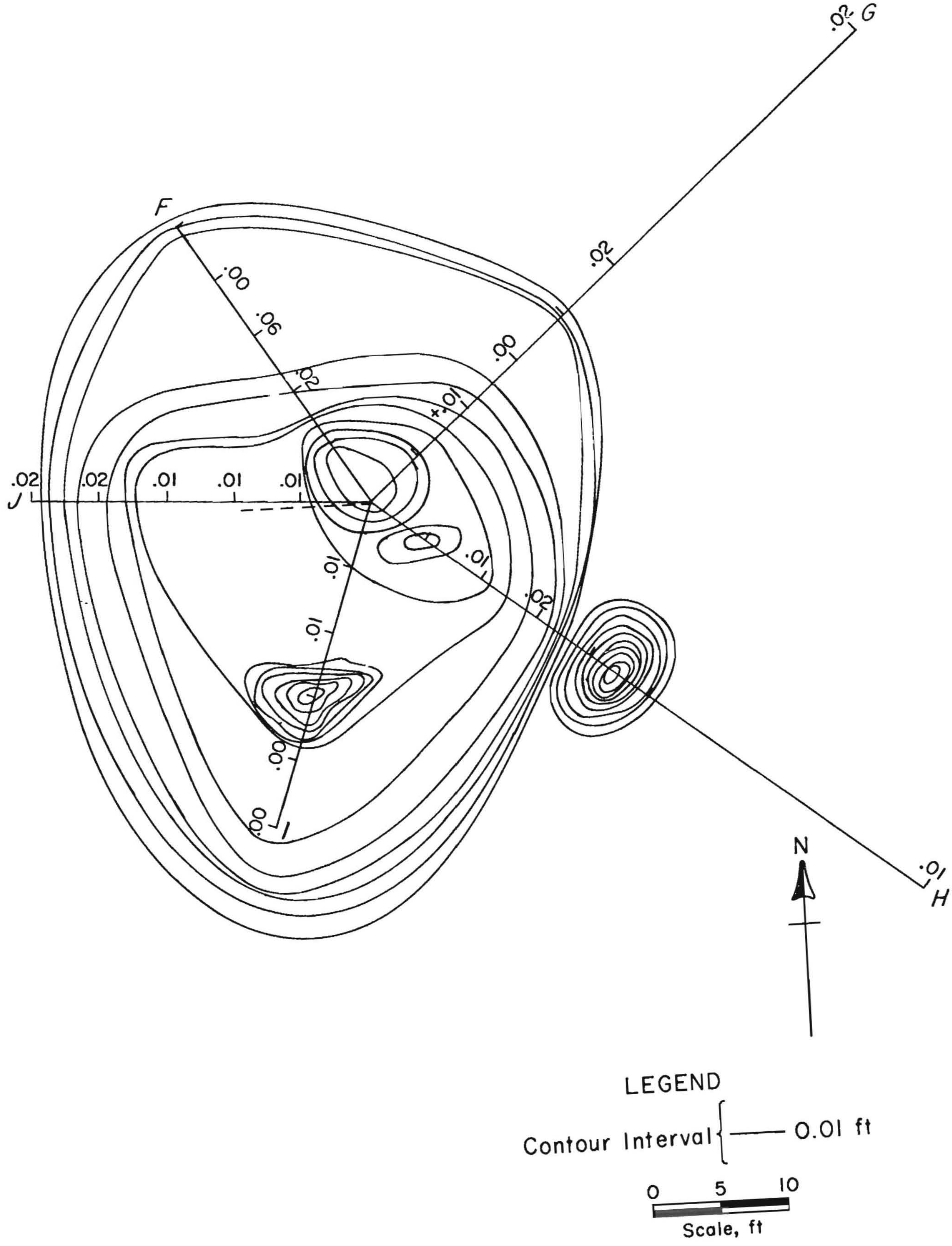

FIGURE 10.—Contour map of borehole 1 site.

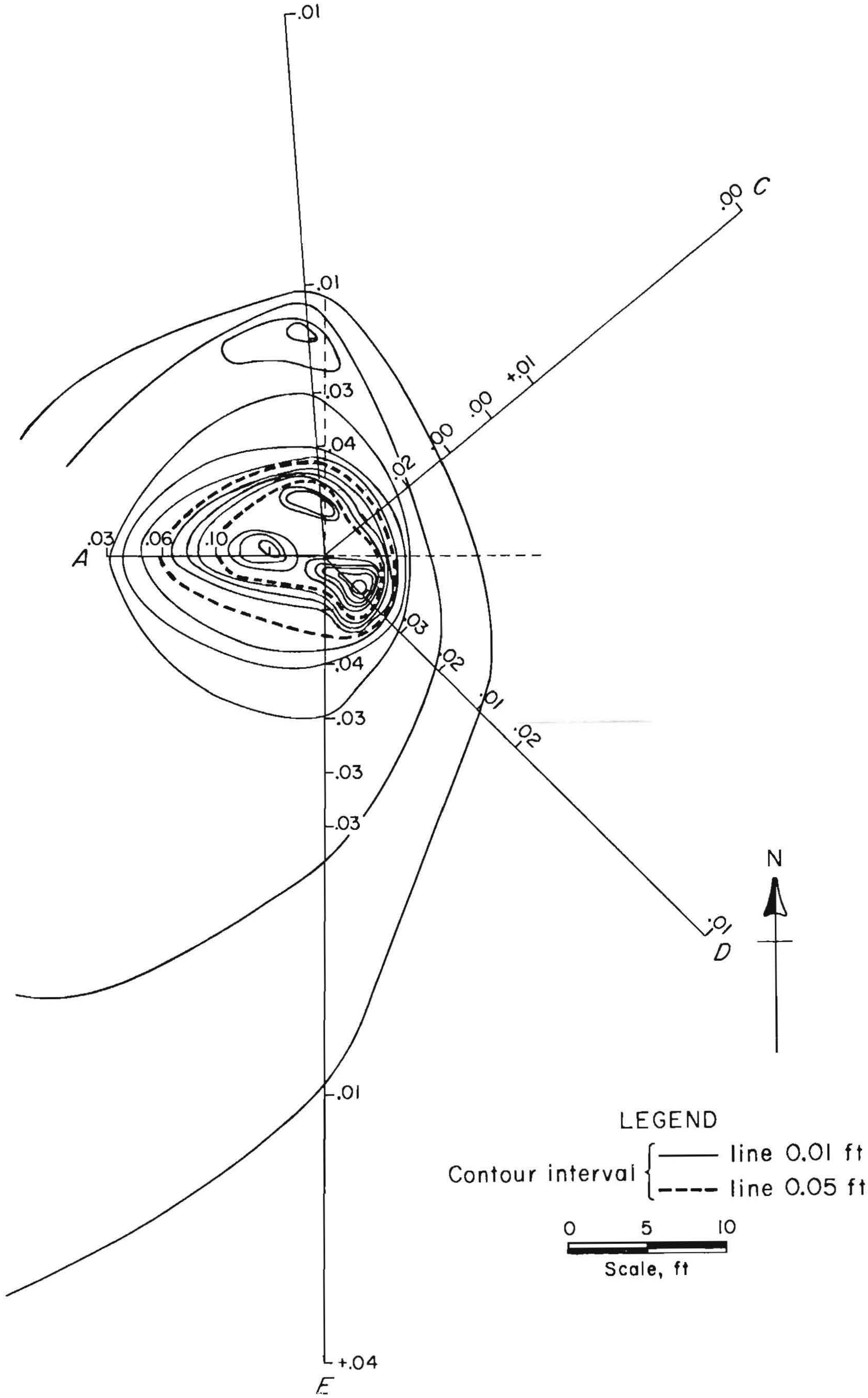

FIGURE 11.—Contour map of borehole 2 site.

FIGURE 12.—Phosphate ore deposited at outlet of mining tool.

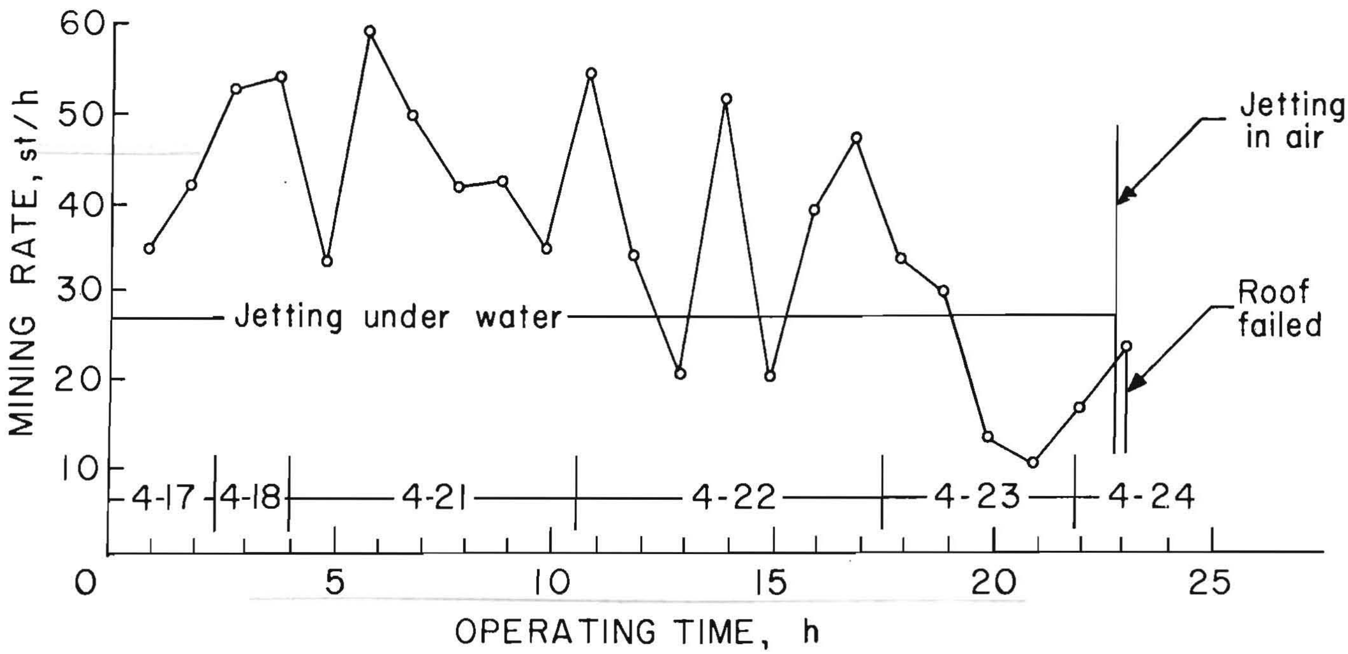

FIGURE 13.—Phosphate production in borehole 1.

