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1. Overview of the Carlsbad potash district, New Mexico

James M. Barker and George S. Austin

New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801

INTRODUCTION

Potash is the common industrial term for potassium in various chemical combinations with sodium, magnesium, chloride, and sulfate (Table 1.1). Potassium is one of the three essential plant nutrients and is the "K" in the "NPK" fertilizer rating, along with nitrogen (N) and phosphorus (P). The potassium in potash is reported as K_2O eq. wt.% (%K_2O hereafter) although potassium oxide is not directly present in natural potassium salts (Table 1.2). For potash fertilizers, K_2O is closest chemically to the form of potassium used by plants (Sullivan and Michael, 1986) and is the best means to compare fairly the diverse mineralogy of potash.

Important natural and commercial soluble potassium salts are sylvite and langbeinite. Sylvinite, a mixture of sylvite and halite, is the typical ore mined in the Carlsbad potash district (CPD) in southeast New Mexico (Fig. 1.1). The CPD is near the northeast border of the Delaware Basin (Fig. 1.1) and contains the largest domestic potash reserves. Soluble potash occurs primarily in Eddy and Lea Counties, which contain the only potash mines in the state. The Potash enclave (Fig. 1.2), also designated the Known Potash Leasing Area (KPLA), consists of that part of the CPD where federal and state lands under BLM management require competitive bidding for mineral leases. The WIPP site (New Mexico Bureau of Mines and Mineral Resources, 1995) is on the southeast edge of the KPLA in secs. 15–22 and 27–34 T22S R31E (Fig. 1.2).

The KPLA lies between Carlsbad and Hobbs, New Mexico, and comprises about 425 mi² (Cheeseman, 1978; Barker and Austin, 1993). The area underlain by other salts and less-soluble potash minerals, such as polyhalite, is much larger than the KPLA (Fig. 1.1). Salado Formation evaporites underlie about 58,000 mi², halite about 37,000 mi², and polyhalite about 27,000 mi² (Jones, 1972). Areal limits of the CPD on the north, east, and south are determined by drilling. The CPD is bounded on the west by dissolution truncation of shallow Salado evaporites caused by circulating ground water in the Pecos River drainage basin (Griswold, 1982).

Potassium products (Table 1.2) from New Mexico are muriate of potash (potassium chloride, KCl; also called MOP, muriate, or sylvite by industry), langbeinite (potassium magnesium sulfate, $K_2SO_4 \cdot 2MgSO_4$, called sulfate of potash magnesia or SOPM), and manufactured potassium sulfate (K_2SO_4, called sulfate of potash or SOP). MOP, sold in various grades (Table 1.3), makes up about 70% of New Mexico potash output; SOPM and SOP account for the remaining 30%. IMC Kalium, the largest producer in the CPD, supplies all three types of soluble potash salts (Table 1.2); Mississippi Chemical produces mostly muriate.

The United States ranked fifth in world potash production at 1.57 million short tons (st) in 1997. New Mexico accounted for about 80% of domestic production (1.26 million st), supplied about 19% of domestic consumption (Table 1.4), and has about 57% of domestic reserves (Searls, 1993). The remaining 81% of consumption was imported primarily from Saskatchewan, Canada (91% of imports). Domestic potash production is composed of 65% as muriate, 30% as sulfate or langbeinite, and 5% in other forms (Searls, 1998).

About 88% of soluble potash minerals is used in fertilizer, so potash market trends closely parallel agricultural supply and demand (Searls, 1998). Most of the remaining 12% is used in chemicals, mainly aqueous electrolysis of potash to potassium hydroxide. Potassium chemicals are used in medicines, pharmaceuticals, salt substitutes, soap, matches, glass, storage batteries, and other uses.

BRIEF HISTORY OF POTASH DEVELOPMENT

The following discussion of potash mining history draws heavily on Walls (1985) and Williams-Stroud et al. (1994). Early large-scale use of potash started in Germany in the mid-19th century. The modern United States potash industry is primarily the product of a World War I (WWI) embargo on German potash—the only large source then known—that drove prices higher than $500/st. Wartime potash (for saltpeter manufacture) was produced at more than 100 plants, mainly in Nebraska and California, each with very small output. Bedded potash was discovered in 1925 in Eddy County, New Mexico, in Snowden McSweeney No. 1 well on a V. H. McNutt permit near the center of that part of the KPLA now mined (Fig. 1.2; T21S R30E). Potash was cored in April 1926, and the Federal Potash Exploration Act was passed in June.

The American Potash Co. was formed in 1926 for potash exploration in southeast New Mexico. A 1,062-ft shaft was started in December 1929 and completed in 1930. The first commercial potash from New Mexico was shipped in March 1931, 12 yrs after WWI. Assets of American Potash, incorporated in 1930 as United States Potash Co., are now owned by Mississippi Chemical (Table 1.5). The Potash Company of America (PCA) was formed in 1931 and completed a shaft in early 1934. The Santa Fe Railroad constructed a 20-mi spur from Carlsbad to the mine; later, spurs were run to other mines and mills. The PCA mine was operated until recently as Eddy Potash. In 1996, it was purchased by Mississippi Chemical. Although the mine is closed, it is being reevaluated and may be opened for solution mining.

By 1934, at least 11 companies were exploring for potash in southeast New Mexico. In 1936, Union Potash & Chemical, Texas Potash, Independent Potash & Chemical, New Mexico Potash, and Carlsbad Potash merged into what is now IMC Kalium and began producing sylvite, langbeinite, and arcanite (Table 1.1) in 1940.

Domestic production supplied virtually all domestic potash consumption between 1941 and 1949. New Mexico produced about 900,000 st of marketable potash containing 475,000 st of K_2O in 1941 and was the largest domestic potash producer in 1944, providing 85% of consumption.

Active exploration by several companies in 1949 resulted in production in 1951 by Duval Texas Sulfur via two mine shafts at the Wills–Weaver mine. Production lasted a relatively short time, and the mine, along with the Saunders mine, is now abandoned. Duval's operations, including the mill on the Saunders property and Nash Draw mine, were purchased by Western Ag–Minerals and in 1997 by IMC Kalium.

In 1952 Southwest Potash began an operation. In the 1990s the property was operated by Horizon Potash but is presently closed. The shaft of National Potash (now owned by Mississippi Chemical) in Lea County, New Mexico, was completed in 1956, and production started in 1957. In 1998 only the surface facilities were used for compaction. It is identified as Mississippi Potash North. The Kerr–McGee facility was completed in 1957 and began operation in 1965. It later operated as New Mexico Potash and in 1996 was pur-

TABLE 1.1—Evaporite minerals and rocks of the Carlsbad potash district (after Griswold, 1982). Only sylvite and langbeinite are presently ore minerals. Hydrated potassium minerals are not amenable to existing concentration methods. *Common minerals and rocks in the Carlsbad potash district; **nc**, not calculated for mixture.

Mineral or rock	Chemical formula	Equivalent wt.% K	KCl	K_2O	K_2SO_4
Anhydrite*	$CaSO_4$	—	—	—	—
Arcanite	K_2SO_4	44.88	—	54.06	100.00
Bischofite	$MgCl_2{\cdot}6H_2O$	—	—	—	—
Bloedite	$Na_2SO_4{\cdot}MgSO_4{\cdot}4H_2O$	—	—	—	—
Carnallite*	$KCl{\cdot}MgCl_2{\cdot}6H_2O$	14.07	26.83	16.95	—
Erythrosiderite	$2KCl{\cdot}FeCl_3{\cdot}H_2O$	23.75	45.28	28.61	—
Glaserite	$K_3Na(SO_4)_2$	35.29	—	42.51	78.63
Glauberite	$Na_2SO_4{\cdot}CaSO_4$	—	—	—	—
Gypsum*	$CaSO_4{\cdot}2H_2O$	—	—	—	—
Halite*	NaCl	—	—	—	—
Hydrophilite	$KCl{\cdot}CaCl_2{\cdot}6H_2O$	13.32	25.39	16.04	—
Kainite*	$MgSO_4{\cdot}KCl{\cdot}3H_2O$	15.71	29.94	18.92	—
Kieserite*	$MgSO_4{\cdot}H_2O$	—	—	—	—
Langbeinite*	$K_2SO_4{\cdot}2MgSO_4$	18.84	—	22.70	41.99
Leonite*	$K_2SO_4{\cdot}MgSO_4{\cdot}4H_2O$	21.33	—	25.69	47.52
Mirabilite	$Na_2SO_4{\cdot}10H_2O$	—	—	—	—
Polyhalite*	$K_2SO_4{\cdot}MgSO_4{\cdot}2CaSO_4{\cdot}2H_2O$	12.97	—	15.62	28.90
Schoenite	$K_2SO_4{\cdot}MgSO_4{\cdot}6H_2O$	19.42	—	23.39	43.27
Sylvinite*	KCl + NaCl	nc	nc	10 to 35	—
Sylvite*	KCl	52.44	100.00	63.17	—
Syngenite	$K_2SO_4{\cdot}CaSO_4{\cdot}H_2O$	23.81	—	28.68	53.06
Tachyhydrite	$CaCl_2{\cdot}2MgCl_2{\cdot}12H_2O$	—	—	—	—

TABLE 1.2—K_2O equivalent wt.% of commercial potash minerals (after Adams and Hite, 1983; Searls, 1985; Sullivan and Michael, 1986).

Chemical compound	Chemical formula	Mineral name	Industry name	Max K_2O eq. wt%	Grades K_2O eq. wt.%	Remarks
Potassium chloride	KCl	sylvite	MOP, sylvite, muriate	63.18	61 USA 60 World 50 World 40 World 30 World	Coarse grades used to match sizes of N-P ingredients to minimize segregation.
Potassium chloride + sodium chloride	KCl+NaCl	"sylvinite"	—	~35	—	Easily mined with continuous miners.
Potassium/magnesium double sulfate	$K_2SO_4{\cdot}2MgSO_4$	langbeinite	SOPM, sulfate of potash magnesia	22.70	22 21.5	Preferred for tobacco, potato, sugar beet, and citrus crops to prevent chloride burn; harder to mine than chlorides.
Potassium sulfate	K_2SO_4	arcanite	SOP	54.06	50	Preferred for tobacco, potato, sugar beet and citrus crops to prevent chloride burn; mostly manufactured, some is natural.
Potassium nitrate	KNO_3	niter	—	—	—	Natural is only 14% K_2O (admixture) crude salt mixed with $NaNO_3$; mostly manufactured, some is natural.
Potassium chloride	KCl	manure salts	—	19	—	Manufactured.

chased by Mississippi Chemical and renamed Mississippi Potash East.

Minable potash was discovered in Saskatchewan, Canada in 1952, but many factors prevented major production until the late 1950s, with exports to the United States commencing in 1962. In 1964, U.S. domestic consumption permanently exceeded domestic production. The highest production year for New Mexico potash was 5.7 million st KCl or 3.3 million st K_2O in 1966. Production has decreased steadily as lower-cost Canadian potash has supplied an increasing share of U.S. potash consumption. The cross-over years were 1970 and 1971 when imports first exceeded domestic production. A low of 1.3 million st K_2O was produced in 1986 in the United States. Overall U.S. potash capacity utilization declined from 83% (1984) to 61% (1985), made more significant because total capacity also declined during this period.

A dumping finding against Canadian producers by the International Trade Commission in 1987 and the 1988 antidumping agreement between the U.S. Department of Commerce and Canadian producers reversed the downward trend in output and utilization and revitalized the industry in New Mexico. Mississippi Chemical was reactivated in 1988 after several years on standby. Potash prices increased after the 1988 antidumping agreement with

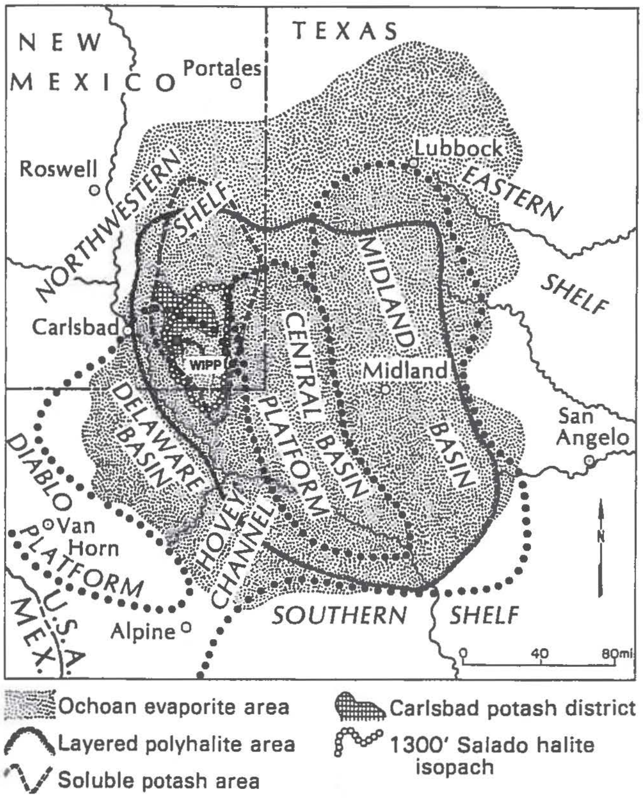

FIGURE 1.1—Carlsbad potash district in the southwestern United States and its relation to the regional subsurface geology (after Jones, 1972; Austin, 1980; Lowenstein, 1988).

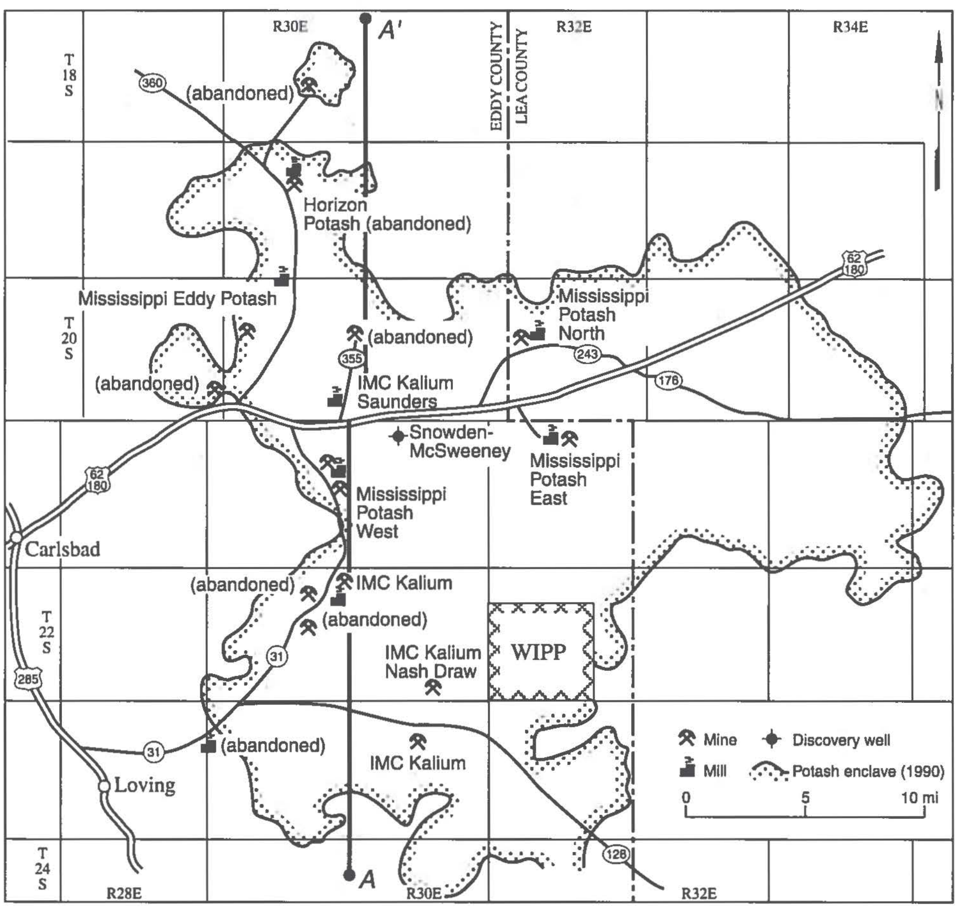

FIGURE 1.2—Active, inactive, and abandoned potash facilities in Eddy and Lea Counties, southeast New Mexico showing general outline of the Potash enclave (KPLA) as of 1984. Only minor adjustments have occurred since 1984 (U.S. Bureau of Land Management, Minerals Management Service, oral comm. June 1990). Cross section *A–A′* along the east side of R30E (north) and R29E (south) is in Fig. 1.3. Note that ranges are offset one range to the east below T20S.