Between April and August 1980, 1,700 st of phosphate ore was produced (fig. 12) from three boreholes that ranged from 232 to 253-ft deep. Mining in the first hole was conducted to determine the feasibility of mining with the borehole filled with water. This borehole yielded 860 st at an average rate of 36 st/h while cutting with a submerged jet (fig. 13) in a 360° arc. The specifications for waterjet mining in borehole 1 were as follows:

Parameter	Specifications
Cutting-jet pressure lbf/in^2..	500-2,000
Cutting-jet flow rate gpm..	500-750
Cutting-jet diam....in..	0.475 and 0.966
Jet pump pressure lbf/in^2..	700-1,500
Jet pump flow rate gpm..	400-700
Jet pump nozzle diam in..	0.68 and 0.80
Jet pump throat diam in..	2.00 and 2.25
Turntable speed....rpm..	2-15
Mining arc.........deg..	360
Mining depth........ft..	232-253
Vertical increment..in..	2-6

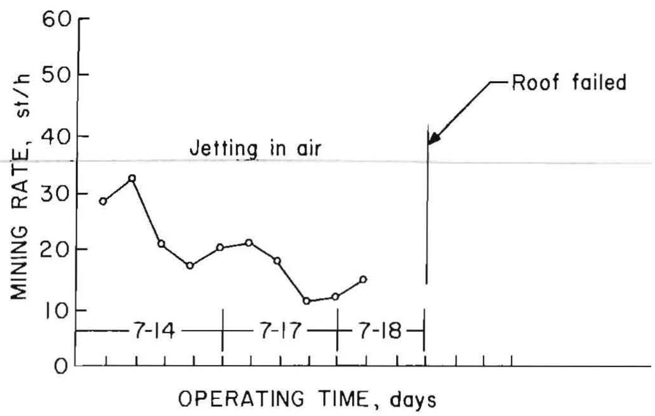

FIGURE 14.—Phosphate production in borehole 2.

When the water was pumped from the cavity, the roof failed, indicating that the water pressure had supported the roof. However, this experiment indicated that borehole phosphate mining in a submerged mode is technically feasible.

Attempts to mine in an air-filled cavity were made in borehole 2 (fig. 14), where mining was confined to a 30° arc and a 330° pillar supported the roof. However, a roof failure occurred after 300 st of ore had been produced. From this test, it was concluded that (1) the roof rock did not have sufficient strength to permit mining in an air environment, and (2) any future mining would require that the cavity be filled with water.

A third borehole tested an "air-shielding concept" designed to combine the need to have flooded conditions and the advantages of mining in air. Under this concept, the water jet was in a shroud of compressed air; this allowed cutting at longer standoff distances while retaining the roof support and increased pumping capability gained by working under a hydrostatic head of water. The water-jet specifications for mining in borehole 3 were as follows:

Parameters	Specifications
Cutting-jet pressure lbf/in^2..	1,000-1,900
Cutting-jet flow rate..gpm..	423-499
Cutting-jet diam........in..	1.00
Air-shield pressure lbf/in^2..	250
Air-shield flow rate ft^3/min..	150 std
Air-shield nozzle opening in..	0.030
Jet pump pressure..lbf/in^2..	490-1,000
Jet pump flow rate.....gpm..	432-491
Jet pump nozzle diam....in..	0.70
Jet pump throat diam....in..	2.00
Turntable speed........rpm..	1.8
Mining arc.............deg..	360
Mining depth............ft..	235-249
Vertical increment......in..	2-6

A total of 430 st was mined in this borehole without actuating the air shield in order to establish the baseline solids production (fig. 15). On August 30, the solids content of the slurry began to decrease, indicating that the submerged jet had reached its maximum effective radius. At this point, the air-shield was activated, and an additional 137 st was mined at the rate of 25 st/h. The cavity radius was about 18 ft, and no roof failure had occurred when the mining stopped. This experiment indicated that phosphate can be mined effectively in a flooded cavity and that air shielding substantially increases water jet effectiveness while operating underwater.

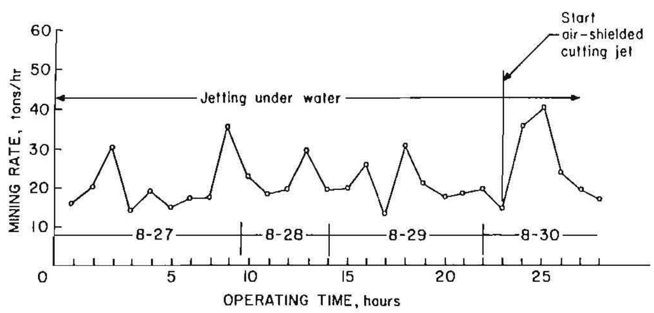

FIGURE 15.—Phosphate production in borehole 3.

To monitor the effects of the mining operation on the groundwater resources of the area, the U.S. Geological Survey designed and implemented a hydrologic data collection network. Six monitoring wells were constructed at various depths above and below the phosphate zone (fig. 16). Water-level measurements and water-quality samples were collected before, at periodic intervals during, and after the mining operation. Continuous-pressure recorders were installed in the wellheads of the two artesian wells to measure the water levels in the Floridan aquifer, below the phosphate zone, and in aquifers immediately above the phosphate zone. The recorder in the artesian well above the phosphate zone registered very large and sudden drops in pressure (fig. 17) when the roof failures occurred in boreholes 1 and 2 when mining in air was attempted.[3] No such pressure changes were noted in the well of the Floridan aquifer, indicating that no break occurred between the mining zone and the Floridan aquifer during the mining operations.

Water quality analyses were performed on samples taken at biweekly intervals from the monitoring well network. Analyses were performed for major

[3] In figure 17, "NGVD of 1929" refers to "National Geodetic Vertical Datum of 1929," which was derived from general adjustments of the first-order level nets of the United States and Canada. (It was formerly called "mean sea level.") The datum was derived from the average sea level during many years at 26 tide stations along the Atlantic and Pacific Coasts and the Gulf of Mexico.

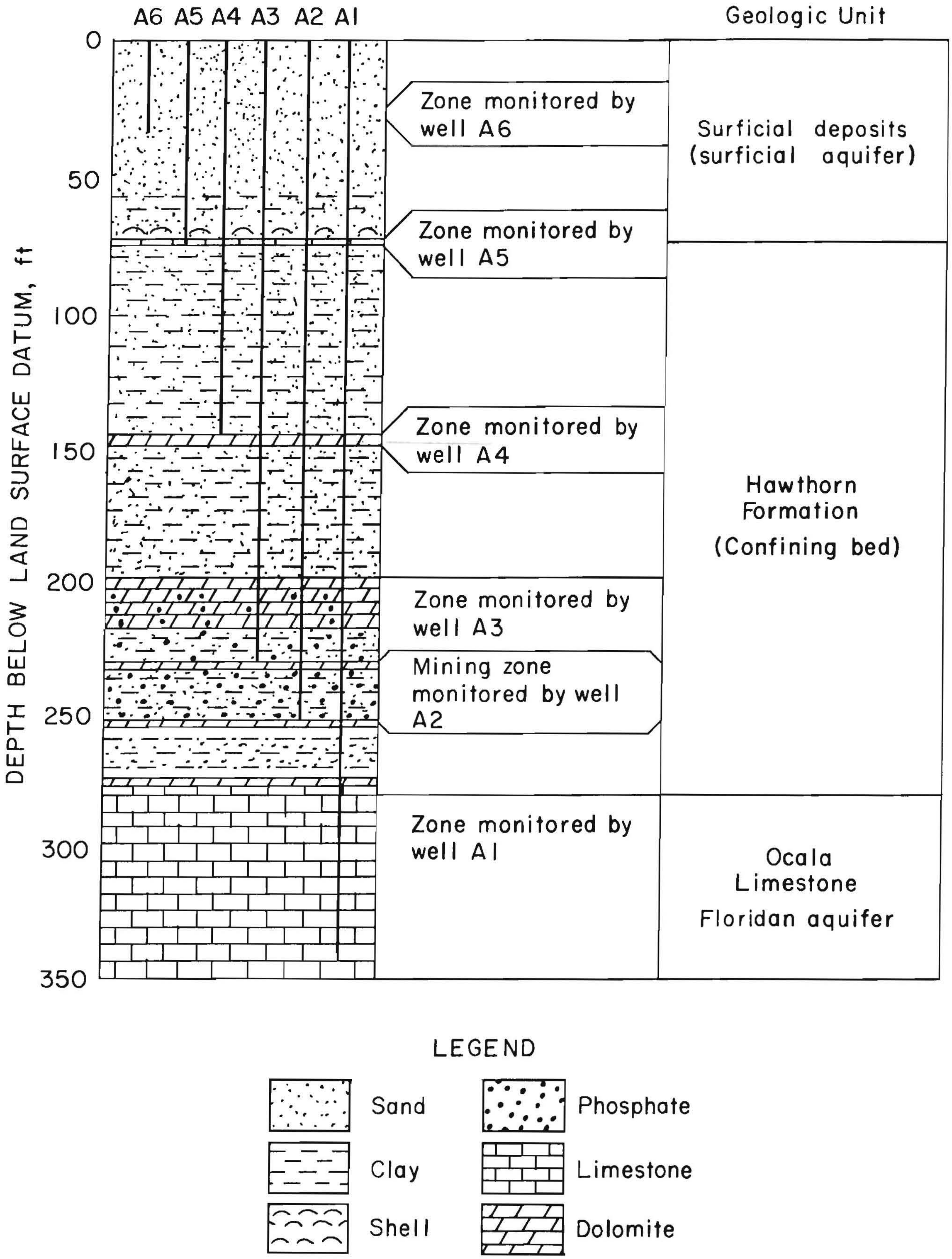

FIGURE 16.—Generalized columnar section showing monitored zones and geologic units.