Canada. This allowed AMAX Chemical to continue operation until its mine was purchased by Horizon in 1992. The impact of Canadian, Russian, and other competition, declining reserves and grades, and increasing mining costs has led to many changes in ownership since 1985. Of the older companies, only Mississippi Chemical and IMC Kalium remained active in 1998 (Table 1.5).

TABLE 1.3—Particle-size grades of muriate of potash (MOP, muriate, sylvite), langbeinite (SOPM), and sulfate of potash (SOP) products (after Searls, 1985). [1]From approximately 2% to 98% by wt. cumulative. [2]Tyler standard. [3]Blend, new grade with midpoint between 8 and 10 mesh introduced by Canadian producers. NA, not applicable.

Grade	Minimum K_2O equiv. wt.%	Approximate particle-size range[1] Mesh[2]	Millimeters	Type of potash	Remarks
Granular	61, 50, 22	6–20	3.35–0.85	Muriate & sulfates	—
Blend[3]	60	6–14	3.35–1.18	Muriate	Replaces granular and coarse grades
Coarse	60	8–28	2.4–0.6	Muriate	—
Standard	60, 50, 22	14–65	1.2–0.21	Muriate & sulfates	—
Special standard	60	35–150	0.4–0.11	Muriate & sulfate	Canada only
Soluble/ suspension	62	35–150	0.4–0.11	Muriate	—
Chemical	63	NA	NA	Muriate	—

TABLE 1.4—Potash statistics for calendar years 1980 through 1997. Data modified from J. P. Searls, U.S. Bureau of Mines, oral comm. 1990, 1993 and written comm. 1995, 1998; and U.S. Bureau of Mines Mineral Commodity Reports, Mineral Commodity Profiles, Mineral Industry Surveys, and Mineral Yearbooks (1980–1998). w*, withheld.

Calendar year	Marketable U.S. production (1,000 st K_2O)	Apparent U.S. consumption (1,000 st K_2O)	Net U.S. import reliance (%)	N.M. share of U.S. production (%)	N.M. supply to U.S. consumption (%)	Avg. price NM marketable Potash ($/st K_2O)	Value NM marketable Potash FOB mine (million $)
1980	2,468	6,999	65	83	29	141	289
1981	2,377	6,849	65	84	29	158	261
1982	1,966	5,647	65	82	29	124	205
1983	1,575	6,231	75	87	22	124	175
1984	1,724	6,638	74	90	23	131	204
1985	1,429	5,893	76	87	21	126	156
1986	1,325	5,338	75	82	20	122	133
1987	1,391	5,609	75	87	22	120	174
1988	1,677	5,803	71	89	26	152	214
1989	1,758	5,678	65	89	31	161	243
1990	1,888	5,963	68	89	28	153	246
1991	1,928	5,779	68	85	28	155	251
1992	1,879	5,898	68	83	27	162	257
1993	1,664	5,984	72	82	23	164	216
1994	1,543	6,403	76	81	21	168	218
1995	1,631	6,403	75	75	19	172	209
1996	1,532	6,491	77	80	19	178	225
1997	1,576	6,491	76	80	19	w*	w*

ECONOMIC GEOLOGY

Potash-bearing evaporites occur in Ochoan (Upper Permian) marine rocks in the Delaware Basin part of the Permian Basin of west Texas and southeast New Mexico. Ochoan rocks about 240 million yrs old overlie Guadalupian carbonates and sandstones in the basin and overlie dominantly reefal carbonates along the basin flanks (King, 1948; Hayes, 1964; Pray, 1988; Ulmer-Scholle et al., 1993). The Ochoan is divided into four formations (Fig. 1.3; Lowenstein, 1988): Castile Formation (oldest)—banded anhydrite/limestone; Salado Formation—potash (ore mainly in the McNutt Member), halite, muddy halite, anhydrite, polyhalite, and dolomite; Rustler Formation—halite, gypsum, anhydrite, siliciclastic rocks, and dolostone; and Dewey Lake Red Beds (youngest)—siliciclastic mudstone. The Castile and basal parts of the Salado have extensive sections of laminated limestone/anhydrite cyclic couplets or "banding" (Madsen and Raup, 1988). Anhydrite interbeds in the Salado, although often replaced by polyhalite, show extensive lateral continuity that allow recognition of 43 marker beds in the CPD (Jones et al., 1960a, b).

The Salado Formation, a maximum of 700 m thick, is an evaporite sequence dominated by 200–400 m of halite and muddy halite in the KPLA (Lowenstein, 1988). It hosts 12 ore zones: 11 in the middle or McNutt Member (Fig. 1.4) and the 12th in the upper member. The area underlain by the 12 ore zones is about 1,900 mi^2 (Jones, 1972; Lowenstein, 1988).

McNutt Member

The McNutt Member of the Salado Formation dips about 1° southeast in the CPD and is approximately 120 m thick (Griswold, 1982). The McNutt contains evaporite minerals consisting of ore-grade sylvite and langbeinite, with halite, muddy halite, and accessory leonite, kainite, carnallite, polyhalite, kieserite, bloedite, and anhydrite (Barker and Austin, 1993; Table 1.1). In addition, the McNutt Member consists of nonevaporite minerals such as primary alkali feldspar, hematite, and quartz; secondary magnesite, illite, clinochlore, talc, talc–saponite, and corrensite; and uniform to completely random, interstratified clinochlore-saponite (Bodine, 1978; Lowenstein, 1988). All the clay minerals are well crystallized with sharp x-ray diffraction maxima.

TABLE 1.5—General mineralogy and minability of ore zones of companies producing in the Carlsbad potash district (after Griswold, 1982; Searls, oral comm. June 1990, June 1998). *Base of marker bed; see Fig. 1.4. **IMC**, IMC Kalium.

Ore zone	Marker bed near base*	General mineralogy	Producing company, mine	Minability
11	MB 117	Mostly carnallite, minor sylvite, leonite	——	Not mined to date
10	MB 120	Sylvite, sylvinite	Mississippi Potash East and West	Second best in the district; high-clay content (6–7%)
9	MB 121	Carnallite, kieserite, sylvite	——	Not mined to date
8	Union	Sylvite	——	Moderate reserves; important in future; high clay
7	——	Sylvite, sylvinite	Mississippi Potash West	Moderate reserves; moderate clay (3–4%)
6	——	Carnallite, kieserite, etc.	——	Not mined to date
5	MB 123	Sylvite, langbeinite	IMC	Moderate reserves; trace clay (1%)
4	——	Langbeinite, sylvite	IMC, IMC Nash Draw	Principal source of langbeinite; mixed ore
3	——	Sylvite, sylvinite	——	Ranks 3rd in production of sylvite
2	MB 125	Carnallite, kieserite, etc.	——	Not mined to date
1	MB 126	Sylvite, sylvinite	——	Was the major sylvite-producing zone, now nearly mined out

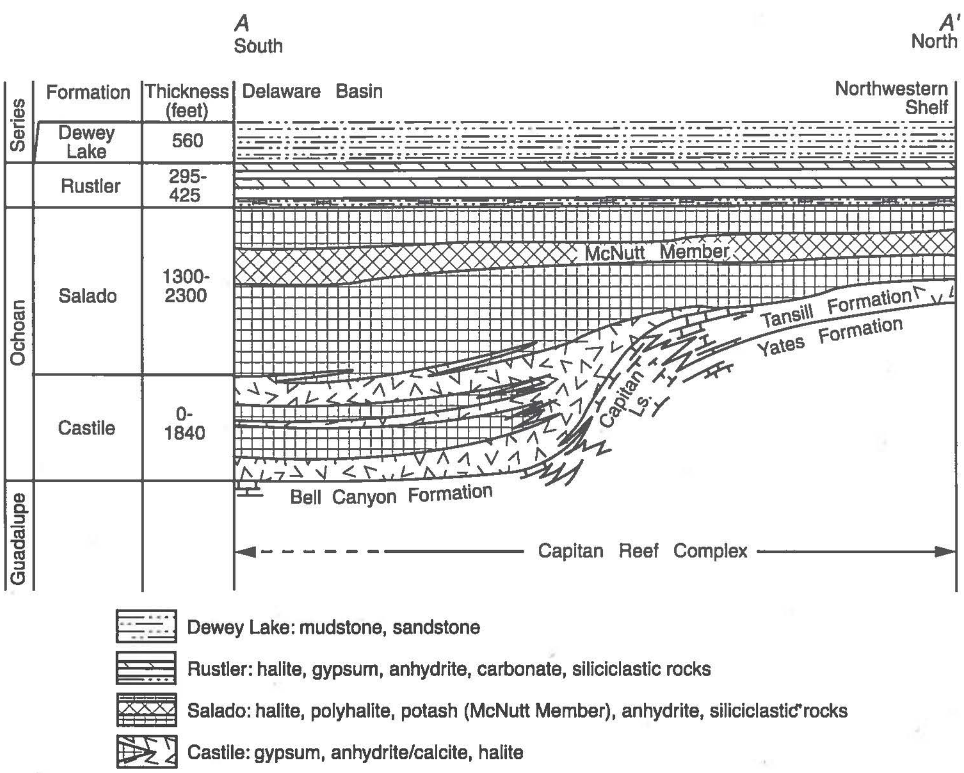

FIGURE 1.3—Diagrammatic north–south cross section and stratigraphic relationships of the north edge of the Delaware Basin, southeast New Mexico (after Jones, 1972; Austin, 1980). Line of section is in Fig. 1.2.

Mudstone and siliciclastic sediment in the muddy halite of the McNutt Member were derived from erosion of the surrounding basin margin dominantly to the north and east (Lowenstein, 1988). Lowenstein (1988) confirmed previous

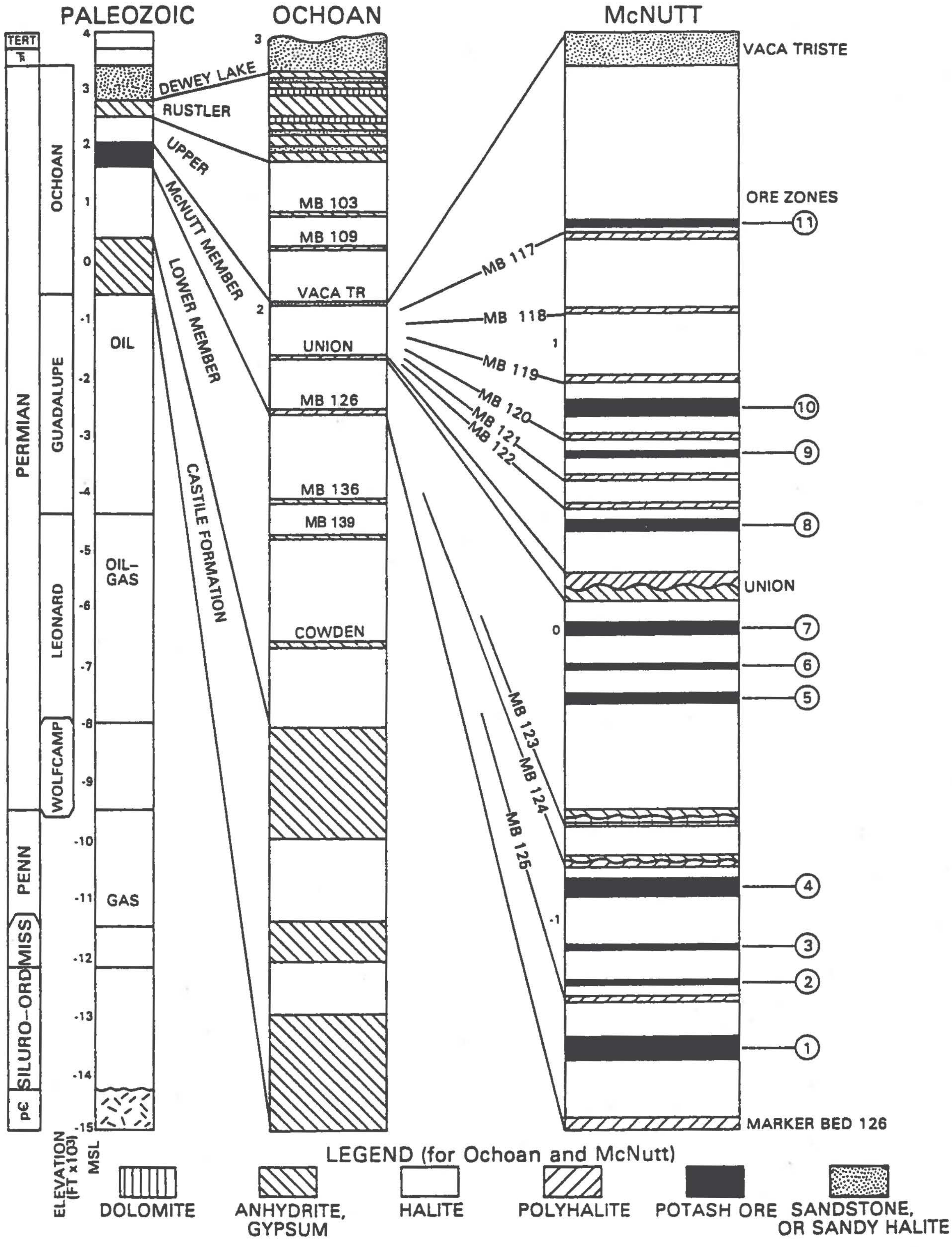

FIGURE 1.4—Regional stratigraphic column with expanded sections of the Ochoan evaporite and McNutt Member of the Salado Formation (modified from Griswold, 1982). Numbers to left of columns are thousands of feet relative to sea level.

observations that the present potash salts formed later than the primary evaporite cycles and that their overall distribution is independent of host lithology.

Potash ore zones are 1–3 m thick and are laterally consistent except where interrupted by barren halite (salt horses), collapse features (Bachman, 1984), and igneous dikes (Calzia and Hiss, 1978). Commercial deposits were created in some localities by magnesium-undersaturated fluids moving through the zones, but in other areas late-stage fluids destroyed ore, producing salt horses. The McNutt Member is absent in the subsurface just west of the present mines (Fig. 1.2).

Ore zone 1 (Fig. 1.4) accounted for about 80% of potash production in the past, but it is essentially mined out at currently economic depths. Production is now chiefly from ore zones 4, 5, and 10, which successively overlie zone 1. Mine levels in zone 7 are on standby. Langbeinite is produced from mixed sylvite and langbeinite ores in zones 4 and 5 (Table 1.5; Harben and Bates, 1990). Near the shallow western boundary of the KPLA, only ore zone 1, stratigraphically lowest, oldest, and richest in potash, was not removed by solution. A typical mixed ore from the Salado in the CPD contains 60% halite and 30% sylvite (usually together as sylvinite), with 5% langbeinite, 2% polyhalite, and 2% insolubles (Cheeseman, 1978).

The average sylvite ore grade in New Mexico decreased from 25–30% K_2O in the 1950s to about 14% today; langbeinite ore now averages 8–10% K_2O. The large potash ore reserves in the district should last for at least 25 to 35 yrs (Table 1.6) at current extraction rates.

SUMMARY OF POTASH-EVAPORITE ORIGIN

Most potash-bearing bedded-salt deposits originate from evaporation of either seawater or mixtures of seawater and other brines in restricted marine basins (Schmalz, 1969). The brine depth in an ancient evaporite basin undergoes fluctuations related to sea level, ground-water inflow, precipitation, runoff, and evaporation. Saline minerals can be deposited in deep or shallow water and sometimes during subaerial exposure (Williams-Stroud et al., 1994).

During evaporation of normal seawater, carnallite ($KCl{\cdot}MgCl_2{\cdot}6H_2O$) rather than sylvite ($KCl$) precipitates because of the high concentration of magnesium in seawater. Mixing marine brines with other brines or with meteoric water may produce evaporite deposits without carnallite. Potash ore zones often are near the tops of halite beds in relatively thin layers because the potash is precipitated from brines of higher salinities occurring near the end of the evaporation sequence, later than halite beds. The sodium-to-potash ratio in seawater is about 27:1, so halite is very abundant compared to potash. Nonmarine evaporite deposits occur but have mineralogy very similar to those in marine evaporites (Lowenstein et al., 1989), presenting further complications to origin interpretation.

Carnallite in a salt sequence can be altered to sylvite by the reaction of calcium- or magnesium-poor brine or meteoric water. In many instances, this diagenetic process occurs shortly after deposition of the carnallite layer, as in the case of potash deposits in Thailand (Hite, 1982). The soluble potassium salts of the Salado Formation and the McNutt Member formed by recycling of either primary carnallite or polyhalite, by migrating Mg- and Ca-poor fluids (Bodine, 1978), or by reactions in place based on changing brine composition, pressure, or temperature. Neither ore minerals, such as sylvite and langbeinite, nor most gangue potash minerals, such as leonite or kainite, are primary in the Salado. Alteration of evaporites is complex and may be syndepositional, postdepositional, or retrograde (Suwanich, 1991). Petrographic and textural relationships and chemical analysis of fluid inclusions of associated halite in potash evaporites suggest that sylvite is primary in some basins (Lowenstein and Spencer, 1990; Wardlaw, 1972). If so, magnesium in the brines must have been removed, perhaps as a result of the enrichment of calcium from other brines. Enrichment of seawater with respect to calcium will result in early depletion of sulfate with gypsum/anhydrite precipitation and will prevent deposition of magnesium sulfates by restricting available sulfate. The magnesium-sulfate-poor potash deposits probably precipitated from brines that were high in calcium. These deposits constitute 60% or more of known potash basins (Hardie, 1991), although the Salado represents magnesium-rich potash deposition.

TABLE 1.6—Active potash mines in New Mexico showing estimated capacity, average ore grade, and mine life at the average 1996 price of \$177.54/K_2O st. Data from J. P. Searls, U.S. Bureau of Mines, written comm. 1998. [1]May not be operating at full capacity. [2]Muriate, langbeinite, and sulfate combined. [3]Langbeinite only.

Operator	County	Product capacity (st/yr[1])	Ore grade (% K_2O)	Mine life (yrs)
IMC Kalium	Eddy	1,000,000[1]	11[2]	33
Mississippi Chemical	Eddy	300,000	15	125
Mississippi Potash East	Eddy	450,000	14	25
IMC Kalium–Nash Draw	Eddy	400,000	8[3]	30

Most sub-basins of high-grade potash salts are found near the basin center surrounded by successively less soluble salt facies (symmetrical model), but some potash is restricted to the margins of the basin (asymmetrical model). An asymmetrical evaporite distribution, such as that in the Ochoan Delaware Basin, could be formed by the reflux model first described by Ochsenius (1888) and later by others (Lowenstein, 1988).

In the reflux model, a shallow bar, or sill, across the mouth of the basin (proximal end) restricts the flow of seawater, which evaporates into a salt-precipitating brine. The dense brine, with maximum concentration at the distal end, sinks to the bottom and sets up an undercurrent of higher-density brine toward the proximal (sill) end. The sill, which restricts the inflow of seawater, allows inhibited flow of evaporation-concentrated brines back to the ocean. The least-soluble salts are precipitated toward the sill, and the most-soluble components precipitate in the deeper parts of the basin. The result is lateral facies changes in a tabular deposit that are due to the asymmetrical salini'y gradients in the brine.

The classic reflux model of potash deposition in the Delaware Basin suggests that the Salado Formation represents repeated cyclic drawdown and brine concentration in a shallow marginal-marine basin with an intermittent inlet (Hovey Channel) to the southwest (Fig. 1.1). The Salado Formation and its middle member (McNutt Member) exhibit vertical stacks of two cycles (Type I and II) on a larger scale (Lowenstein, 1988) than cycles in the Castile. Some secondary potash salts are not included in the cycles. Relative subsidence is necessary to allow the stacks to develop at least 46 Type I cycles in the Salado (Jones et al., 1960b).

The Type I cycle in the Salado is dominated by marine processes (seawater) and consists of an upward sequence, 1–11 m thick, of calcareous/siliciclastic mudstone, anhydrite/polyhalite after gypsum, halite, and muddy halite. These record basin shallowing and brine concentration upward during progression from a stratified perennial lake or lagoon to a shallow ephemeral saline lake. The Type I cycle is related to sea-level rise relative to the Salado basin and is not as common as Type II cycles (Lowenstein, 1988).

The Type II cycle in the Salado is dominated by continental processes (meteoric water) with some seawater from seepage or residual brines (brackish water). A Type II cycle is related to a drop in sea level and is volumetrically more important and more frequent than Type I cycles. It is 0.3–6 m thick and consists of halite grading upward into muddy halite. One or more Type II cycles separate Type I cycles, yielding vertically stacked sedimentary packets representing a maximum time interval of 10^5 yrs per cycle. The Type II cycle is similar to the upper portion of a Type I cycle. The Type II cycle shows no evidence of prolonged subaqueous

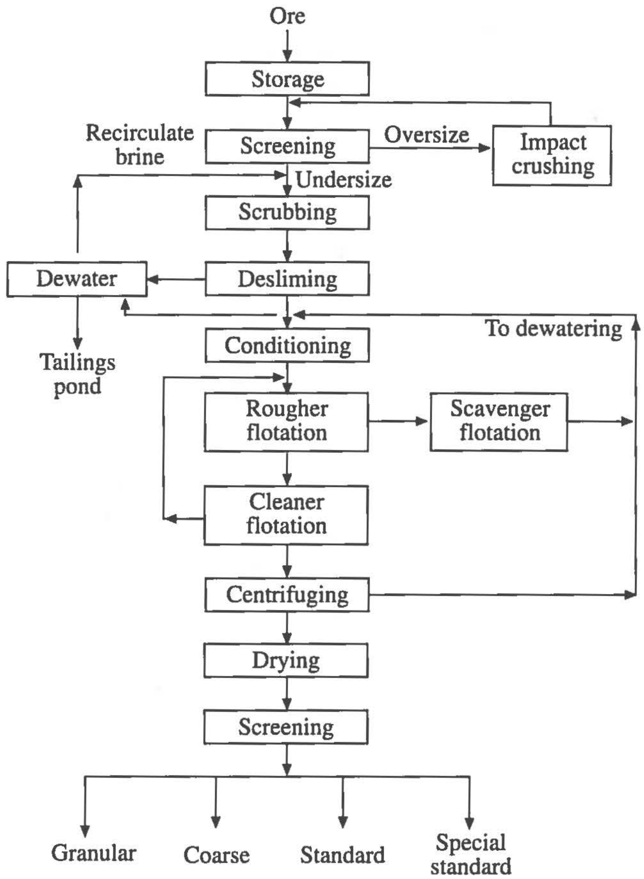

FIGURE 1.5—Simplified potash flotation circuit (from Sullivan and Michael, 1986).

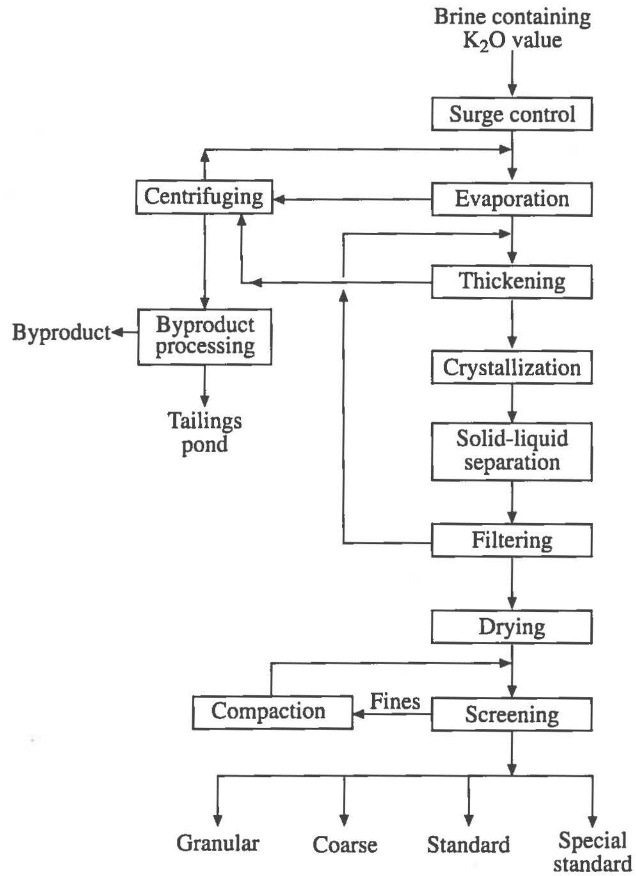

FIGURE 1.6—Simplified potash crystallization circuit (from Sullivan and Michael, 1986).

exposure, compared to Type I cycles, and has no anhydrite–gypsum, polyhalite, or mudstone layers. The cumulative thickness of a Type II cycle exceeds that of a Type I cycle in the McNutt (Lowenstein, 1988).

Other hypotheses on the origin of Ochoan rocks near Carlsbad, New Mexico, differ slightly to greatly from the classic reflux model. Leslie et al. (1993) proposed that the laminated couplets of anhydrite and calcite/organic material, interbedded with massive to poorly laminated halite in the Castile and Salado Formations, were formed below wave base during a period of restricted circulation of marine water. Anderson (1993) suggested that the Castile Formation may be a "nonmarine" evaporite with considerable meteoric recharge.

MINING

The high solubility of most potash ores in the New Mexico climate limits them to the subsurface—hence all mines in the CPD are underground. Mine depths range from approximately 270 to 425 m. These room-and-pillar mines are relatively clean, dry, and orderly because the beds being exploited are relatively shallow, regular, tabular, and nearly flat. Room-and-pillar mining is flexible and allows selective mining (Sullivan and Michael, 1986), so salt horses are easily bypassed and ore grade control is good. The location of salt horses is unpredictable, but they can make up 10% of the ore horizons and must be avoided. Low concentrations of methane are rarely found. Relief holes are drilled in ceilings to dissipate nitrogen (Williams–Stroud et al., 1994). All mines in the CPD consist of at least two shafts for safety and ventilation, and older mines have three or more shafts because working faces are now 5–8 km, or more, from the main shaft (Searls, 1985).

Continuous mining equipment adapted from coal mining is used to mine most potash ore although blasting is also used. Beds as thin as 1.2 m are mined with mechanical drum miners. Some harder ores, particularly langbeinite, require mechanical undercutters to prepare the working face for drilling and blasting, usually with ammonium nitrate and fuel oil (ANFO) explosives. In all cases, mechanical loaders, underground crushers, and conveyor belts are used to handle broken ore. Room-and-pillar methods remove 60–75% of the ore during initial mining. Subsequent removal of most of the support pillars allows extraction to exceed 90% (Sullivan and Michael, 1986; Barker and Austin, 1993). This is not done routinely, particularly if unmined overlying ore zones are present, but it is done when an area of the mine is being permanently closed.

MILLING

Mills in the CPD produce potash by combinations of separation, flotation, crystallization, leaching, and heavy-media circuits designed for a specific ore. Output from these circuits is dried in fluid-bed or rotary dryers and sized over screens to yield final products. Potash ore is ground to break up sylvite-halite agglomerates (Searls, 1985) followed by froth flotation (Fig. 1.5). Frothers such as cresylic acid, pine oil, or alcohol are added to the slurry. Sylvite is floated from halite in an aqueous solution saturated with both sodium and potassium chlorides at pulp densities of 20–35% solids, and recovery generally exceeds 80%. Collectors typically are hydrochloride and acetate salts of aliphatic amines with carbon chain lengths of 12 to 24. IMC Kalium uses heavy-media separation on sylvite/langbeinite ore prior to flotation and produces potassium sulfate by reacting potassium chloride with various sulfate materials including langbeinite. IMC Kalium's Saunders mill washes langbeinite ore to leach more-soluble gangue without a flotation stage. Fine-grained MOP from flotation must be coarsened by compaction between rollers, then crushed and sized to bulk-blended fertilizer specifications.

The abundance and mineralogy of clay minerals are significant in processing potash ores, particularly the clay-rich 10th ore zone. Clay-size particles (slimes), composed dominantly of clay minerals, make up from a trace to about 10% of ore zones in the CPD. Clay minerals adsorb the reagents added before the crystallization stage, thus raising reagent cost and hindering recovery, among several deleterious effects. Each mill is designed for a specific slime content in its feed stock (Fig. 1.6). Thus, some ore zones cannot be processed efficiently in specific plants. For example, the Mississippi East mill can handle up to 4.5% slimes. Beneficiation by dissolution and vacuum recrystallization is used on clay-rich or fine-grained ores. This method is used by Mississippi Chemical East whose ores contain about 7% clay (Searls, 1985).

Clay minerals preferentially interact with the amines used to coat sylvite in sylvinite ores and with the frothers used in flotation cells (Searls, 1985). This is a result of the large surface areas of clays, their residual charges, adsorption, absorption, and colloid formation. Expandable trioctahedral clay minerals such as corrensite, saponite, and clinochlore-saponite have more surface area than other clay minerals and can form colloids with the brines of either the flotation or crystallization circuits. These characteristics of clay minerals interfere with beneficiation and increase chemical use.

Potash tailings in the CPD, largely halite and clay, are stored or disposed of on the surface. Solid wastes are piled and monitored for salt leakage, which is minimal in the semi-arid climate. Brines are evaporated in impoundments or in a natural saline lake that has increased in size because of mine-tailing influx. Methods for returning tailings to the mine are being studied but are more likely to be initiated in potash districts less production-cost sensitive than the CPD.