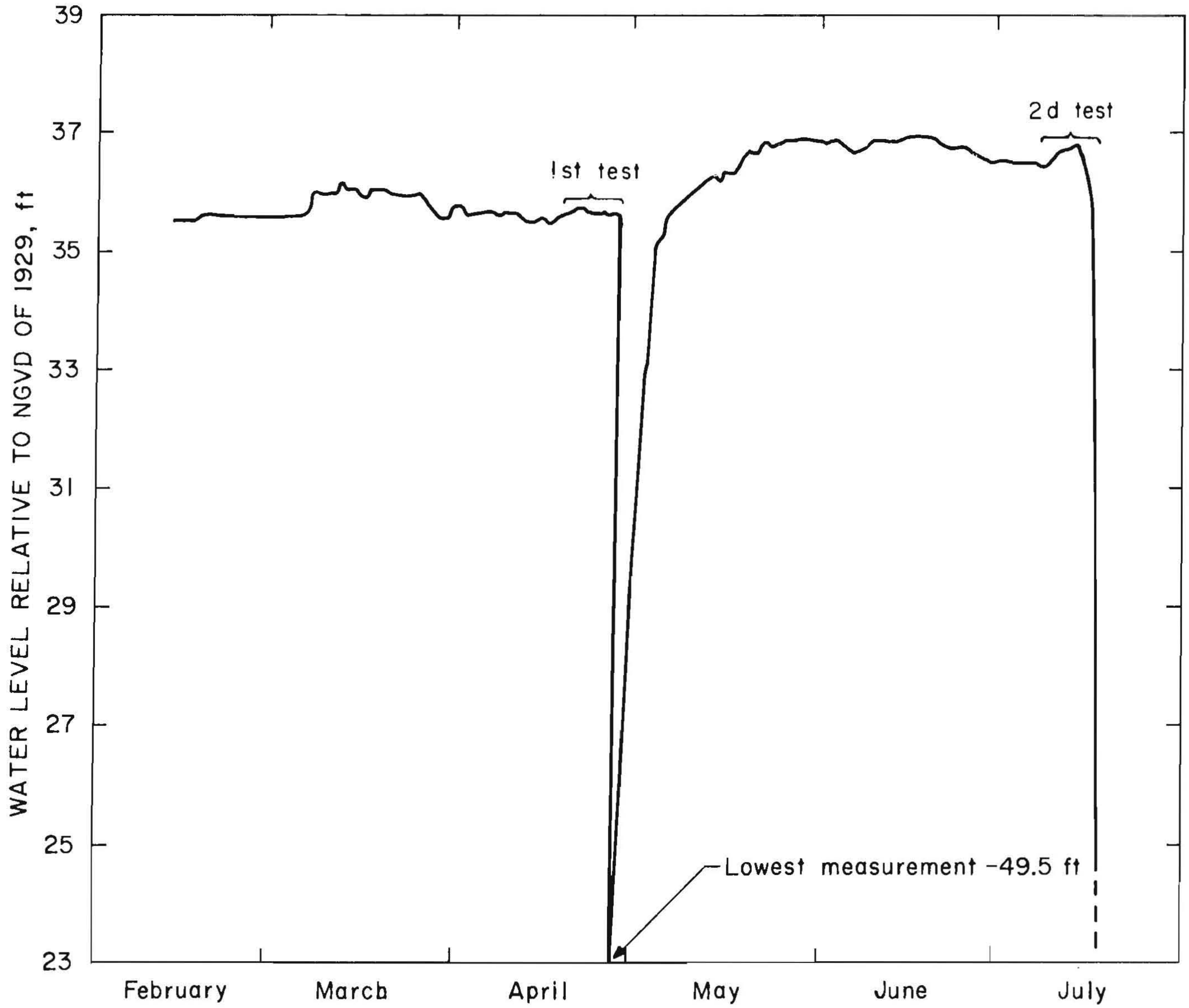

FIGURE 17.—Hydrographs of well A3 showing first and second test periods.

dissolved constituents, dissolved uranium, and radium-226 (tables 6-11).

During the three mining tests, changes in water quality occurred only in the zone being mined and in the zone monitored by well A4 (fig. 18). The water-quality changes in the mining zone were the result of the mixing of the formation water with the water jet used to fragment and slurrify the ore. The quality of the water in the water jet differed significantly from the quality of the original formation water. These changes were noted only in samples taken from the mining borehole. No changes in quality occurred in the mining zone 40 ft from the borehole at well A2. Changes in alkalinity, calcium content, degree of hardness, and strontium content occurred in the zone monitored by well A4. These changes were probably not related to the mining operation because the changes were detected after the mining operation had ended, and they were not accompanied by water-level changes, which might have suggested a relationship with the mining. No significant changes in water quality occurred in any of the other monitored zones above and below the mining zone.

TABLE 6. - Water-quality data for well A1

Sample date, 1980	2/12	4/28	5/12	5/30	6/11	6/27	7/11	7/27	11/10
Alkalinity.........mg/L as $CaCO_3$..	150	150	NA	NA	NA	NA	NA	NA	NA
Hardness.....total mg/L as $CaCO_3$..	320	330	310	310	320	330	320	330	310
Calcium, dissolved..........mg/L..	75	76	71	70	72	75	71	75	69
Magnesium, dissolved........mg/L..	31	35	32	32	33	34	34	34	32
Sodium, dissolved...........mg/L..	55	62	61	61	63	64	67	64	61
Potassium, dissolved........mg/L..	3.0	3.0	2.5	2.7	2.9	2.9	3.1	2.9	3.0
Chloride, dissolved........ mg/L..	110	110	NA	110	110	120	110	120	110
Sulfate, dissolved..........mg/L..	160	160	170	160	160	150	170	150	160
Fluoride, dissolved.........mg/L..	0.9	1.0	0.9	1.0	0.9	0.9	0.9	0.9	1.0
Silica, dissolved...........mg/L..	27	28	26	26	27	27	27	27	27
Iron, dissolved.............µm/L..	0	30	NA	NA	NA	NA	NA	NA	NA
Strontium, dissolved........µg/L..	3,000	NA	NA	NA	NA	NA	NA	NA	2,900
Radiochemical analyses:									
Uranium, dissolved...µg/L as U..	0.02	NAp	NAp	NAp	NAp	NAp	NAp	NAp	0.05
Radium-226 by RN.........pCi/L..	0.46	NAp	NAp	NAp	NAp	NAp	NAp	NAp	0.58

NA Not available. NAp Not applicable.

TABLE 7. - Water-quality data for well B1

Sample date, 1980	2/12	5/12	5/30	6/11	6/27	7/11	7/27	11/10[1]
Alkalinity..............mg/L as $CaCO_3$..	180	NA	NA	NA	NA	NA	NA	140
Hardness..........total mg/L as $CaCO_3$..	250	260	270	280	280	280	280	230
Calcium, dissolved...............mg/L..	54	56	60	60	61	61	61	50
Magnesium, dissolved.............mg/L..	27	29	30	31	32	31	32	26
Sodium, dissolved................mg/L..	54	53	50	52	53	47	53	61
Potassium, dissolved.............mg/L..	6.8	6.4	6.3	6.5	6.3	6.2	6.3	6.5
Chloride, dissolved..............mg/L..	38	54	55	54	71	55	71	39
Sulfate, dissolved...............mg/L..	150	170	160	170	160	160	160	150
Fluoride, dissolved..............mg/L..	1.2	1.3	1.3	1.2	1.3	1.2	1.3	1.3
Silica, dissolved................mg/L..	48	45	44	43	44	43	44	49
Iron dissolved...................µm/L..	120	NA	NA	NA	NA	NA	NA	NA
Strontium, dissolved.............µg/L..	2,300	NA	NA	NA	NA	NA	NA	2,200
Radiochemical analyses:								
Uranium, dissolved........µg/L as U..	1.2	NAp	NAp	NAp	NAp	NAp	NAp	0.30
Radium-226 by RN.............pCi/L..	2.2	NAp	NAp	NAp	NAp	NAp	NAp	3.1

NA Not available. NAp Not applicable.
[1]Sample taken from well A2, which was finished in phosphate zone.

TABLE 8. - Water-quality data for well A3

Sample date, 1980	5/2	5/12	5/30	6/11	6/27	7/11	7/27	11/10
Alkalinity..........mg/L as $CaCO_3$..	NA	NA	NA	NA	NA	NA	NA	180
Hardness......total mg/L as $CaCO_3$..	160	160	170	170	180	170	180	150
Calcium, dissolved...........mg/L..	32	32	33	33	35	33	35	30
Magnesium, dissolved.........mg/L..	20	20	21	22	22	21	22	19
Sodium, dissolved............mg/L..	50	49	51	56	56	49	56	50
Potassium, dissolved.........mg/L..	7.0	6.8	NA	7.5	7.2	7.3	7.2	7.1
Chloride, dissolved..........mg/L..	25	26	23	24	32	24	32	33
Sulfate, dissolved...........mg/L..	51	54	58	61	59	62	59	61
Fluoride, dissolved..........mg/L..	1.5	1.7	1.8	1.7	1.8	1.7	1.8	1.8
Silica, dissolved............mg/L..	63	62	63	64	65	63	65	63
Iron dissolved...............µm/L..	90	NA	NA	NA	NA	NA	NA	NA
Strontium, dissolved.........µg/L..	NA	NA	NA	NA	NA	NA	NA	1,200
Radiochemical analyses:								
Uranium dissolved.....µg/L as U..	0.40	NAp	NAp	NAp	NAp	NAp	NAp	0.30
Radium-226 by RN..........pCi/L..	4.8	NAp	NAp	NAp	NAp	NAp	NAp	4.3

NA Not available. NAp Not applicable.