SUMMARY OF ECONOMIC FACTORS

Activity by other industries can affect the production of potash from southeast New Mexico; notable are agriculture, petroleum, and deep geologic-waste disposal. The main use of potash as a fertilizer ties it to cyclic trends in the agricultural industry. These trends are related to complex interactions between weather and climate; advances in crop genetics, soil science, and farming practices; GNP of importing nations; farm income; population growth; distribution-system efficiency; freight rates and backhauls; taxes; and tariffs (Williams–Stroud et al., 1994).

Decisions to drill for petroleum below potash beds, presumably rendering the potash unminable, are decided by the Bureau of Land Management (BLM), who manages the federal and state land within the KPLA in consultation with representatives of the potash and petroleum industries (Searls, 1992). The BLM historically has decided in favor of preserving potash reserves rather than petroleum production unless the petroleum well can be drilled from outside the KPLA. Also impacting the potash industry is the Waste Isolation Pilot Plant (WIPP) at the southeast boundary of the KPLA (Fig. 1.2).

The development of substantial amounts of low-cost potash in other countries, such as Ukraine or Thailand in the future and Canada now, inhibits exploitation of lower-grade, higher-cost resources in the CPD. A protected domestic potash-mining industry is possible, but not likely, because Canada, a close and friendly neighbor, is the United States' principal foreign source of potash.

The potash industry is also subject to overcapacity worldwide. In 1990, capacity utilization ranged from 40% to 100% and averaged about 75% (Williams–Stroud et al., 1994). Overcapacity is buffered mainly by withheld Canadian production where about 60% capacity utilization is used to prop up prices by limiting supply. Transportation limits and unique potash products such as langbeinite yield partially protected markets to some producers. The CPD is thus a mature mining district with deeper ore of lower grade and amortized capital costs, which means diminishing potential for new producers, but with increased positive effects from extending current operations and embracing new technology. Overall, the CPD will continue to produce potash (Table 1.6) at competitive prices for many years.

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2. Future mining technology

George B. Griswold

6692 Pueblo Vista, Las Cruces, NM 88005

USING THE PAST TO PREDICT THE FUTURE

Looking at past developments is always the best method to predict what may occur in the future. The Carlsbad potash mining district has a long history extending from its discovery in 1925 to the commencement of production in 1931 and onward to the present, when it still accounts for 85% of all domestic production. The period from 1931 until 1965 was one of continuous expansion until there were seven operating companies. The need for potash was increasing throughout North America, and the potash deposits at Carlsbad were the richest source of supply. In the late 1960s rich deposits in Canada were brought on stream, and a period of competition ensued not only with Canadian imports but among the seven Carlsbad producers as well. Simultaneously with these events the ore grade at Carlsbad declined. Mining in the early years was from the rich and thick 1st ore zone. The mining height averaged 8 to 12 ft, and the grade ranged from 20 to 25% K_2O as sylvite. Langbeinite ores, mainly from the 4th ore zone, were also thick and averaged better than 10% K_2O as langbeinite.

Today many ore beds are thinner than the mining machines can excavate, which causes dilution of the in-place ore. The rich 1st ore zone is now almost depleted, and sylvite ores are mined mostly from the 5th, 7th, and 10th ore zones. The grade of these ores is now about 14% K_2O as sylvite. The major source of langbeinite continues to be the 4th ore zone, but the mining height is kept as low as possible and the average grade has dropped to 8% K_2O as langbeinite.

The Carlsbad area remains competitive in the domestic and international agricultural-fertilizer industry because the local operators continuously improve productivity. In addition, IMC Global, Inc. has a unique technology that treats mixed langbeinite/sylvite ore.

A review of the historical data given in Table 7.1 illustrates the increase in productivity of the Carlsbad mining companies. The measure of productivity used was tons of ore per man-year and tons of product per man-year. The tons of ore per man-year increased 5.44 times (from 1878 tons in 1940 to 9,921 tons in 1994). The tons of product per man-year increased, in spite of continuing decline in grade, from 793 to 1,929 tons, representing a 2.43-fold increase. The concentration ratio of the tons of ore required to make a single ton of product has increased from slightly less than three to more than five today, reflecting the continuing drop in ore grade.

The increase in the tons of ore to make a ton of product needs some qualification. In 1940, little langbeinite was produced, whereas today it accounts for about one-third of the product sold. The production data for langbeinite are held confidential to protect the privacy of the two producers, IMC Global, Inc. and Western Ag–Minerals Company. Therefore, the annual production of "product" (Table 7.1, second column) is a combination of sylvite, langbeinite, and manufactured arcanite. However, the tons of ore required to make a ton of product are not the same. To illustrate, it takes about 5.2 tons of sylvite ore to make one ton of product. Whereas, for langbeinite it takes only about 3.2 tons to make one ton of product. However, mining and processing costs are higher for langbeinite than for sylvite. Therefore, the end result is that the price to cost ratio remains about the same for sylvite and langbeinite. What has changed is the ability of the mines to continuously increase the tons of product per man-year.

Note that worker productivity for both ore and product appears to have increased steadily from 1940 to the present. There are occasional bumps in the data, but they exhibit a relatively consistent growth. Improvements in technology account for the productivity increases. Among them are improvements in mining technology:

1. conversion from track haulage to conveyors;
2. use of mechanical-arm loaders and undercut machines;
3. use of shuttle buggies and ram cars to move ore from the face to conveyors;
4. utilization of diesel and diesel-over-hydraulic for equipment to enhance mobility;
5. use of rock bolts for ground control;
6. usage of higher voltages and larger electric motors underground;
7. use of ammonium nitrate–fuel oil explosive (ANFO) along with non-electric and consumable detonation systems;
8. the advent first of boring machines then drum mining machines;
9. continuous improvements in belt conveyors including new extendible types;

and in processing technology:

1. flotation of non-metallic minerals;
2. continued improvement in flotation reagents;
3. improvement in flotation-cell design and operation;
4. use of cyclones and centrifuges for separation of slimes;
5. compacting of fines to produce coarser products;
6. improvement in screening and sizing techniques;
7. application of non-caking agents to products;
8. continued improvement in handling, storage, and loading of products.

This listing is neither comprehensive nor chronological. Instead it is meant to illustrate that many improvements have been made over the years, none of which are called revolutionary, but in combination they result in a steady increase in efficiency of the overall process starting with the taking of raw ore from the underground mining face and ending with a salable product loaded into a rail car or truck.

Along with the improvements listed above came treatments of mixed sylvite/langbeinite ore. IMC Global, Inc. commenced work on the process almost immediately after opening their mine in 1940. Duval Sulphur and Potash Corporation produced manufactured arcanite (K_2SO_4) when they opened the Nash Draw mine in 1962; however, this process was terminated after a few years, and since then the mine has produced only langbeinite. The Nash Draw mine is now owned and operated by Western Ag–Minerals Company. The details of the process that IMC uses are held proprietary, so little technical information is available other than what is described in Chapter 7.

IMC must be successful with their process because that company continues to be the largest producer in Carlsbad while mining ores below the cut-off grades for single product. In addition, IMC appears to be steadily increasing the percentage of sulfate products in proportion to their muriate products. The company dominates the world market for langbeinite as a fertilizer mineral and is very competitive in the K_2SO_4 market.

The conclusion is that IMC or a company that has gained their expertise will be a candidate to mine the known potash resources in the vicinity of the WIPP site. Indeed, IMC formerly held mineral leases within the WIPP boundary area, which were purchased by DOE in 1989 for a price exceeding $25 million. The company is attempting to replace those resources. They are now vying with Yates Petroleum Corporation and Pogo Production Company for potash mineral leases from the BLM along the northeastern borders of the WIPP site. This is the same area that contains the bulk of the potash resources evaluated in this study. Therefore, it is the technology IMC possesses and the future technical advances they may make that have the most relevance to whether or when the resources evaluated will be mined.

DEVELOPMENTS THAT CAN BE EXPECTED IN THE FUTURE

There are some developments that are almost certain to occur within the next decade or so.

Mineral processing

New techniques for better "in stream" analysis will become available to determine the exact mineral percentages of ore being processed in order to more efficiently tailor plant operations to increase recovery and lower energy consumption. Neutron-activation analysis holds this promise, but development of rugged instruments that can provide reliable and real-time analysis is a challenge that has not quite been met.

Better methods of compacting and sizing products will emerge in order to meet better the needs of the fertilizer industry. Western Ag–Minerals was recently granted a patent on a new process, and new developments are expected to occur. Other improvements will be in the area of materials handling, for example the use of tube conveyors to eliminate dust and particle degradation at conveyor-belt transfer points.

Recycling of water and reagents is expected to improve. The "energy crisis" of the late 1970s made all operators become more efficient in energy consumption at their plants, and continued improvement is expected.

Underground mining

The mines are now highly mechanized, so no revolutionary concepts are foreseen in the near term. What can be expected is that heavier and more powerful drum miners will be used to mine the hard langbeinite ores of the 4th ore zone. Western Ag–Minerals Company is now investigating the use of such a machine. The advantages of converting to drum miners are several: increase in mining extraction, mining at a lower height to improve ore grade, minimizing the workforce at the mining face which improves safety, and better ground control because mining advance is more rapid. A factor yet to be determined is whether drum miners will reduce the amount of langbeinite fines and so improve processing recovery.

IMC Global, Inc. is studying faster and safer ways of transporting personnel from the shaft entry out to the working faces. Distances are now five or more miles from the man-shafts, so transportation of personnel consumes a significant portion of working time.

Extendible conveyors, which are placed between the miners and the main belt lines, will be improved. The devices now in use were developed for coal mines, and the companies that use them for potash are making modifications to improve performance in their specific operations.

Remote control of mining machinery will increase. Today most continuous miners are operated by the worker using telemetry. New laser-guidance systems will be used to direct the mining advance and to continually adjust the height mined to minimize dilution. Mining height has been reduced to 4.5 ft and may be reduced further to 4 ft or perhaps even less.

Roof bolting is used as the major method of ground control. Bolting can be done with on-board bolting machines on the continuous miners. This practice has not been fully implemented to date, but it will become customary where ground conditions require regular bolting.

DEVELOPMENTS THAT CAN BE EXPECTED ONLY IN THE FAR FUTURE

Solution mining is the only method that can be reasonably predicted for the Carlsbad district. The system has been in use in Canada for ultra-deep (>4,000 ft) sylvite in Saskatchewan and in thick but highly folded strata in New Brunswick.

Most people familiar with the Carlsbad potash deposits believe that the ore beds are too thin for the application of solution mining as it is now practiced in Canada. In addition, the deposits evaluated at WIPP contained langbeinite, which is not readily soluble. So if solution mining is employed in the vicinity of the WIPP site, it will be to recover only sylvite.

In the United States solution mining is used near Moab, Utah, to recover sylvite from an evaporite deposit that proved to be too difficult to mine conventionally because the strata were folded and contained considerable methane. In Carlsbad, one experiment was conducted using hydraulic-fracturing techniques in an attempt to connect two relatively closely spaced holes to prepare for solution mining. The experiment was only partially successful (Shock and Davis, 1970).

However, all mines have held open the option of using solution mining once their sylvite deposits are fully mined out. The concept would rely on the fact that the open spaces left over from mining would allow ore remaining in pillars to be recovered. No specific plan has ever been formulated whereby a mine would be intentionally flooded and saturated sylvite brine recovered from boreholes. Solar evaporation would need to be used to concentrate the brine because the solutions would be very dilute.

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3. Potash processing technology

Ibrahim Gundiler

New Mexico Bureau of Mines and Mineral Resources, Socorro, NM 87801-4796

INTRODUCTION

Potash ores must be beneficiated to remove halite (NaCl), clays, and other insoluble material to produce marketable products. Silvinite (KCl + NaCl) and langbeinite ($K_2SO_4 \cdot 2MgSO_4$) are the two ore types currently mined in the Carlsbad potash district. The average K_2O grade of silvinite ores is about 14–16% and that of langbeinite about 8–10% (Austin and Barker, 1993).

Sylvinite ores are generally beneficiated by flotation of sylvite (KCl) in saturated brine solutions using cationic collectors (primary aliphatic amines) and frothers. The product, muriate of potash, contains 60% K_2O and is marketed in different size grades. Presence of clay minerals, however, may interfere with the flotation process. Clay minerals preferentially absorb the flotation reagents, causing excessive reagent consumption and hindering the recovery of sylvite. Therefore, they are removed prior to flotation by scrubbing and desliming (Scroggin, 1978). Flotation of clay minerals remaining in the pulp is further suppressed by using a starch or cellulose derivative and some fuel oil. Ores with much higher insoluble and clay content, i.e., 6–7%, are beneficiated by dissolution and selective crystallization from the resulting brines (Case, 1978; Zandon, 1985).

Langbeinite is mined in only two locations in the world. It has been mined continuously in the Carlsbad district since 1940 and intermittently in the Stebnik mine in the Ukraine since the 1930s (Rempe, 1982). Langbeinite is much less soluble than either sylvite or halite. Most often, it can be upgraded to 22% K_2O levels by selective dissolution of the more soluble minerals. However, polyhalite ($K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$), a frequent impurity, has solubility similar to langbeinite and may be difficult to remove.

Alternatively, because langbeinite has higher specific gravity (S.G. 2.83) than either sylvite (S.G. 1.99) or halite (S.G. 2.16), it can be separated from mixed ores using heavy-media separation processes in coarse sizes (Zandon, 1985). Langbeinite fines can be further beneficiated using anionic collectors (fatty acids) in conventional flotation circuits. The world's first langbeinite flotation circuit and a heavy-media circuit were installed at IMC's Carlsbad plant during the mid-60s, but the details of these operations have not been disclosed.

Excellent reviews on potash resources and potash processing are available in the readily accessible literature (Williams-Stroud et al., 1994; Sullivan and Michael, 1986; Zandon, 1985). Therefore, only a brief review of the recent advances in basic theory and processing technology, as it pertains to the Carlsbad district, is given here.

FLOTATION CHEMISTRY

Recently, nonequilibrium electrokinetic mobility measurements with a laser-Doppler electrophoresis technique allowed determination of dynamic surface charges of alkali halides in their saturated solutions (Yalamanchilli et al., 1993). It has been shown that, contrary to previously advanced theories (Roman et al., 1968), the surface charge of KCl is negative in KCl–NaCl saturated brine, whereas NaCl is positively charged. Furthermore, it is well known that KCl flotation occurs when amine concentrations exceed their solubility limits and micelle formation takes place. Recently, it was also shown that collector colloids exhibit distinct electrochemical properties; the iso-electric-point (iep) for dodecylamine is around pH 11 and iep's for other long-chain amines are in the pH range from 10.2 to 11. Up to pH 11 these colloids are positively charged, and it is exactly at this pH that flotation of KCl ceases and flotation of NaCl begins. Therefore, it is concluded that collector colloids, rather than collector ions, affect the flotation of these salts (Laskowski, 1994).

An excess of potential-determining ions (i.e., K^+ and Na^+) can also change the surface charge of these salts. In addition, the presence of carnallite ($KCl \cdot MgCl_2 \cdot 6H_2O$) (or kieserite [$MgSO_4 \cdot H_2O$]) also effect the flotation of sylvite ores. The solubilities of both KCl and NaCl are drastically reduced in the presence of Mg^{2+} ions. A few percent $MgCl_2$ in KCl+NaCl brine, or sulfate-ion concentration in brine exceeding 2.5%, also depress sylvite flotation. These effects are more pronounced in the presence of carbonaceous clays (Laskowski, 1994). A better understanding of flotation chemistry may thus lead in the future to better plant control and improved recoveries.

INSOLUBLE SLIMES/CARNALLITE FLOTATION

Identifying insoluble slimes and clay minerals in sylvinite ores, and the mechanism of collector absorption on different clays, have enabled Russian researchers to formulate reagents for better control of clay flotation using polymeric flocculants. These improvements have reportedly resulted in 20–40% decrease in collector consumption (Arsentiev and Leja, 1977). The U.S. Bureau of Mines researchers studied carnallite flotation and separation of clay minerals (Thompson and Huiatt, 1979; Foot et al., 1982, 1984). Continuous pilot-plant studies comparing (1) depression of insoluble slimes and direct flotation of carnallite and (2) flotation of insoluble slimes before carnallite flotation resulted in similar recoveries and products. Carnallite is the major potash mineral that occurs with kieserite at the 2nd, 6th, 9th, and 11th ore zones in the district (Griswold, 1982). It is not mined commercially in this district, but it occurs as an impurity in sylvinite ores in some ore zones. High concentrations of carnallite adversely affect the sylvite flotation and may necessitate the installation of a pre-leach or bleed circuit before flotation (Zandon, 1985).

FLOTATION TECHNOLOGY

Column flotation pilot-plant trials in Canada (Aliaga and Soto, 1993) and England (Burns et al., 1994) have shown better recoveries for coarse (+1.19 mm) particles, improved recoveries of fines (+5%), improved product grade, reduced insol recovery, and reduced power costs. These improvements justified replacement of two banks of rougher cells and one bank of cleaner cells with column cells at the Cleveland Potash, Ltd. plant (Burns et al., 1994).

Decreasing ore grades in the Carlsbad district would require finer grinding of ores to meet the product grade standard. It is, therefore, reasonable to assume that most flotation circuits in the district would benefit from the column cell technology, and it is likely that aging mechanical cells will eventually be replaced by column cells, particularly in the cleaning circuits.

PLANT CONTROL

IMC Esterhazy operations improved plant efficiency by on-stream analysis of ore, improved flotation reagents and reagent control, centralized process control, and improved energy efficiency of the operation (Mayor, 1983). Implementation of such modifications in process control can be expected in most operations in the Carlsbad district.

ELECTROSTATIC SEPARATION

Potash operations in Germany (Singewald and Neitzel, 1983) and pilot-plant trials at PCS Mining in Canada (Larmour, 1983) have shown that electrostatic separation is a viable alternative to flotation and heavy-media processes. The advantages to be gained by dry processing are both environmentally and economically significant. The process requires conditioning the ore with reagents in a controlled-humidity environment and passing the ore through a separator where different minerals are attracted to oppositely charged electrodes. Reportedly, this process was developed and extensively tested in pilot-plant trials at IMC's Carlsbad plant, but the details of these tests have not been disclosed (Zandon, 1985).

HEAVY-MEDIA SEPARATION

As discussed above, heavy-media separation (HMS) is used in the Carlsbad district for langbeinite processing. In this process, a fine suspension of magnetite is used to provide a medium in which the coarse heavy mineral (langbeinite) sinks and the light minerals (sylvite, halite) float. Usually, a cone- or drum-type vessel is used to facilitate separation, and the medium (magnetite) is recovered from the screen undersize by magnetic separators. Heavy-media cyclones, which are widely used in coal cleaning, can exploit much smaller differences in the specific gravity of the minerals than conventional separators. For example, IMC's Esterhazy operations in Canada reportedly produce substantial tonnages of crystalline muriate from sylvinite ores (Zandon, 1985). Sylvinite ores in the Carlsbad district are known to have finer grain size than the Esterhazy ores; however, potential exists for wider use of heavy-media processes, particularly in langbeinite preconcentration prior to leaching and in processing mixed ores.

SOLUTION MINING, PURIFICATION, AND CRYSTALLIZATION

Thinly bedded deposits, scarce fresh-water supplies, and high solution temperatures resulting in high salt solubility render solution mining unlikely in the Carlsbad district (Davis and Shock, 1970; Husband, 1973). However, it is possible to envision wider use of solar energy and utilization of some technologies related to solution mining, such as solvent extraction (Rice and Chapman, 1990), to affect solution purification, concentration, and crystallization processes.

DISCUSSION

Although there have been significant advances in understanding the mechanism of soluble-salt flotation and innovations in potash-processing technology, these advances are not expected to have an immediate impact on the Carlsbad potash district. The declining sylvinite ore reserves, thinly bedded deposits of ancillary potash minerals in the district, and the proximity of vast Canadian potash reserves and abundant supplies render major changes in processing technologies in the Carlsbad district highly unlikely.

The Carlsbad potash district operators, however, have traditionally been highly innovative and adaptive to changing market conditions. It is reasonable to assume that some of the new technologies, such as column flotation and heavy-media cyclone separation processes, would be implemented in the district. Nevertheless, these developments should not affect the ore-reserve calculations as far as the mineral potential of the WIPP site is concerned.

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4. Mining technology

George B. Griswold

6692 Pueblo Vista, Las Cruces, NM 88005

OUTLINE OF MINING IN THE CARLSBAD POTASH DISTRICT

The early years

An excellent overview from the initial potash ore discovery in 1925 to 1998 has been given by Barker and Austen (*see* Chapter 1, this circular). Production commenced in 1931 with sylvite mining from the 1st ore zone. By 1940 three companies were operating, and mining of langbeinite as well as sylvite was underway. The peak production year was 1966 when a total of seven companies hoisted over 20 million tons that produced 5.1 million tons of marketable sylvite and langbeinite products worth $382 million in equivalent 1994 dollars. The total tons of product sold from startup through 1994 had a total market value of almost $15 billion in equivalent 1994 dollars. A complete history of production data is given in Table 4.1.

The Carlsbad miners faced a period of readjustment from 1972 through 1985 when an oversupply of muriate came on stream from vast sylvite deposits in Canada. A series of trade agreements negotiated between the U.S. and Canada stabilized the market. These agreements were included in the recently signed North American Free Trade Agreement (NAFTA), so the future appears to be one of stability.

Current status

In 1995, five Carlsbad potash producers were operating: IMC Global, Inc., Eddy Potash, New Mexico Potash, Western Ag–Minerals, and Mississippi Potash (Table 4.2; *see also* Chapter 1 and Table 1.6).

Langbeinite production data are not released by the State or the U.S. Bureau of Mines (USBM) to protect the privacy of the two producing companies. Instead, these agencies report production combined of the three products: muriate (sylvite), langbeinite, and manufactured K_2SO_4. However, a reasonable estimate is on the order of 1,000,000 tons of langbeinite and K_2SO_4 products that are now equivalent to one-third of all Carlsbad production. The percentage-of-sales value is slightly higher. It is important to note that langbeinite is produced only at Carlsbad. Occurrences are known elsewhere in the world, but production from them is minimal.

The five operating companies are vertically integrated, i.e. they mine, process, transport, and market agricultural fertilizers. The industry is quite competitive both on national and international scales, and it would be difficult for a new company to enter into potash mining in Carlsbad without the marketing capabilities that the current operators possess. This includes expertise in and production of other chemical fertilizers such as ammonium nitrate and phosphates. Most farmers fertilize their fields with mixes of these three chemicals plus others, so having production capabilities in all three is a distinct advantage.

The production capacity at Carlsbad is larger than that shown in Table 4.2, and this is true throughout the world. The reasons are twofold: first, there was a tendency to overexpand during the 1960s in the U.S., Canada, and elsewhere; and second, agriculture historically goes through cycles, both nationally and worldwide. Therefore, having surplus capacity is a must if a producer wishes to always satisfy (and thereby keep) its customers. The capital expense for constructing the processing plants has been amortized long ago, so having surplus capacity does not affect current operating cost on a ton-produced basis. However, the Carlsbad workforce has declined since 1965, when it peaked at 3,760, down to a current force of about 1,400.

A unique feature of the chemical-fertilizer industry is the need for vast warehousing of products so as to maintain a steady production rate at the mines and plants while accommodating the farmers' cyclical needs for those products during the year. This explains the large warehouse structures that one sees at Carlsbad mines. A rule-of-thumb is that storage capacity amounts to about one-half of annual production capacity. The warehouses are full at the end of a calendar year and depleted by mid-summer.

Carlsbad in relation to other producing areas

The Carlsbad operators have been providing about 85% of domestic production, but that production falls far short of the nation's need for potassium chloride fertilizer. Therefore, even if the four sylvite mines were operating at full capacity, there still would be the need for imports of muriate. The nation's needs for potassium sulfates (as either langbeinite or K_2SO_4) could be met because the two producers (IMC and Western Ag–Minerals) are in fact the world's largest suppliers of that special mineral. It is estimated that more than one-third of the langbeinite is exported, and the demand is growing on a worldwide basis. Table 4.3 summarizes the last available data, i.e., 1988 through 1994.

Most of Carlsbad's muriate is shipped by rail to farm consumers in the southern and coastal states. Shipments are increasingly being made by trucks because such a mode allows for the product to go directly to the fields, bypassing interim storage points. Langbeinite finds its principal use on citrus and tobacco crops, so again much of this product (and manufactured K_2SO_4) goes to the south. Langbeinite and K_2SO_4 are exported, with China, Japan, and Canada being the largest consumers recently. A full description of the potash-fertilizer industry is given annually by the U.S. Bureau of Mines.

Outlook for the future

The muriate production appears to be secure and stable for the foreseeable future. The Carlsbad mines have a freight advantage over imports from Canada. Much attention has focused on imports from Europe, particularly from the former U.S.S.R. There may be brief periods of dumping of muriate from those sources. However, the mines in Belarus have to transport and market the product through other newly independent states, each of which will seek a share of export earnings, which makes that supply not much of a threat to Carlsbad. The deposits in the Urals are burdened by a long rail route to export ports. In Thailand and Laos the known deposits are carnallite, which requires more expensive processing. When developed, these resources will no doubt find their buyers within the rapidly expanding Asian markets.

The outlook for langbeinite must be considered as bright until a new discovery is made elsewhere. Such a discovery is most likely to occur in the former U.S.S.R., but it would be plagued with the same complexity of mining, transport, and

TABLE 4.1—Carlsbad potash production and productivity from 1932 to 1994.

Year	Tons product thousands	Tons K_2O thousands	Value $ million	Tons ore millions	Work force	Product grade	Concentration ratio	Price index	Product $/ton	1994 $/ton	Tons ore man-year	Tons product man-year
1932		55	2.10					11.2				
1933		139	5.30					11.4				
1934		114	2.81					12.9				
1935		193	5.00	0.500				13.8				
1936		247	6.97	0.600				13.9				
1937		284	9.02	0.700				13.9				
1938		317	9.75	0.900				13.5				
1939		312	12.00	0.900				13.3				
1940		380	12.60	1.200				13.5				
1941		434	14.10	2.270	1209			15.1			1878	
1942		549	19.60	3.060	1412			17.0			2167	
1943	1179	604	21.90	3.433	1487	51.23%	2.91	17.8	18.58	126.79	2309	793
1944	1304	680	24.70	3.749	1362	52.15%	2.88	17.9	18.94	128.57	2753	957
1945	1360	733	25.50	3.950	1527	53.90%	2.90	18.2	18.75	125.17	2587	891
1946		789	27.20	4.310	1816			20.8			2373	
1947	1659	881	28.00	4.656	1900	53.10%	2.81	25.6	16.88	80.10	2451	873
1948	1851	968	29.20	5.108	2354	52.30%	2.76	27.7	15.78	69.19	2170	786
1949	1744	932	28.00	4.853	2473	53.44%	2.78	26.3	16.06	74.17	1962	705
1950	1878	1073	31.90	5.802	2632	57.14%	3.09	27.3	16.99	75.60	2204	714
1951	2126	1218	43.43	6.616	2805	57.29%	3.11	30.4	20.43	81.64	2359	758
1952	2439	1411	52.48	7.853	3098	57.85%	3.22	29.6	21.52	88.32	2535	787
1953	2662	1553	58.08	9.010	3595	58.33%	3.38	29.2	21.82	90.78	2506	740
1954	2954	1732	64.37	9.750	3508	58.64%	3.30	29.3	21.79	90.36	2779	842
1955	3098	1826	69.06	10.956	3408	58.94%	3.54	29.3	22.29	92.44	3215	909
1956	3279	1931	72.80	11.941	3591	58.89%	3.64	30.3	22.20	89.03	3325	913
1957	3353	1977	73.24	12.895	3438	58.96%	3.85	31.2	21.84	85.06	3751	975
1958	3650	2157	75.34	12.224	3345	59.10%	3.35	31.6	20.64	79.36	3654	1091
1959	3821	2258	76.73	13.933	3201	59.09%	3.65	31.7	20.08	76.97	4353	1194
1960	4092	2412	78.71	15.071	3380	58.94%	3.68	31.7	19.24	73.72	4459	1211
1961	3882	2281	87.42	15.653	3542	58.76%	4.03	31.6	22.52	86.59	4419	1096
1962	4206	2476	95.85	14.115	3575	58.87%	3.36	31.7	22.79	87.35	3948	1177
1963	4213	2484	94.23	16.414	3582	58.96%	3.90	31.6	22.37	86.00	4582	1176
1964	4815	2814	110.77	17.356	3590	58.44%	3.60	31.6	23.01	88.45	4835	1341
1965	4607	2677	110.42	18.557	3759	58.11%	4.03	32.3	23.97	90.16	4937	1226
1966	4872	2827	104.67	20.105	3619	58.03%	4.13	33.3	21.48	78.39	5555	1346
1967	4797	2784	88.79	18.906	3479	58.04%	3.94	33.4	18.51	67.33	5434	1379
1968	4425	2511	70.20	15.092	2773	56.75%	3.41	34.2	15.86	56.36	5442	1596
1969	4433	2521	64.86	15.519	2624	56.87%	3.50	35.6	14.63	49.94	5914	1689
1970	3966	2227	78.30	16.246	2645	56.15%	4.10	36.9	19.74	65.01	6142	1499
1971	4101	2317	89.32	16.117	2646	56.50%	3.93	38.1	21.78	69.46	6091	1550
1972	4089	2285	89.86	17.285	2563	55.88%	4.23	39.8	21.98	67.09	6744	1595
1973	4414	2422	103.04	17.092	2894	54.87%	3.87	45.0	23.34	63.03	5906	1525
1974	3885	2061	126.62	17.206	2801	53.05%	4.43	53.5	32.59	74.02	6143	1387
1975	3221	1749	150.62	17.809	2953	54.30%	5.53	58.4	46.76	97.29	6031	1091
1976	3889	2083	165.35	17.308	3058	53.56%	4.45	61.1	42.52	84.55	5660	1272
1977	4012	2085	169.62	18.985	3104	51.97%	4.73	64.9	42.28	79.15	6116	1293
1978	4097	2142	183.55	19.290	2846	52.27%	4.71	69.9	44.80	77.87	6778	1440
1979	4269	2210	228.78	19.128	2724	51.77%	4.48	78.7	53.59	82.73	7022	1567
1980	4018	2060	289.00	19.876	2874	51.28%	4.95	89.8	71.93	97.32	6916	1398
1981	3437	1765	261.23	20.382	3075	51.35%	5.93	98.0	76.01	94.23	6628	1118
1982	3166	1650	204.60	17.296	2660	52.12%	5.46	100.0	64.63	78.52	6502	1190
1983	2783	1409	174.70	13.713	1644	50.61%	4.93	101.3	62.77	75.28	8341	1693
1984	3085	1563	204.10	15.556	1641	50.66%	5.04	103.7	66.15	77.51	9479	1880
1985	2479	1235	156.00	12.469	1329	49.80%	5.03	103.2	62.93	74.09	9382	1865
1986	2219	1088	132.90	10.779	1170	49.03%	4.86	102.2	59.89	71.20	9213	1897
1987	2896	1458	174.20	12.566	1329	50.36%	4.34	102.8	60.16	71.10	9455	2179
1988	2794	1401	213.80	13.788	1327	50.14%	4.93	106.9	76.51	86.96	10390	2106
1989	2988	1505	242.62	15.616	1619	50.35%	5.23	112.2	81.19	87.92	9646	1846
1990	3217	1599	245.57	16.458	1644	49.73%	5.12	116.3	76.35	79.76	10011	1957
1991	3191	1620	250.87	17.952	1742	50.78%	5.63	116.5	78.61	81.99	10305	1832
1992	3162	1583	256.62	17.680	1723	50.05%	5.59	117.2	81.14	84.12	10261	1835
1993	2754	1312	215.90	14.289	1398	47.64%	5.19	118.9	78.41	80.12	10221	1970
1994	2701	1301	218.00	13.889	1400	48.16%	5.14	121.5	80.72	80.72	9921	1929
Totals		95,664	6,432.27	716.732								
1994 dollars			14,464.64									

Sources: Production data from US Bureau of Mines. All data converted to short tons.
Employment data from NM Mine Inspector 1941–1972, MSHA 1973–1993, 1994 estimated.
Producer Price Index from US Bureau of Census.