TABLE 9. - Water-quality data for well A4

Sample date, 1980	2/12	4/28	5/12	6/11	6/27	7/11	7/27	11/10
Alkalinity................mg/L as $CaCO_3$..	200	170	NA	NA	NA	NA	NA	93
Hardness...........total mg/L as $CaCO_3$..	150	140	150	140	150	130	150	73
Calcium, dissolved.................mg/L..	34	30	31	29	31	27	31	14
Magnesium, dissolved...............mg/L..	16	16	17	16	17	16	17	11
Sodium, dissolved..................mg/L..	21	24	26	27	26	24	26	24
Potassium, dissolved...............mg/L..	5.0	4.8	4.8	4.6	4.9	5.0	4.9	5.0
Chloride, dissolved................mg/L..	15	14	15	14	NA	14	24	14
Sulfate, dissolved.................mg/L..	1.8	NA	2.0	2.7	NA	0.7	0.6	1.6
Fluoride, dissolved................mg/L..	0.8	0.9	0.9	0.8	0.9	0.8	0.9	0.8
Silica, dissolved..................mg/L..	28	NA	21	12	NA	NA	6.4	6.9
Iron dissolved.....................μm/L..	0	NA	NA	NA	NA	NA	NA	NA
Strontium, dissolved...............μg/L..	720	NA	NA	NA	NA	NA	NA	140
Radiochemical analyses:								
Uranium dissolved...........μg/L as U..	0.01	NAp	NAp	NAp	NAp	NAp	NAp	0.03
Radium-226 by RN................pCi/L..	0.39	NAp	NAp	NAp	NAp	NAp	NAp	0.11

NA Not available. NAp Not applicable.

TABLE 10. - Water-quality data for well A5

Sample date, 1980	2/12	4/28	5/12	6/11	6/27	7/11	7/27	11/10
Alkalinity................mg/L as $CaCO_3$..	NA	190	NA	NA	NA	NA	NA	210
Hardness............total mg/L as $CaCO_3$..	190	170	180	170	180	180	180	180
Calcium, dissolved.................mg/L..	60	54	55	53	57	57	57	55
Magnesium, dissolved...............mg/L..	9.6	9.7	10	10	10	10	10	9.8
Sodium, dissolved..................mg/L..	11	12	13	14	13	12	13	11
Potassium, dissolved...............mg/L..	3.0	3.0	2.7	2.9	3.1	3.2	3.1	3.1
Chloride, dissolved................mg/L..	14	13	14	13	20	14	20	16
Sulfate, dissolved.................mg/L..	0.4	0	NA	NA	0.3	1.1	0.3	1.6
Fluoride, dissolved................mg/L..	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Silica, dissolved..................mg/L..	NA	12	29	22	15	12	15	NA
Iron dissolved.....................μm/L..	50	NA	10	NA	NA	NA	NA	NA
Strontium, dissolved...............μg/L..	650	NA	NA	NA	NA	NA	NA	620
Radiochemical analyses:								
Uranium dissolved...........μg/L as U..	0.02	NAp	NAp	NAp	NAp	NAp	NAp	0.05
Radium-226 by RN................pCi/L..	0.36	NAp	NAp	NAp	NAp	NAp	NAp	0.25

NA Not available. NAp Not applicable.

TABLE 11. - Water-quality data for well A6

Sample date, 1980	2/12	5/12	6/11
Alkalinity................mg/L as $CaCO_3$..	230	NA	NA
Hardness.............total mg/L as $CaCO_3$..	220	220	220
Calcium, dissolved.................mg/L..	83	82	82
Magnesium, dissolved...............mg/L..	2.7	2.9	3.0
Sodium, dissolved..................mg/L..	13	14	15
Potassium, dissolved...............mg/L..	0.7	0.6	0.4
Chloride, dissolved................mg/L..	22	22	22
Sulfate, dissolved.................mg/L..	0.4	0.8	0.2
Fluoride, dissolved................mg/L..	0.1	0.2	0.1
Silica, dissolved..................mg/L..	25	25	25
Iron dissolved.....................μm/L..	60	NA	NA
Strontium, dissolved...............μg/L..	510	NA	NA
Radiochemical analyses:			
Uranium dissolved...........μg/L as U..	0.26	NAp	NAp
Radium-226 by RN................pCi/L..	0.19	NAp	NAp

NA Not available. NAp Not applicable.

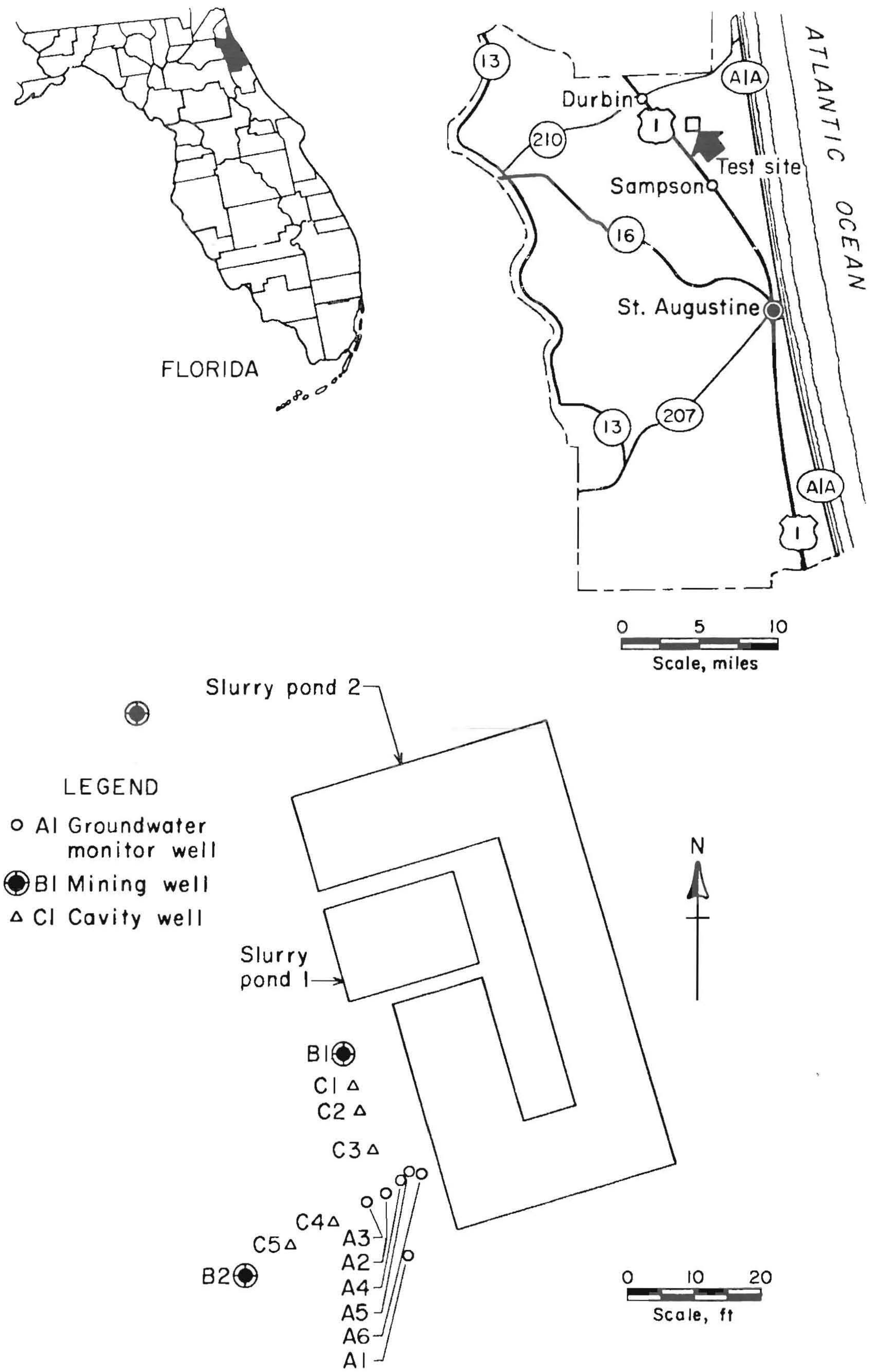

FIGURE 18.—Location and generalized configuration of test site.

BACKFILLING OF BOREHOLE-MINED CAVITIES

Surface subsidence and the presence of tailings piles are the major potential adverse environmental impacts of borehole mining operations. Methods of mitigating these impacts have been investigated under a contract (17) with Flow Industries.

Flow Industries tested three methods of backfilling the cavities at the Nine-Mile Lake site with the sand produced during previous borehole uranium mining operations. The project consisted of intervals of backfilling followed by photographic surveys to determine the distribution of backfill in the hole. The backfilling methods investigated included bulk dumping down the borehole, slurry jetting in air, and slurry jetting under water. Slurry jetting under water was found to be the most effective method. More than 90 pct of the sand removed from the cavity was returned by that technique. Figure 19 shows the cavity half filled with backfilled sand.

A 1 wt pct cement-sand mixture was introduced into a 4-in-ID pipe through a hopper, upstream of the centrifugal slurry pump (fig. 20). The outlet pipe from the pump is connected via a loose victaulic coupling (which acted as a swivel) to a similar pipe terminated by a 4-in ID elbow in the borehole. Slurry was injected at the rate of 350 gpm through 4-in (10.2-cm) pipe rotating under water in the cavity. Sand was backfilled at the rate of 16 st/h.

Analysis of cores taken from the backfilled cavity after 6 months indicated that adding 1 wt pct of cement to the backfill did not increase the stability of the backfill material. It is estimated that a 5 wt pct mix would be required.

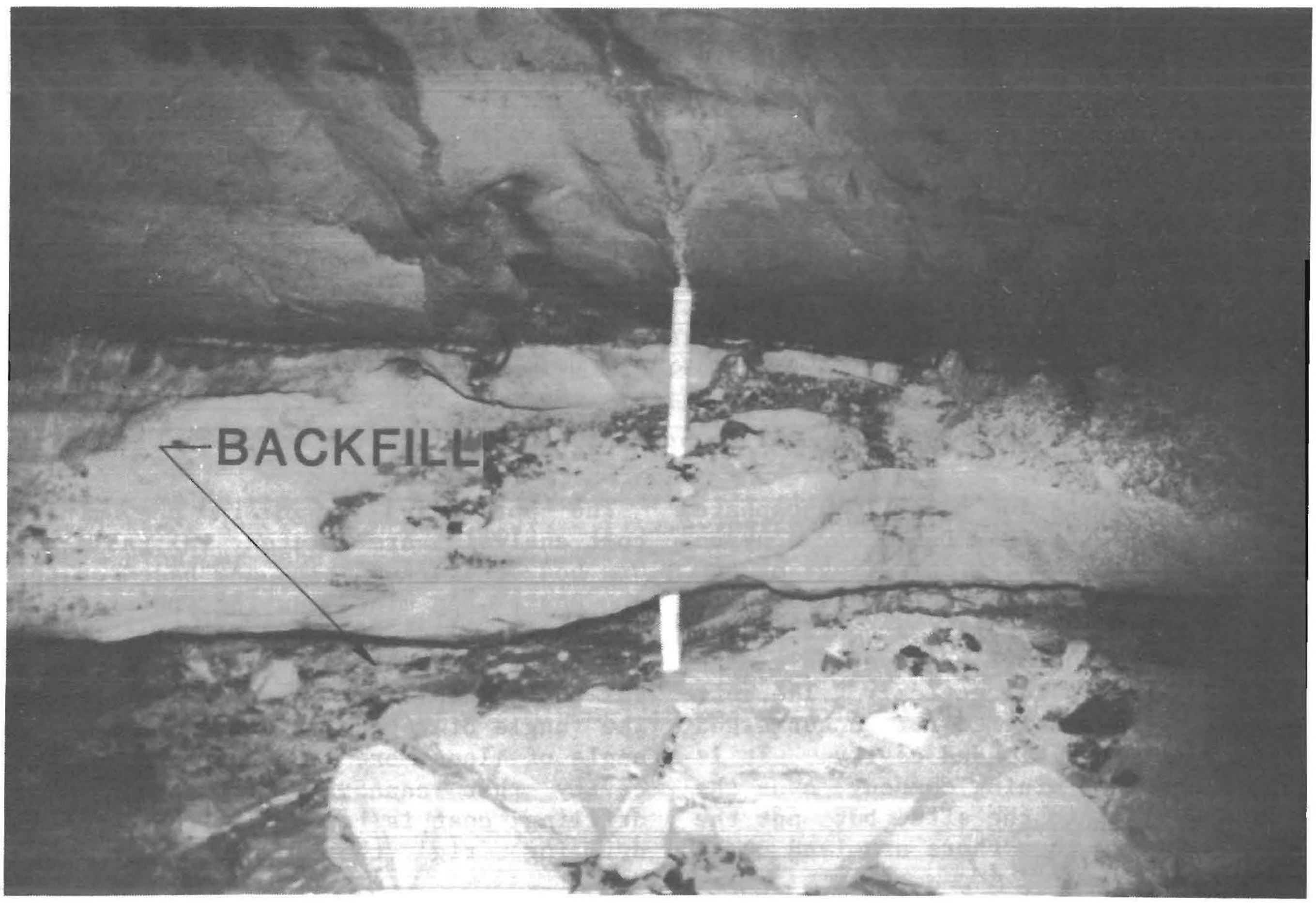

FIGURE 19.—Borehole cavity partially backfilled.

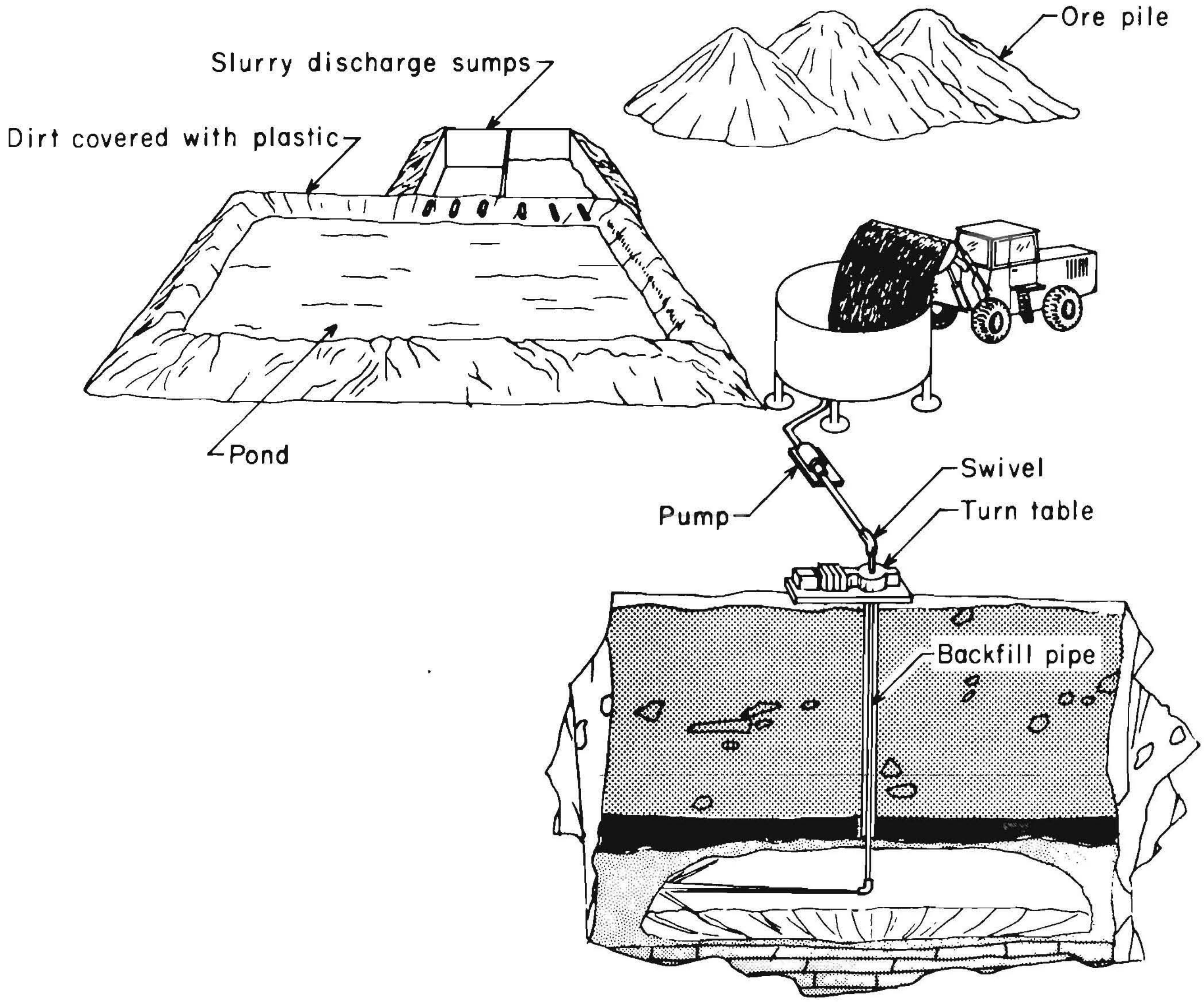

FIGURE 20.— Schematic of backfilling apparatus.

ECONOMICS OF PHOSPHATE MINING

Production costs for borehole phosphate mining were estimated based on a hypothetical mining system operating at the Florida test site. No cost analyses were made of the case when the cavity was pumped free of water because this case was found to be impractical. The cost analyses were performed for a submerged cutting jet in a flooded cavity. It is assumed that the mining company owns the mineral rights to the site, but not the surface rights, thus there are land costs during mining.

The parameters used in the mining cost analysis are listed in table 12. Ore-body characteristics are based on the phosphate bed mined during the study. The maximum radius of the underwater cavity is based on the use of a more powerful unit than that used for the tests. The angle of repose refers to the slope angle of loose ore on the floor of the cavity that cannot be recovered. The drilling cost is based on using a small drilling rig that produces only a

TABLE 12. - Economic analysis of submerged cutting jet: input parameters

Ore-body characteristics:	
Cavity radius..........ft..	30
Cavity separation..........ft..	10
Ore thickness..........ft..	20
Ore depth..........ft..	250
Ore grade..........units of product per short ton mined..	0.45
Ore density..........lbf/ft^3..	88
Angle of repose..........deg..	3
Drilling cost per foot..........	$5.00
Capital costs, based on 20-yr mine life:	
Working capital..........pct of annual operating costs..	20
Borehole mining system cost per unit..........	$700,000
Miscellaneous mining equipment per unit..........	$40,000
Processing plant cost to produce wet rock conc..........	$33,000,000
Miscellaneous capital costs..........	$2,500,000
Operation data:	
Mine capacity..........st/d..	10,000
Average mining rate per unit..........st/h..	50
Daily utilization..........h..	24
Annual utilization..........days..	330
Time needed to change boreholes..........h..	4
Mining unit availability time..........pct..	90
Annual site preparation cost..........	$300,000
Maintenance supplies, annual cost per unit..........	$30,000
Annual health and safety cost..........	$190,000
Power, annual cost per unit..........	$600,000
Transportation cost per short ton mined..........	$0.18
Plant operating cost per short ton mined..........	$0.62
Waste disposal and reclamation cost per short ton mined..........	$0.82
Mining labor:	
Operating labor cost per unit-hour..........	$12.00
Ratio, support labor to operating labor..........pct..	80
Ratio, maintenance labor to operating labor..........pct..	25
Ratio, supervisory labor to direct labor..........pct..	20
Payroll benefits..........percent of direct and supervisory labor..	30
Payroll overhead..........do..	40
Financial data:	
Product value per unit of product[1]..........	$30.00
Local taxes and insurance..........percent of capital cost..	2
Extraction tax rate..........percent of revenue..	5.57
Income tax..........percent of taxable income--depletion..	46
Depletion allowance..........percent of depletion base..	14
Cost of capital (interest rate)..........pct/yr..	15

[1]68 pct BPL rock; Engineering and Mining Journal, July 1981.