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TABLE 4.2—Operating companies and their capacities.

Company	Production (tons/yr)	Products
IMC Global, Inc.	1,100,000	muriate, langbeinite, potassium sulfate
Eddy Potash	450,000	muriate
New Mexico Potash	500,000	muriate
Western Ag-Minerals	375,000	langbeinite
Mississippi Potash	400,000	muriate
1993 production	2,825,000 (estimate)	

Source: Barker and Austin (1993) and others. *See* Table 1.6, p. 13.

TABLE 4.3—Salient potash[1] statistics. Thousand metric tons and thousand dollars, unless otherwise specified. (From USBM *Potash–1992* and *1994*.)

	1990	1991	1992	1993	1994
UNITED STATES:					
Production	3,360	3,450	3,340	3,070	2,830
K_2O equivalent	1,710	1,750	1,710	1,510	1,400
Sales by producers	3,390	3,330	3,470	3,030	2,970
K_2O equivalent	1,720	1,710	1,770	1,480	1,470
Value[3]	$303,000	$305,000	$334,000	$286,000	$284,000
Average value per ton of product	$89.46	$91.52	$96.45	$94.36	$95.94
Average value per ton of K_2O equivalent	$176.80	$178.20	$189.36	$192.72	$193.32
Exports[4]	1,020	1,260	1,330	935	997
K_2O equivalent	470	624	663	415	462
Value[5]	$136,000	NA	NA	NA	NA
Imports for consumption[4,6]	6,950	6,860	7,010	7,200	7,920
K_2O equivalent	4,160	4,160	4,250	4,360	4,740
Customs value	$546,000	$550,000	$580,000	$578,000	$642,000
Consumption,	9,330	8,930	9,150	9,300	9,890
apparent[7] K_2O equivalent	5,410	5,240	5,350	5,430	5,750
Year-end producers' stocks, K_2O equivalent	303	343	283	305	234
WORLD:					
Production, marketable K_2O equivalent	27,500	26,100	23,900	[R]20,300	22,500

NA, Not available.
[1] Includes muriate and sulfate of potash, potassium magnesium sulfate, and some parent salts. Excludes other chemical compounds containing potassium.
[2] Previously published and 1994 data are rounded by U.S. Bureau of Mines to three significant digits.
[3] F.o.b. mine.
[4] Excludes potassium chemicals and mixed fertilizers.
[5] F.a.s. U.S. port.
[6] Includes nitrate of potash.
[7] Calculated from sales plus imports minus exports.

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marketing as are their vast sylvite deposits.

Finally, the demand for chemical fertilizers will continue to grow in parallel with the world's population and even more so as underdeveloped nations attempt to become more efficient in their farming methods and as land resources for such activity continues to shrink. The world's known potash production and reserves were reported by the USBM in table 2 of their WIPP potash evaluation (Weisner et al., 1978). If correct, then the reserves are capable of supplying potash for the world's markets for the next 400 yrs.

The reserves in the Carlsbad district have been estimated at around 51 million tons equivalent K_2O (Energy, Minerals and Natural Resources Department, 1992). The life of the district would be on the order of 25 yrs from present. However, Barker and Austin (1993) have pointed out that longevity of individual mines varies considerably, with one lasting less than a decade and another more than 100 yrs.

CURRENT MINING METHODS

Conventional mining

Conventional mining is a term often used in the Carlsbad mines to define the undercut-drill-blast-load-transport-convey mining method. In fact, this system is now limited to hard langbeinite ore mining only, so it is not the most common mining method currently used because sylvite ores are mined with drum-mining machines. Nonetheless, a description of the conventional system is worthwhile in that it was used to evaluate the economics of mining and processing the 4th ore zone langbeinite resources in the WIPP area.

Fig. 4.1 is a rather typical layout for conventional mining. The method is room and pillar. Pillar dimensions range from 30 to as much as 60 ft on a side depending on mining depth and extraction ratio. The pillars can be equidimensional or rectangular, but the aspect ratio is always near 1.0. Room widths hold fairly close to 28 ft. Fig. 4.1 shows barrier pillars, but their use is not universal and later pillar extraction is always contemplated. For langbeinite ores the maximum pillar load is limited to about 4,000 psi. The mining depth of the 4th ore zone in the WIPP area ranges from 1,650 to 1,850 ft. At that depth, the extraction for conventional room and pillar mining would be about 50%; however, 60% could be achieved if advance is rapid or if a retreat mining method is utilized.

A typical mining crew for conventional mining of langbeinite ores would consist of an undercut machine operator, a drill jumbo operator, an explosives person, an arm-type loader operator, two shuttle car operators, a roof bolt operator, a relief person, an electrician, a mechanic, and a foreman. This 11-man crew can mine on the order of 1,500 to 2,000 tons in a 10-hour shift. Incidentally, 10-hour shifts have become rather common for underground personnel at Carlsbad mines in recent years. At one mine the total mine work force from Superintendent down to the relief worker hovers around 100, and that mine produces on the order of 1.3 million tons of raw ore annually. The traditional 2,080 hours per employee year translates into an overall mine production rate of 6.25 tons per man-hour. At another mine, using similar methods but with better equipment, the productivity is probably around 10 tons per man-hour. Therefore, productivity is rather high at Carlsbad for underground mining using the conventional method.

Partial pillar extraction has been proven feasible at moderate depths in Carlsbad and in areas where there is little danger of flooding from overlying brine aquifers. The total extraction has reached over 80% of the in-place reserves. Surface subsidence does occur when pillars are extracted.

Mining heights reach the full thickness of the ore bed, which on occasion becomes as much as 12 ft, but a more typical mining height is in the range of 6 to 8 ft. The size of the current ram or shuttle cars limits mining to no less than 5 ft. The ore mined by blasting can contain large fragments, so breakers are installed at all belt-feeder locations.

Continuous mining using drum miners

Most of the sylvite ores are being mined with the use of continuous mining methods utilizing drum miners. Extendible conveyor systems have been introduced in recent years so that the drum miners feed directly onto conveyors. One company utilizes diesel-powered ram cars that tram short distances to belt feeders. Figs. 4.2 and 4.3 show typical mine layouts. Long (up to 5,000 ft) panels are mined in a retreating chevron or "herringbone" pattern. When mining sylvite at moderate depths (800 to 1,200 ft) the extraction can exceed 90%. In deeper locations, barrier pillars are used to give long-term protection of beltways, in which case the overall extraction drops to about 80% but some of the barriers can be recovered.

One company has automated to the fullest possible extent the operation of the continuous mining machine and the mobile and extendible feed conveyor so that only two people are required at the mining face. Another company using a similar but more fully controllable extendible conveyor needs four people at the face. Productivity per mining-face operator is as much as 50 tons per man-hour with either of these systems.

Continuous mining is ideal for thin ore seams. Currently, the mining height is as low as 4.5 ft, and the equipment in use can mine as low as 4.0 ft. Immediate subsidence occurs over the mined area. A general rule is that the surface expression of subsidence over high-extraction areas amounts to 50–75% of the thickness mined.

Mineral processing

A separate section (*see* Chapter 3, this circular) describes potash mineral processing, but an overview of the process that would be used for the specific langbeinite and mixed sylvite-langbeinite ores that are common in the WIPP area is included here because that type of plant was used in this economic evaluation. Fig. 4.4 is a simple flow sheet that is being used by IMC Kalium to treat mixed ores. If the ore is just langbeinite, then it is treated by a rather simple but carefully controlled leaching method to produce as many as four final products depending on the grain sizes of the raw ore.

If the ore is mixed, then it is first passed through a heavy-media circuit to separate the two ore minerals. The heavy fraction (langbeinite-bearing) is passed back into the langbeinite-processing part of the plant. The sylvite fraction is concentrated by flotation. Additional langbeinite that escaped separation in the heavy-media plant is recovered by refloation of the sylvite tailing. The recovered product is passed back in the langbeinite circuit.

An important ability of the IMC process is to combine the fine-particle products from both the langbeinite and sylvite circuits for additional treatment in a separate (not shown in Fig. 4.4) part of the plant to manufacture K_2SO_4 product. The exact process is held proprietary to IMC; however, the process includes a first step of hydrating the langbeinite followed by reaction with dissolved sylvite to form K_2SO_4 and $MgCl_2$.

Hence, three products are produced from a mixed ore: sylvite, langbeinite, and manufactured arcanite (K_2SO_4). If the ores present within the WIPP area are mined, then the IMC method of treating mixed ores could be utilized.

ESTIMATION OF MINING, PROCESSING, AND CAPITAL COSTS

We estimated mining and processing cost on the basis of direct operating expense exclusive of those related to corporate costs away from the mine facility. Direct operating cost consists of all costs including normal repair and maintenance and periodic replacement of mining and processing components, but it does not include the major capital cost for initial installation and equipping of the mine or processing plants. The costs do include all support operations required to sustain continuing operations of a major potash-producing facility such as administration, tailing disposal, product storage, load-out facilities, regulatory compliance, etc.

We selected three scenarios of how the potash resources would be developed: Scenario I—mining encroaches into the area from a nearby mine, in which event there is no development cost. Scenario II—mining encroaches into the area, but there is the need for a new shaft to provide quick access for mining crews and equipment plus improvement of ventilation. And Scenario III—a new mining and processing plant is to be constructed solely for exploitation of the resources in the WIPP area.

We believe that the first two scenarios are the most likely to occur, and Scenario III presents a case that would occur only if mining had ceased for whatever reason in the Carlsbad area for an extended period of time. The orebodies we

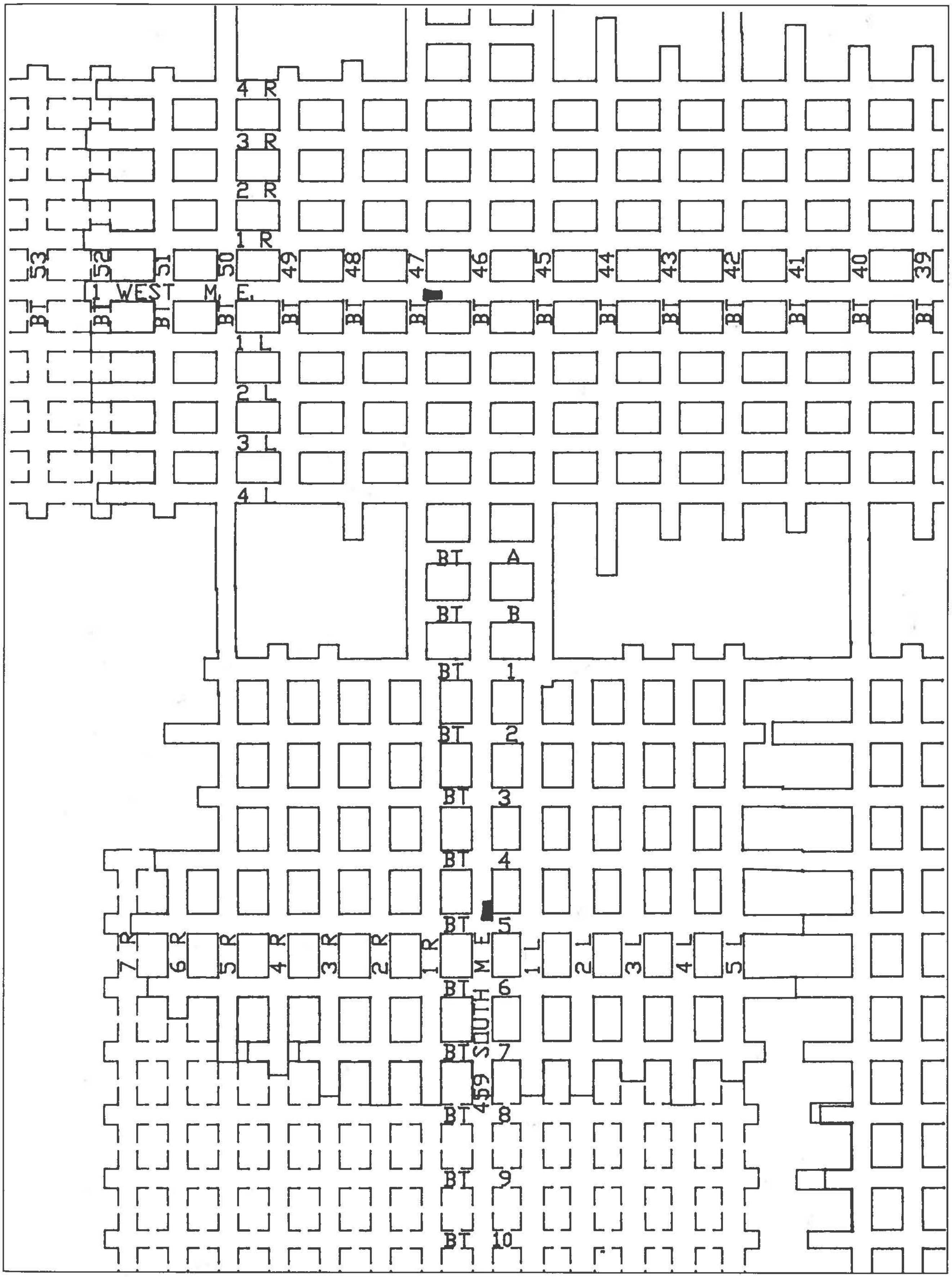

FIGURE 4.1—Room and pillar mining. Approximate scale: slightly less than 1″ = 200′. Courtesy of Western Ag–Minerals Co.