12-in-diam hole for an 8-in-diam submerged mining tool.

The miscellaneous mining equipment includes the support equipment for installing casing in the boreholes. The processing plant cost is based upon a cost estimate for a 4-millon-st/yr plant to produce wet-rock concentrate quoted at $80 to $100 million. If the capital cost of the beneficiation plant is assumed to be proportional to its ore capacity, then a smaller plant with a capacity of 1.485 million st/yr (10,000 st/d) could be estimated to cost approximately $33 million, based on the ratio 1.485/4 and assuming a $90 million cost for the larger plant (90,000,000 × (1.485/4 = $33,000,000). Miscellaneous capital costs include a bulldozer or grader for site preparation and reclamation, health and safety equipment, a $2 million maintenance facility, and replacement parts.

Under operating costs, the average mining rate for each mining unit is based on doubling the 25-st/h rate demonstrated during the test program. This increased mining rate is predicted based on a factor-of-three increase in cutting-jet power and the doubled slurry flow rate that is expected from a production phosphate mining unit relative to the Bureau of Mines BMT's used in this study. BMT availability is based on an estimated 10-pct downtime for maintenance and a factor to account for nonproduction time spent changing boreholes. Site preparation costs used include payments to land surface owner of $1,000 per acre (not required when surface rights are owned by the mining company) and the cost of operating the site-preparation equipment.

Transportation costs correspond to pipeline costs of $0.18/st-mile of ore transported. The plant operating costs are estimated at $2.50/st of product including depreciation. Subtracting the straight-line depreciation cost yields a cost of $1.38/st of product ($0.62/st mined). The cost of backfilling waste rock into the borehole cavity is $1.50/st backfilled ($0.82/st mined).

Mining labor costs are based on one operator per unit at $12/h. Support labor consists of one employee per two units of direct support at $10/h. Maintenance labor consists of one employee per five mining units. Supervisors are provided at a ratio of one supervisor per six direct-labor employees.

Product value is based on 68 pct bone phosphate of lime (BPL) at $30/st of product. The Florida severance tax of $1.67/st of product was converted to 5.57 pct on revenue at a product value of $30/st.

The input parameters listed in table 12 were analyzed and resulted in the data shown in table 13. The tables show that the borehole phosphate mining in the submerged mode is economically attractive. The dollar values given in table 13 are in 1981 dollars.

An economic-sensitivity study was performed on four parameters around the baseline case for submerged mining. These parameters are mining unit cost, average mining rate, maximum cavity radius, and drilling cost. The results are summarized in figure 21. It can be seen that the mining cost is insensitive to the mining system unit cost. However, the average mining rate, maximum cavity radius, and drilling cost are all important parameters; the average mining rate is especially important at low values. The sensitivity analysis indicates that it is cost-effective to develop a mining system that (1) has a higher average mining rate and (2) is capable of producing a larger radius cavity while using a smaller bore-hole diameter to reduce drilling costs.

TABLE 13. - Economics analysis of submerged cutting jet: output parameters

Ore-body characteristics:	
Recovery..........pct of ore body extracted..	63.14
Ore-body requirements..........st/yr..	5,226,540
Ore-body area required..........acres/yr..	136.35
Ore recovery per borehole..........st/yr..	2,357.74
Effective availability of mining units..........pct..	82.96
Units required..........	10
Effective mining rate per unit..........st/h..	50.22
Boreholes required per year..........	1,399.65
Capital costs:	
Mining units..........	$7,000,000
Miscellaneous mining equipment..........	$400,000
Total equipment and facilities..........	$42,900,000
Annual operating costs:	
Drilling..........	$1,889,520
Operating labor..........	$950,400
Support labor..........	$760,320
Maintenance labor..........	$237,600
Supervisory labor..........	$389,660
Total payroll..........	$2,337,980
Payroll benefits..........	$701,400
Payroll overhead..........	$935,190
Power..........	$6,000,000
Maintenance supplies..........	$300,000
Equipment operation..........	$18,000,090
Annual income tax data:	
Gross revenue..........	$44,549,990
Taxes and insurance..........	$858,000
Extraction taxes..........	$2,481,430
Cost of working capital..........	$675,000
Operating income..........	$22,535,460
Depreciation..........	$2,145,000
Taxable income before depletion allowance..........	$20,390,460
Depletion allowance..........	$6,237,000
Taxable income after depletion allowance..........	$14,153,470
Income tax..........	$6,510,590
Return on investment:	
Working capital, first year..........	$4,500,020
Total investment, first year..........	$47,400,020
Net cash flow per year..........	$16,024,870
Rate of return on investment..........pct..	33.71
Overall unit costs to produce 1,485,000 units of product:	
Capital cost of mining equipment..........	$7,400,000
Mining cost per unit of product..........	$8.98
Total cost per unit of product..........	$20.65
Profit after taxes per unit of product..........	$9.35

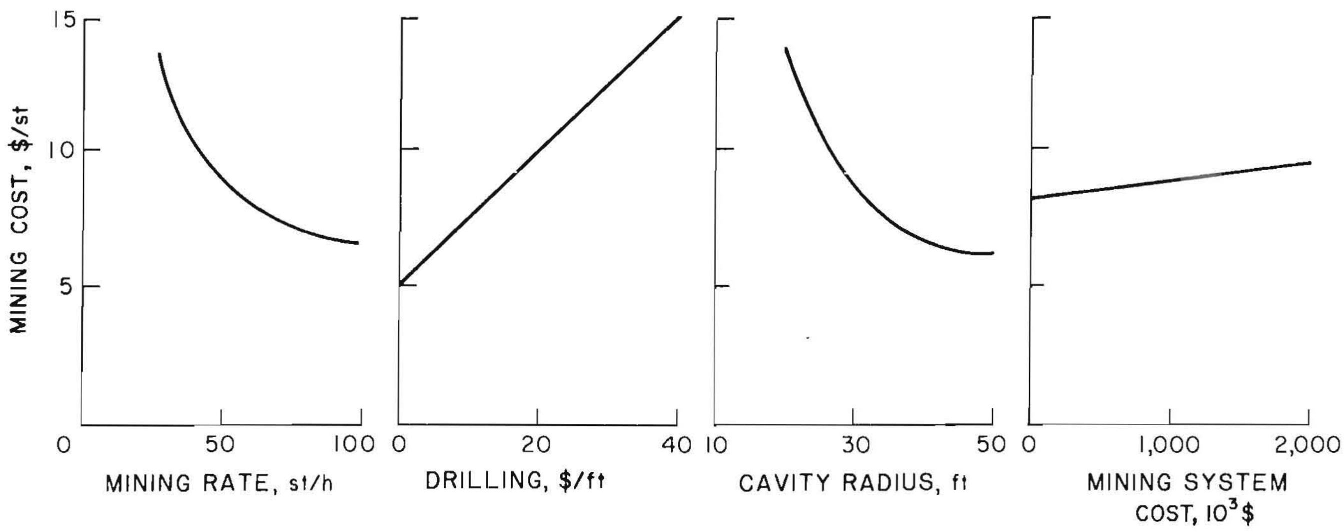

FIGURE 21.—Mining cost sensitivity using submerged cutting jet.

ECONOMICS OF URANIUM MINING

Three sets or uranium ore-body characteristics are analyzed. The pessimistic case is a hard sandstone in a thin (10-ft), deep (400-ft) seam. The most likely case is a soft sandstone of intermediate (15-ft) thickness and intermediate (300-ft) depth. The optimistic case is unconsolidated sand in a thick (20-ft) seam near the surface (150 ft). The initial capital investment and the operating costs of the borehole mining systems for the three types of bodies are summarized in table 14.

TABLE 14. - Cost summary for uranium mining

	Optimistic	Most likely	Pessimistic
Initial capital investment, $10^3$$:			
Mill	14,000	14,000	14,000
Borehole mining units	3,000	6,000	10,500
Exploration	2,500	2,500	2,500
Reservoirs and water supply	101	101	101
Slurry and water lines	8	16	28
Miscellaneous	250	250	250
Total	19,859	22,867	27,379
Operating costs, $/st:			
Labor	1.30	2.60	4.54
Payroll benefits	.39	.78	1.36
Payroll overhead	.52	1.04	1.82
Fuel	.44	.87	1.53
Drilling	.76	3.15	12.74
Milling	8.00	8.00	8.00
Trailings disposal	1.52	1.52	1.52
Maintenance supplies	.45	.91	1.59
Tax and insurance	1.21	1.39	1.66
Transportation	2.00	2.00	2.00
Miscellaneous operating supplies	.76	.76	.76
Total	17.35	23.02	37.52

The number of mining units required for mining of sand, soft sandstone, or hard sandstone (two, four, and seven, respectively) has an important effect on total investment and labor operating costs. The number of boreholes drilled per year (45, 98, and 286, respectively) and the depth of the boreholes have a significant effect on operating costs.

The return on investment is shown in figure 22 as a function of ore grade for the three ore-body types. The gross revenue is based on \$40/st of U_3O_8, royalty payments of 7 pct of the gross revenue have been deducted, and a straight-line depreciation schedule has been assumed. A depreciation allowance has been deducted from the taxable income. The

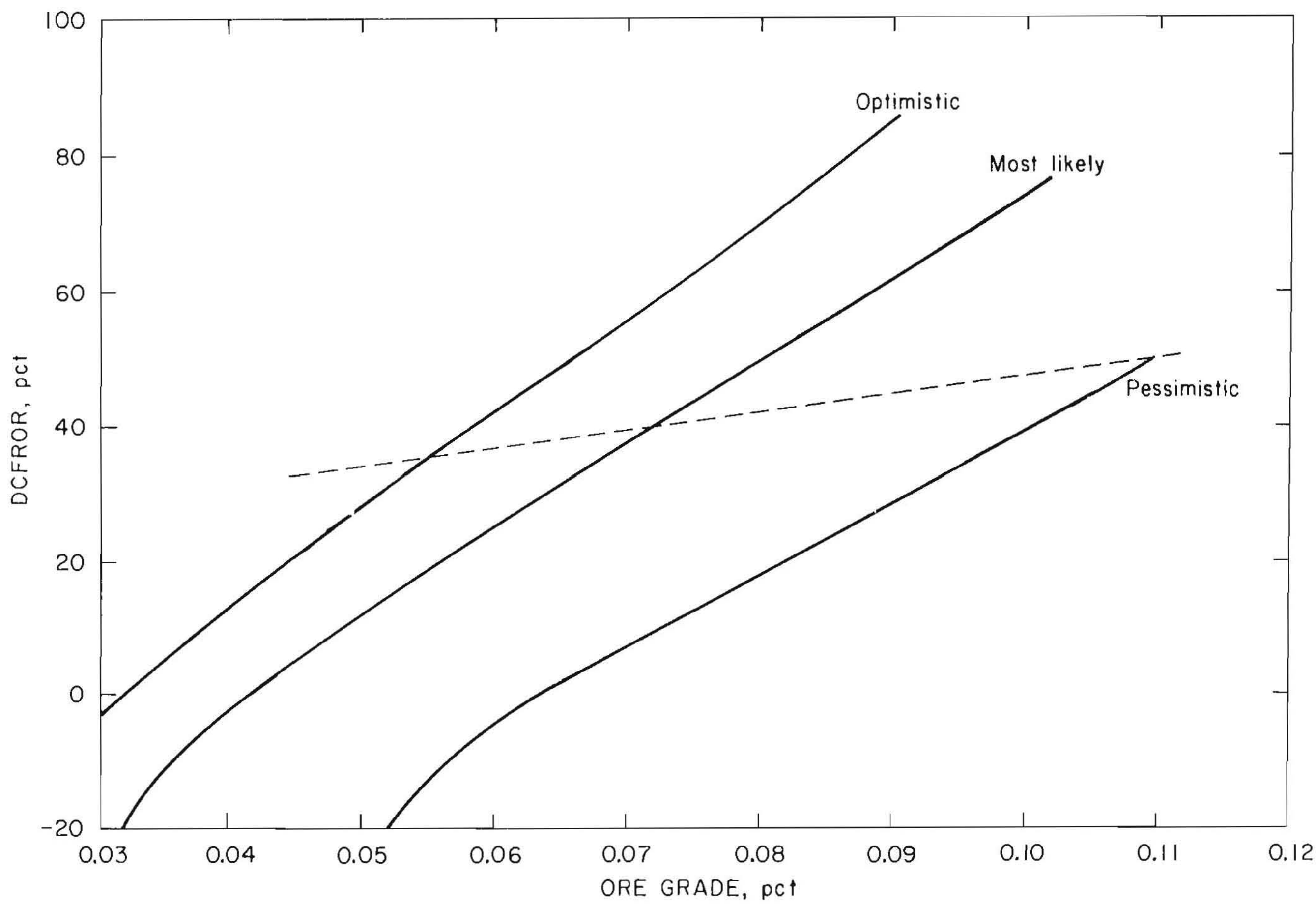

FIGURE 22.—Uranium mining: effect of type of ore body on profitability.

TABLE 15. - Uranium mining assumptions

	Optimistic	Most likely	Pessimistic
Cavity radius..............ft..	45	35	25
Mining arc................deg..	270	270	360
Ore thickness..............ft..	20	15	10
Ore depth..................ft..	150	300	400
Drilling cost per foot..........	$25	$25	$35
Mining rate, nominal......st/h..	40	20	10

amount is based on one of the following, whichever is lesser: (1) 22 pct of the gross revenue minus royalty, or (2) 50 pct of the taxable income before depletion allowance. Income tax of 46 pct of the taxable income after depletion allowance and the initial working capital of 25 pct of the annual gross revenue have been included. The net cash flow is the operating income less (1) income tax, (2) working capital (first year only), and (3) initial capital investment (first year only).

The six operating parameters affected by the type of ore body are shown in table 15: the radius of a complete borehole cavity, the shape of the cavity, ore seam thickness, ore seam depth below the surface, estimated drilling costs, and the mining rate. Estimated drilling costs and mining rate vary because of rock hardness. Depletion allowance of 22 pct of the gross revenue minus royalty applies above the dashed line in figure 22, whereas a depletion allowance of 50 pct of the taxable income before depletion allowance applies below the line.

ECONOMICS OF OIL-SAND MINING

A detailed list of parameters used in the mining cost analysis is given in table 16. Parameters relevant to the Bureau of Mines tool used at the Taft, CA, test site are ore thickness (25 ft), overbearing thickness (125 ft), and average mining rate (14 st/h). Another analysis is performed for a hypothetical borehole mining system. This system will have a faster average mining rate (20, 40, or 100 st/h) than the Bureau of Mines system (14 st/h) and will be used at a site having an ore thickness of 200 ft and an overburden thickness of 200 ft.

The initial capital investment and operating cost of the two borehole mining systems are summarized in table 17. The second column shows the results for the Bureau of Mines tool (14 st/h) with the selling price adjusted to give a discounted cash flow-rate of return (DCFROR) of 20 pct. The next three columns are results for the hypothetical tool at the mining rates (20, 40, and 100 st/h) with the selling price adjusted to give a DCFROR of 20 pct.

Table 18 summarizes differences between the Bureau and the hypothetical systems. The number of mining units and the number of boreholes drilled per year affect operating costs.

Figures 23-27 illustrate the sensitivity of DCFROR to various mining parameters including cavity radius, ore thickness, overburden thickness, ore grade, and average mining rate. The figures are based on the most likely hypothetical case with the selling price set at $25/bbl, and

TABLE 16. - Basis for mining cost analysis

	Bureau of Mines tool	Hypothetical tool
Ore body:		
Cavity radius...ft..	25	25
Cavity separation...ft..	10	10
Ore thickness...ft..	25	200
Overburden thickness...ft..	125	200
Ore recovery...bbl/st..	0.50	0.50
Ore body width...ft..	2,000	2,000
Ore density...lbf/ft^3..	118	118
Mining arc...deg..	360	360
Drilling cost per foot...	$25	$25
Capital cost data:		
Exploration cost...	$2,000,000	$2,000,000
Capital depreciation period...yr..	10	10
Working capital...pct..	25	25
Mining system cost per unit...	$1,500,000	$1,500,000
Slurry and water lines per unit...	$15,000	$15,000
Plant...	$30,000,000	$30,000,000
Miscellaneous capital costs...	$5,000,000	$5,000,000
Operation:		
Mine capacity...st/d..	10,000	10,000
Av. mining rate per unit...st/h..	14	20, 40 or 100
Daily utilization...h..	24	24
Annual utilization...days..	330	330
Mining unit availability time...pct..	60	60
Reservoirs and water supply, cost per year...	$400,000	$400,000
Annual maintenance supplies per unit...	$150,000	$150,000
Misc. operating supplies per year...	$1,200,000	$1,200,000
Annual fuel costs per unit...	$100,000	$100,000
Transportation per short ton...	$0.40	$0.40
Plant operation per short ton...	$3.50	$3.50
Tailings disposal per short ton...	$1.50	$1.50
Mining labor (excl. plant and drilling):		
Operating labor per unit per hour[1]...	$18.00	$18.00
Support labor...pct oper. labor..	25	25
Maintenance labor...do..	25	25
Supervisory labor...pct dir. labor..	20	20
Payroll benefits...pct total labor..	30	30
Payroll overhead...do..	40	40
Finance:		
Local taxes and insurance...pct capital cost..	2	2
Royalty payments...pct gross revenue..	7	7
Income tax...pct taxable income..	46	46
Depletion allowance...	0	0

[1]Based on an average of 1.5 workers per unit.

TABLE 17. - Cost summary for oil-sand mining

	Bureau of Mines tool	Hypothetical tool: Low mining rate	Hypothetical tool: Most likely	Hypothetical tool: High mining rate
Initial capital cost items, 10^3\$:				
Separation plant	30,000	30,000	30,000	30,000
Borehole mining units (number)	75,000(50)	52,500(35)	27,000(18)	10,500(7)
Working capital	27,638	21,450	15,676	11.963
Exploration	2,000	2,000	2,000	2,000
Slurry and water lines	750	525	270	105
Miscellaneous	5,000	5,000	5,000	5,000
Total capital cost	140,388	111,475	79,945	59,568
Operating cost items, \$/bbl:				
Reservoirs and site preparation	.24	.24	.24	.24
Drilling	2.93	.91	.91	.91
Mining:				
Payroll	7.78	5.44	2.80	1.09
Payroll benefits	2.33	1.63	.84	.33
Payroll overhead	3.11	2.18	1.12	.43
Fuel	3.03	2.12	1.09	.42
Maintenance supplies	4.55	3.18	1.64	.64
Misc. operating supplies	.73	.73	.73	.73
Ore transportation	.80	.80	.80	.80
Separation plant	7.00	7.00	7.00	7.00
Tailings disposal	3.00	3.00	3.00	3.00
Total direct cost	35.50	27.23	20.17	15.59
Indirect cost items, \$bbl:				
Local taxes and insurance	1.37	1.09	.78	.58
Royalty payments	4.69	3.64	2.66	2.03
Federal income tax	8.56	6.71	4.83	3.64
Deprecitation	8.51	6.76	4.84	3.61
Total indirect cost	23.13	18.20	13.11	9.86
Profit after taxes (for DCFROR of 20 pct), \$/bbl	8.37	6.57	4.72	3.55
Total (selling price)	67.00	52.00	38.00	29.00

TABLE 18. - Production summary for oil-sand mining

	Bureau of Mines tool	Hypothetical tool[1]
Recovery..........percent ore in place	55	55
Ore-body requirements..........10^3st/yr	6,050	6,050
Ore-body length required..........ft/yr	2,051	256
Ore per borehole..........st	2,896	23,169
Boreholes required per year	1,139	142
Annual production..........10^3bbl	1,650	1,650

[1]Data shown are the same for all mining rates.