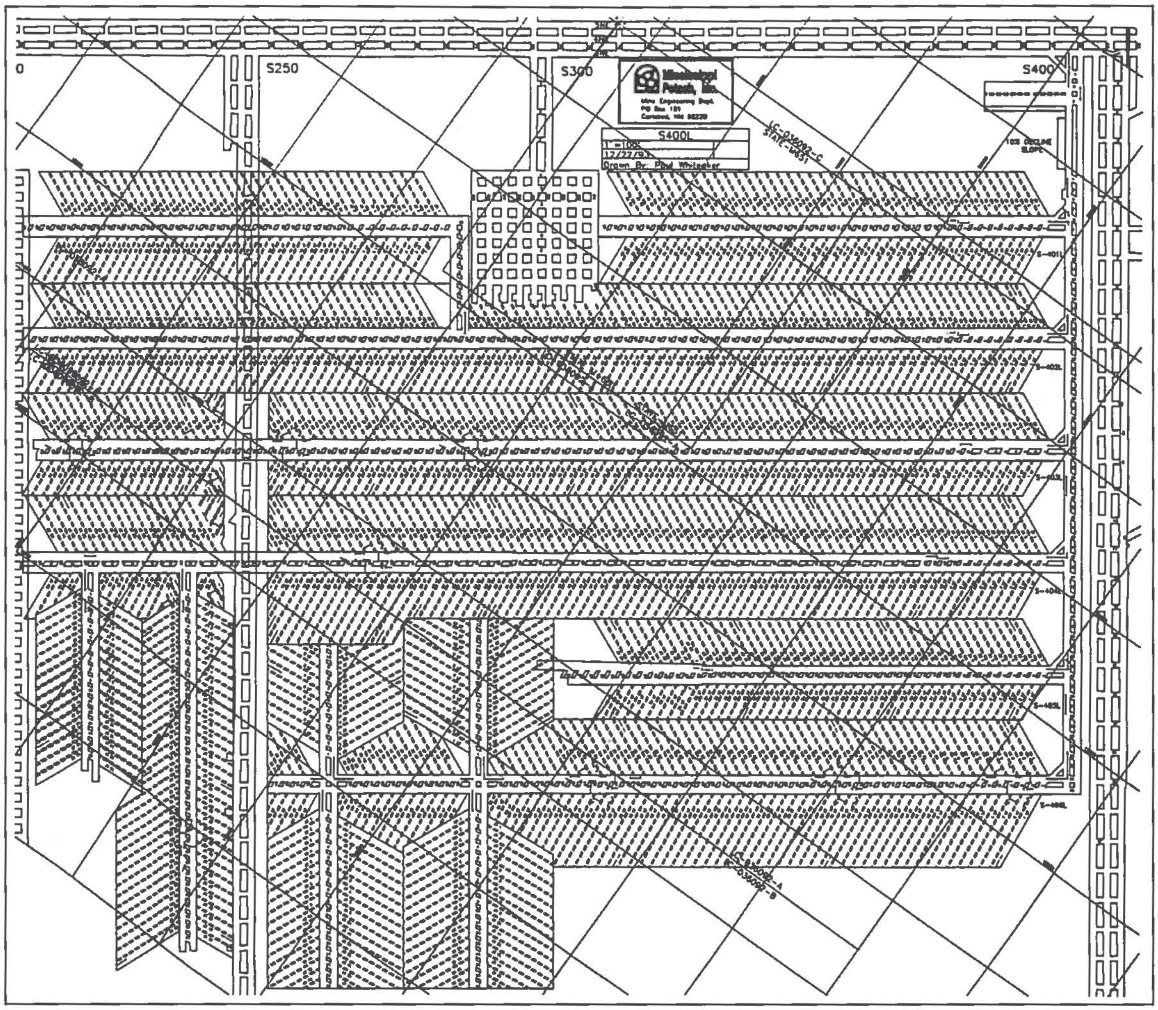

FIGURE 4.2—Continuous mining. Courtesy of Mississippi Potash Co.

have evaluated extend both north and south into currently active mines, so we concluded that the most logical and economic means for resources in the WIPP area to be mined will be by extension of existing operations rather than by developing an entirely new facility.

Two models of total operating costs were run for the 4th and 10th ore zones. The input assumptions are given in Table 4.4. Discussions with mine operators and BLM officials and professional judgment indicate that these two cases fall within the range of costs and grades either mined historically in the Carlsbad potash district or economically achievable with current equipment and methods.

The first case was based on a conservative estimate of total costs for a hypothetical low-volume/high-cost producer. The analyses yield calculated cut-off grades of 6.25% K_2O for langbeinite ores of the 4th ore zone and 12.25% K_2O for sylvite ores of the 10th ore zone.

In the second case for a high-volume/low-cost producer, the cut-off grades and mining height were assumed and operating costs were calculated. Grade and mining height were set at the BLM "Potash Classification Standards" that are 4% K_2O for langbeinite and 10% K_2O for sylvite, both at a mining height of 4.0 ft. Discussion with the BLM has confirmed that significant quantities of ore meeting these requirements have been mined in recent years.

4th ore zone

We selected two mining methods for exploitation of the langbeinite-dominant ores of the 4th ore zone in the WIPP area. One was to use conventional mining and where the mining height was maintained at 6.0 ft. The second method assumed that heavy drum miners can be developed in the near future to allow continuous mining at 4.5 and 4.0 ft height. We also considered three extraction percentages: 60, 80, and 90% depending on the mining method used. This resulted in three mining plans that we called Cases 1, 2, and 3. Mining cost was the same for Cases 1 and 2, the difference being the percentage of mining extraction. Case 3 was assigned lower cost and the highest mining extraction. Plant recovery was held at 85% for all three cases.

10th ore zone

We believed that the 10th ore zone could be mined by the more economical continuous mining method (Case 3) and extraction of 90% of the in-place reserve. We believe the lower mining and processing cost is justified because the efficiency of the continuous mining system has been demonstrated in nearby mines and because mineral processing is simpler for sylvite. However the recovery was dropped to 80% because much of the ore is mixed and in parts has considerable insolubles.

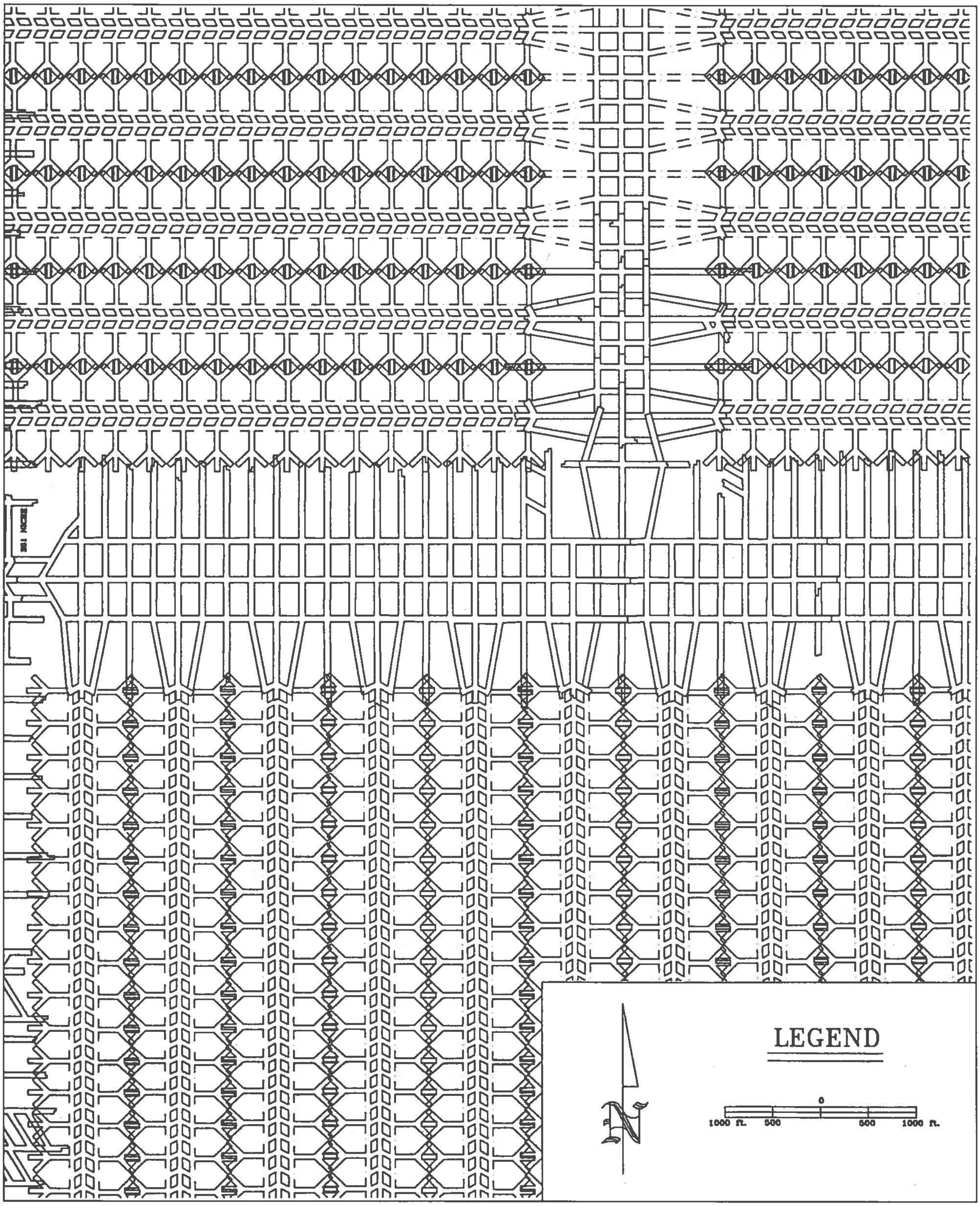

FIGURE 4.3—Continuous mining with barrier pillars. Courtesy of New Mexico Potash Co.

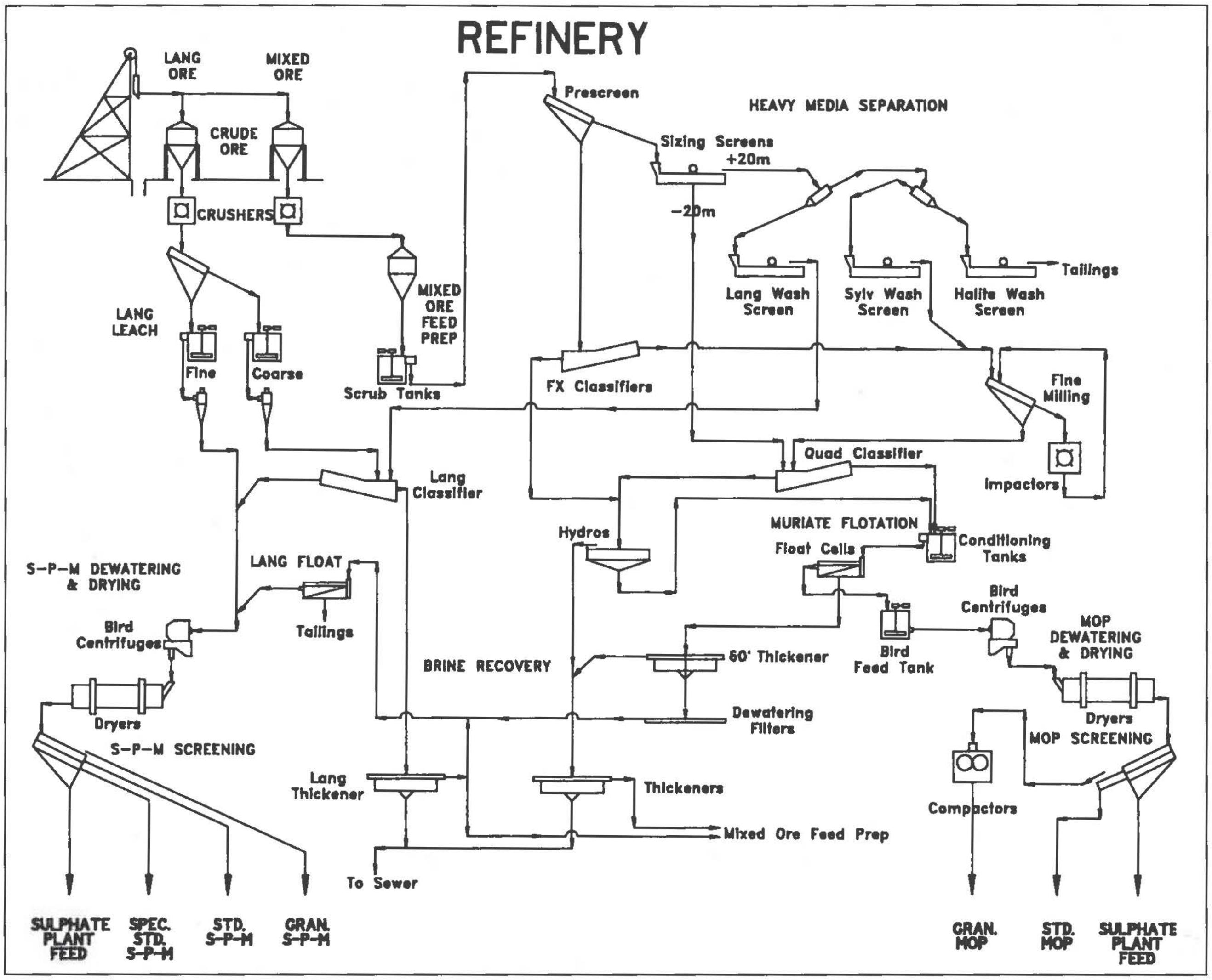

FIGURE 4.4—Mineral processing of mixed ore. Courtesy of IMC Kalium.

Market prices for products

We have assumed that langbeinite (along with a varying amount of manufactured K_2SO_4) will be sold fob at the plant site for $77/ton of product containing 22% K_2O. For sylvite the selling price was set at $74/ton of product containing 60% K_2O. On a per-unit basis (defined as the value of 1% K_2O contained in the product) the net selling prices are $3.50/unit K_2O in langbeinite and $1.23/unit K_2O in sylvite products. Market prices have varied over a considerable range, but this is our best judgment for the current price in relationship to cost. The prices fall well within the high and low averages over the last 12 yrs (Table 4.1).

Ore reserves

Tables 4.5A and 4.5B list the ore reserves in 0.5% K_2O grade steps that were used for economic evaluations. It was assumed that the highest grade ores would be mined first continuing down to the appropriate cut-off grade. This is an idealistic assumption but one that can be achieved with good mine-development planning.

Estimate of capacity

The reserves for the 4th and 10th ore zones are large, and we have not attempted to optimize the production rate to maximize profit in terms of rate of return on invested capital. Instead, for the higher cut-off grades we set the capacity of the langbeinite at 350,000 product (containing 22% K_2O) tons/year, which is equivalent to about one-third of the current production from the entire Carlsbad potash district. For 10th-ore-zone sylvite reserves, we set the annual capacity at 400,000 tons muriate (containing 60% K_2O). We believe these production rates are within a range compatible with future markets for potash products from Carlsbad assuming that the current mines are depleting current reserves.

When evaluating the BLM cut-off grades, we increased production rates to 500,000 tons for langbeinite and 600,000 tons for sylvite to compensate for the larger reserves in those categories. These rates approximately match those of the largest potash producer in the district.

We also have assumed that the reserves would be mined by a single operator. The reserves of both the 4th and 10th ore zones are adjacent and to a certain extent stacked, i.e., the 10th overlying the 4th.