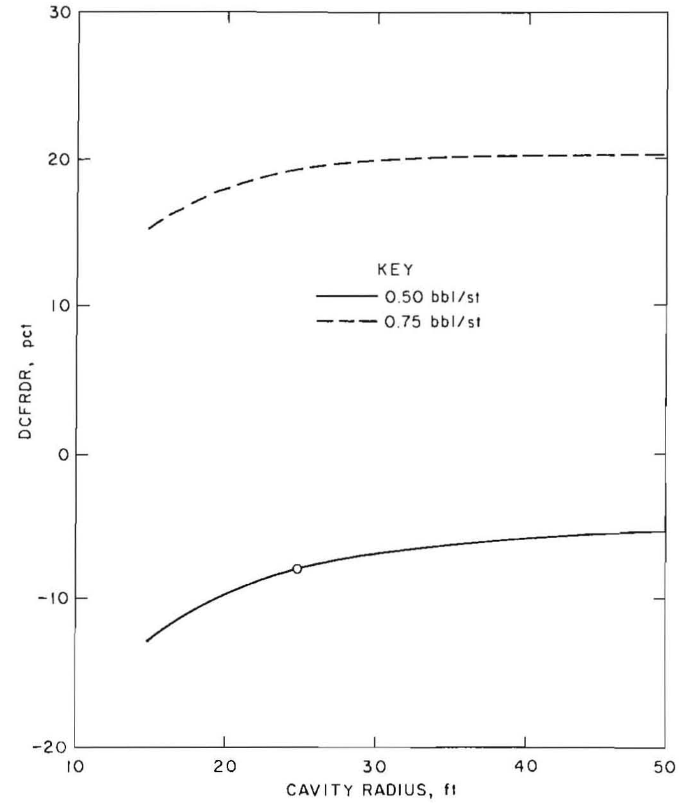

FIGURE 23.—Oil-sand mining: return on investment versus cavity radius.

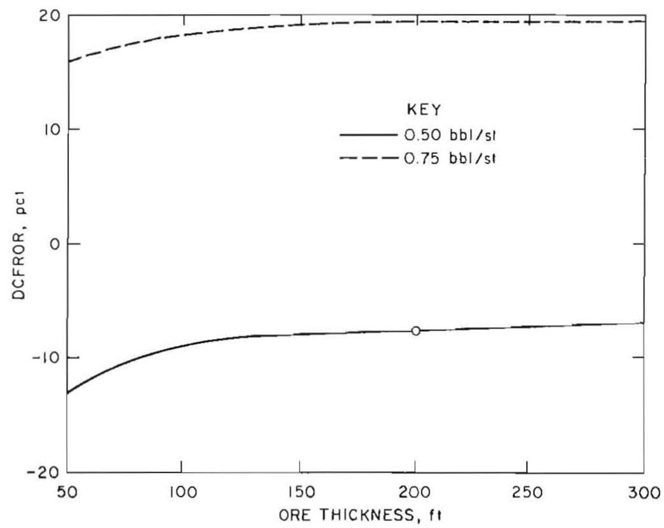

FIGURE 24.—Oil-sand mining: return on investment versus ore thickness.

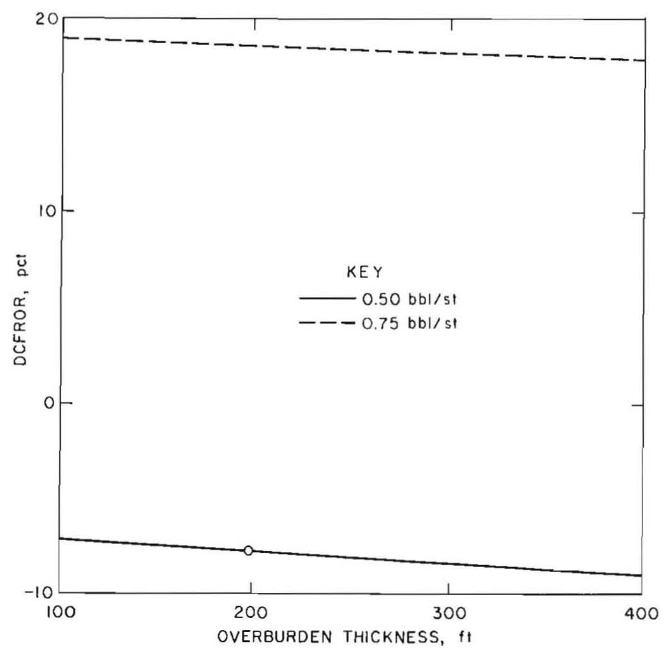

FIGURE 25.—Oil-sand mining: return on investment versus overburden thickness.

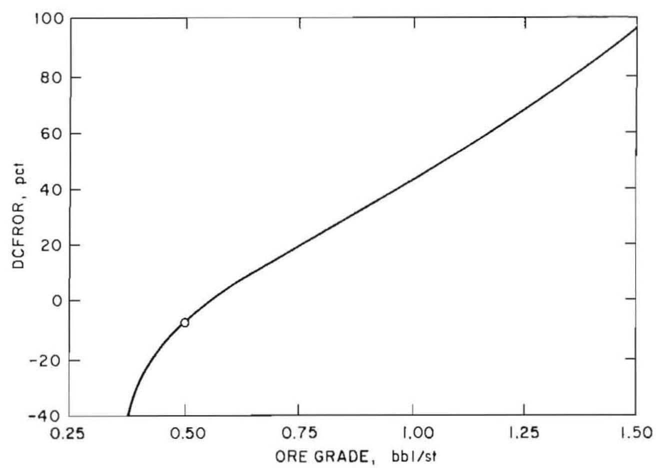

FIGURE 26.—Oil-sand mining: return on investment versus ore grade.

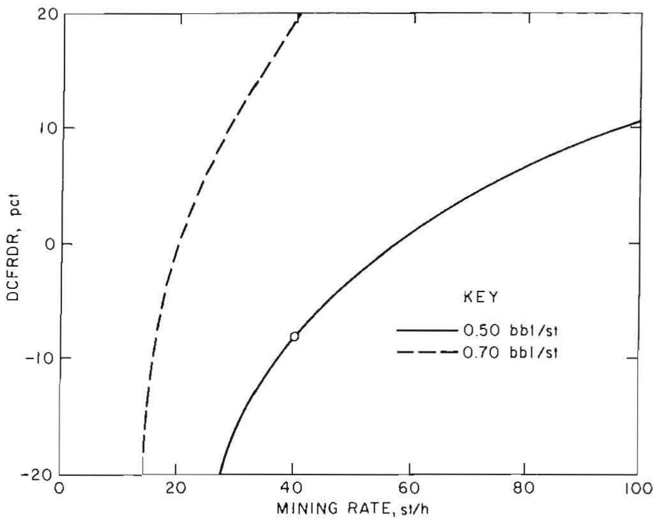

FIGURE 27.—Oil-sand mining: return on investment versus mining rate.

each figure includes curves for two ore grades. It is shown that the sensitivity results do not vary with grade and that good rate of return values are possible with moderate improvements in ore grade. A circle on the 0.50-bbl/st curve shows the baseline data point, the condition chosen for the cost analysis in table 15. This analysis shows that there is insensitivity to cavity radius over 30 ft (fig. 23), ore thickness over 100 ft (fig. 24), and overburden thickness under 400 ft (fig. 25). Ore grade (fig. 26) has a large effect on the economics, as does the mining rate (fig. 27). If an ore body exists with a grade higher than 0.75 bbl/st, it could be mined very profitably at 40 st/h or more.

SUMMARY AND CONCLUSIONS

This paper has reviewed research in borehole (slurry) mining conducted by the Bureau of Mines from 1975 to 1980. This research has successfully demonstrated the technical feasibility of the remote extraction of coal, oil sands, uranium ore, and phosphates as a slurry through a borehole. It has also shown that borehole mining can be performed so that the associated environmental impact is minimal.

Borehole mining of phosphates was the most successful of the field trials. The productivity was higher than that of the other commodities because of the lack of induration of the phosphate ore, and because of the high-positive suction head on the slurry pump owing to the fact that mining took place with the borehole filled with water.

The Agrico Mining Co. plans to conduct further testing in St. Johns County with the aim of ultimately conducting commercial mining of the deep phosphate deposits of northeast Florida.

Borehole mining fulfills the need for a method to mine "incremental" uranium ore. Incremental ore refers to those small, irregular, high-grade uranium ore bodies that, although adjacent to working open pits, cannot be mined from these pits because of engineering limitations. The small size and the irregularity of these deposits make them ideal candidates for borehole mining because of the high areal selectivity of the borehole mining method.

The borehole mining field tests of oil sands and coal demonstrated the technical feasibility of the remote extraction of these commodities through boreholes, but the rates at which these fuels were produced were too low for commercial viability. The test demonstrated the need for developing borehole mining equipment that will allow higher productivity.

Backfilling of borehole-mined cavities by horizontal, underwater jetting of slurry into the cavities was proven to be feasible. Backfilling is likely to be an attractive method to prevent subsidence in those cases where a suitable supply of granular fill is available. Disruption to the environment would be minimal unless fill would have to be obtained from a borrow pit.

Environmental monitoring for groundwater pollution and subsidence conducted during these mining tests indicated the virtual absence of both phenomena. This indicates that borehole mining may be an attractive candidate for mining environmentally sensitive areas.

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