Estimate of development cost and time to bring into production

For Scenario II, we have estimated the cost of sinking a new man-shaft 1,900 ft deep at $10 million and the time required to commence mining at one year. The cost would be shared equally between the two mining horizons. In that sce-

TABLE 4. 4—Summary of operating and development factors.

	Area of evaluation	4th ore zone (langbeinite) WIPP	Additional	Combined	10th ore zone (sylvite) WIPP	Additional	Combined
FACTORS HELD CONSTANT							
	Net selling price, $/ton product	77.00	77.00	77.00	74.00	74.00	74.00
	Net selling price, $/unit K_2O/ton	3.50	3.50	3.50	1.23	1.23	1.23
	Plant recovery, percent	85	85	85	80	80	80
	Time to develop, years						
Scenario I	None required	0.0	0.0	0.0	0.0	0.0	0.0
Scenario II	New shaft only	1.0	1.0	1.0	1.0	1.0	1.0
Scenario III	New plant constructed	3.0	3.0	3.0	3.0	3.0	3.0
HIGHER CUT-OFF GRADE CONDITIONS							
	Cut-off grade, %K_2O equivalent	6.25	6.25	6.25	12.25	12.25	12.25
	Annual production rate, million tons product	0.35	0.35	0.35	0.40	0.40	0.40
	Mining extraction, percent of in-place reserve						
Case 1	Conventional, no pillar extraction @ 6.0 ft	60	60	60			
Case 2	Conventional, pillars extracted @ 6.0 ft	80	80	80			
Case 3	Continuous mining @ 4.5 ft	90	90	90	90	90	90
	Mining and processing Cost, $/ton ore						
Case 1	Conventional, no pillar extraction @ 6.0 ft	18.00	18.00	18.00			
Case 2	Conventional, pillars extracted @ 6.0 ft	18.00	18.00	18.00			
Case 3	Continuous mining @ 4.5 ft	16.00	16.00	16.00	12.00	12.00	12.00
	Development cost, million dollars						
Scenario I	None required	0	0	0	0	0	0
Scenario II	New shaft only	5.00	5.00	5.00	5.00	5.00	5.00
Scenario III	New plant constructed	70.00	70.00	70.00	80.00	80.00	80.00
BLM CUT-OFF GRADE CONDITIONS							
	Cut-off grade, %K_2O equivalent	4.00	4.00	4.00	10.00	10.00	10.00
	Annual production rate, million tons product	0.50	0.50	0.50	0.60	0.60	0.60
	Mining extraction, percent of in-place reserves						
Case 3	Continuous mining @ 4.0 ft	90	90	90	90	90	90
	Mining and processing cost, $/ton ore	11.56	11.56	11.56	9.6	9.6	9.6
	Development cost, million dollars						
Scenario I	None required	0	0	0	0	0	0
Scenario II	New shaft only	5.00	5.00	5.00	5.00	5.00	5.00
Scenario III	New plant constructed	100.00	100.00	100.00	120.00	120.00	120.00

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nario we assumed that underground mining would be simultaneously extended into the area from IMC Kalium mining operations that had mined up to the southern and eastern boundaries of the WIPP site. Conversely, mining could reach the area from the north by expansion southward from the NM Potash mine. A precise location was not selected for the new shaft other than it be located just northwest and outside WIPP.

For Scenario III, we used an estimation of $200/ton of annual plant product capacity resulting in: $70 million for the 6.25% cut-off and $100 million for the 4% cut-off for developing the 4th ore zone, and $80 million for the 12.25% cut-off and $120 million for the 10% cut-off for developing the sylvite reserves of the 10th ore zone. These totals would include two new shafts in addition to the processing plant. We further assumed that three years would be needed to bring the new mine on stream. Some may say these costs are low for a new "greenfield" plant, but we believe they may considered as perhaps even high because the new plant would probably be built by a combination of modernization and expansion at an existing plant site where ancillary facilities such a power, railhead, warehouses, and most importantly waste-disposal facilities already existed.

Historical trend of mining and processing cost versus market price

A study of the productivity, mining and processing cost, and the market price for Carlsbad potash products given in Table 4.1 has indicated that the operators have remained competitive over the years. As costs have increased, so have productivity and the market price. We compared the price of the products to the Composite Producers Price Index and found a linear relationship. This indicated that the price of Carlsbad potash products has escalated in parallel with national inflation trends. Therefore we believe, as mining and processing costs increase for the Carlsbad producers, so will the price received for their products.

Determination of profitability

Simple nondiscounted cash flows were calculated using the criteria given in Table 4.4. The results are shown in Tables 4.5A and 4.5B. No consideration was given to the initial development costs for scenarios II and III. The reserves are minable at a profit. Detailed economic evaluations are given in Chapter 9 that include initial development cost, the

TABLE 4.5A—Ore reserves and projected gross income for the 4th ore zone.

4th ore zone	WIPP	Additional	Combined	WIPP	Additional	Combined	WIPP	Additional	Combined
Mining height, ft	4.00	4.00	4.00	4.50	4.50	4.50	6.00	6.00	6.00
Grade									
4.25	3.75	8.75	12.50	4.74	12.53	17.27	5.44	19.05	24.49
4.75	4.11	10.93	15.04	2.90	24.27	27.17	3.11	7.83	10.94
5.25	2.26	18.46	20.72	3.10	17.64	20.74	1.63	4.24	5.87
5.75	2.81	16.79	19.60	3.57	10.41	13.98	2.47	3.90	6.37
6.25	4.85	12.51	17.36	3.84	7.42	11.26	3.61	4.93	8.54
6.75	3.14	7.50	10.64	2.42	4.23	6.65	3.38	6.80	10.18
7.25	2.56	3.50	6.06	2.20	2.76	4.96	4.41	10.03	14.44
7.75	6.24	4.25	10.49	6.23	4.62	10.85	6.70	11.88	18.58
8.25	2.76	4.29	7.05	3.19	4.82	8.01	2.03	9.78	11.81
8.75	2.78	3.91	6.69	2.49	4.75	7.24	1.12	6.13	7.25
9.25	1.39	4.08	5.47	1.57	6.20	7.77	0.40	5.28	5.68
9.75	0.96	4.35	5.31	1.12	5.64	6.76		2.62	2.62
10.25	0.57	4.71	5.28	0.90	7.67	8.57		1.47	1.47
10.75	1.00	6.80	7.80	0.20	5.79	5.99		0.42	0.42
11.25	0.55	7.33	7.88	0.40	3.73	4.13		0.00	
11.75	0.37	3.00	3.37	0.10	2.84	2.94		0.00	
12.25	0.29	2.43	2.72	0.10	1.22	1.32		0.00	
12.75	0.10	1.51	1.61		0.21	0.21		0.00	
13.25		0.94	0.94		0.00			0.00	
Tons >4.00	40.49	126.04	166.53	39.07	126.75	165.82	34.30	94.36	128.66
Tons >6.25		20.92	54.48	75.40	18.04	54.41	72.45		
Grades >4.00	6.99	7.30	7.23	6.84	6.94	6.91	6.53	6.67	6.63
Grade >6.25				8.24	9.40	9.07	7.59	8.07	7.95
Tons mined									
Case 1							10.82	32.65	43.47
Case 2							14.43	43.53	57.96
Case 3	36.44	113.44	149.88	18.83	49.03	67.86			
Tons product									
Case 1							3.17	10.18	13.35
Case 2							4.23	13.57	17.80
Case 3	9.84	31.99	41.87	5.99	17.81	23.78			
Sales									
Case 1							244.41	783.77	1028.12
Case 2							325.88	1045.03	1370.83
Case 3	757.80	2463.55	3223.74	461.55	1371.18	1831.08			
Cost									
Case 1							194.83	587.63	782.46
Case 2							259.78	783.50	1043.28
Case 3	421.26	1311.32	1732.58	301.25	784.51	1085.76			
Gross profit									
Case 1							49.58	196.15	245.66
Case 2							66.10	261.53	327.55
Case 3	336.54	1152.23	1491.16	160.30	586.67	745.32			
Mine life, years									
Case 1							9.07	29.08	38.15
Case 2							12.09	38.78	50.87
Case 3	19.68	63.99	83.73	17.13	50.88	67.94			

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time value of future earnings, taxes, royalties, amortization, etc. Discounted cash analysis is relevant to estimating the expected present value of the potash reserves to an outside investor or the impact of withdrawal of those reserves to accommodate the requirements for WIPP.

Actual exploitation of the potash resources will depend on factors such as future markets, the ability to acquire the mining leases by competitive bid with others who also want to exploit the potash resources, and when the potash would be needed to replace ore now being depleted at neighboring mines. However, most of the potash resources could be mined at a profit.

Table 4.5B—Ore reserves and projected gross income for the 10th ore zone. *Adjusted grade is where all reserves ≥ 19.25% were reduced to 19.25%.

10th ore zone	WIPP	Additional	Combined	WIPP	Additional	Combined
Mining height, ft	4.00	4.00	4.00	4.50	4.50	4.50
Grade						
10.25	3.05	3.12	6.17	3.26	2.63	5.89
10.75	3.87	3.13	7.00	3.39	3.02	6.41
11.25	3.42	3.82	7.24	4.71	5.62	10.33
11.75	3.96	5.06	9.02	3.96	6.85	10.81
12.25	3.57	7.38	10.95	4.84	8.96	13.80
12.75	4.17	6.14	10.31	5.59	6.88	12.47
13.25	3.57	6.99	10.56	3.72	8.50	12.22
13.75	2.82	6.07	8.89	3.50	7.06	10.56
14.25	3.47	5.50	8.97	3.08	7.45	10.53
14.75	2.38	9.33	11.71	3.37	8.97	12.34
15.25	2.25	7.13	9.38	1.60	5.49	7.09
15.75	4.07	6.93	11.00	0.98	5.82	6.80
16.25	2.73	6.78	9.51	1.16	4.32	5.48
16.75	1.99	3.40	5.39	1.00	3.96	4.96
17.25	1.50	3.38	4.88	1.34	3.06	4.40
17.75	0.88	3.67	4.55	0.80	3.42	4.22
18.25	1.47	5.01	6.48	1.48	2.43	3.91
18.75	0.84	3.81	4.65	0.93	2.60	3.53
19.25	0.69	2.36	3.05	0.69	1.88	2.57
19.75	0.49	2.00	2.49	0.41	1.85	2.26
20.25	0.18	1.01	1.19	0.10	0.95	1.05
20.75	0.60	0.58	1.18	0.52	0.69	1.21
21.25	0.21	0.38	0.59	0.21	0.31	0.52
21.75	0.11	0.93	1.04	0.11	0.77	0.88
22.25		0.47	0.47		0.31	0.31
22.75		0.40	0.40		0.23	0.23
23.25		0.23	0.23		0.23	0.23
Tons >10.00	52.29	105.01	157.30	50.75	104.26	155.01
Tons >12.25				30.59	77.18	107.77
Grade >10.00	13.99	14.96	14.64	13.58	14.53	14.22
Grade >12.25				15.06	15.57	15.42
Adjusted grade*				15.00	15.46	15.33
Tons mined						
Case 3	47.06	94.51	141.57	27.53	69.46	96.99
Tons product						
Case 3	8.78	18.85	27.63	5.51	14.32	19.83
Sales						
Case 3	649.60	1395.00	2044.95	407.46	1059.56	1467.08
Cost						
Case 3	451.79	907.29	1359.07	330.37	833.54	1163.92
Gross profit						
Case 3	197.82	487.72	685.88	77.09	226.02	303.16
Mine life, years						
Case 3	14.63	31.42	46.06	13.77	35.80	49.56

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5. Method of potash reserve evaluation

George B. Griswold and James E. Griswold

6692 Pueblo Vista, Las Cruces, NM 88005

INTRODUCTION

Evaluation of potash reserves was based solely on subsurface information from 40 core holes previously drilled within and around the WIPP site. The nearest underground mine operations are currently no closer than one mile from the outer boundary of WIPP. All 40 holes were drilled using brine (containing potassium as well as sodium chloride) to inhibit dissolution of potassic minerals. The results of chemical analyses of the ore-bearing intervals were adjusted to calculate the percentage equivalent as individual natural mineral species. Only the K_2O percentages as either sylvite or langbeinite were used to compute ore reserves.

The locations of the 40 drill holes used to compute potash reserves are shown in Fig. 5.1. Also shown are 34 other potash core holes, all surrounding the WIPP boundary, that were drilled by potash or exploration companies. Records of ore intercepts of these 34 holes were not available to us. Information on them is held in confidence by the Bureau of Land Management (BLM) in accordance with CFR 3590. The reserve calculations are valid for the area *within the WIPP site* itself because all drill-hole information within those bounds was available to us. Only the BLM, which has drilling records of all holes in the entire Carlsbad potash mining district, can verify the validity of reserve estimates made for the area outside of WIPP. A reasonable estimate of the potash reserves is possible for an area extending about one mile outside of the WIPP boundary excepting the southwest quadrant of this perimeter area. The essential results of the reserve calculation follow.

1. The 4th ore zone contains *BLM Lease Grade* langbeinite ore in the amounts of:
   40.5 million tons @ 6.99% K_2O grade within the WIPP area;
   126.0 million tons @ 7.30% K_2O grade outside of the WIPP area;
   166.5 million tons @ 7.22% K_2O grade in the entire study area.
2. The 10th ore zone contains *BLM Lease Grade* sylvite ore in the amounts of:
   52.3 million tons @ 13.99% K_2O grade within the WIPP area;
   105.0 million tons @ 14.96% K_2O grade outside of the WIPP area;
   157.3 million tons @ 14.64% K_2O grade in the entire study area.
3. Potash resources are present in the 2nd, 3rd, 5th, 8th, 9th, and 11th ore zones within the WIPP site, but with minor exceptions do not meet the lease-grade standards currently used by the BLM. These resources could only become minable if advanced thin-seam mining methods are developed in the future.
4. Most of the BLM Lease Grade reserves in the 4th and 10th ore zones are profitable using mining and processing technology currently employed by nearby potash producers. For economic modelling we also determined the tonnages and grades under more stringent conditions where the mining height was increased and mining and processing costs were set to emulate a low-volume/high-cost producer. This then provided two sets of reserve bases for subsequent economic evaluation. We used the term *Higher Grade Reserve* for this part of the reserve base that is
   4th ore zone: 72.4 million tons (6.0 ft mining height, >6.25% K_2O as langbeinite) of which 18.0 million tons lie within and 54.4 million tons outside of WIPP;
   10th ore zone: 107.8 million tons (4.5 ft mining height, >12.25% K_2O as sylvite) of which 30.6 million tons lie within and 77.2 million tons outside of WIPP.

FORMULATION OF THE DRILL-HOLE DATABASE

Drill holes available for use in reserve calculations

In 1976 Sandia National Laboratories (SNL) in cooperation with the U.S. Geological Survey (USGS) drilled 21 potash-evaluation holes within and immediately adjacent to the current WIPP site. Complete records of these 21 holes have been reported by Jones (1978). In addition, 18 potash-evaluation drill holes (seven within the current site and 11 immediately adjacent to the site) were drilled by private companies that submitted records of assayed intervals to the USGS Conservation Division (subsequently transferred to the BLM). Copies of these records were obtained from the BLM Carlsbad Resource Area Office. One additional hole, AEC No. 8, drilled as part of an earlier WIPP site evaluation, was cored and assayed for potash. The hole lies just northeast of the WIPP boundary. These 40 holes provided the database for potash reserve calculations.

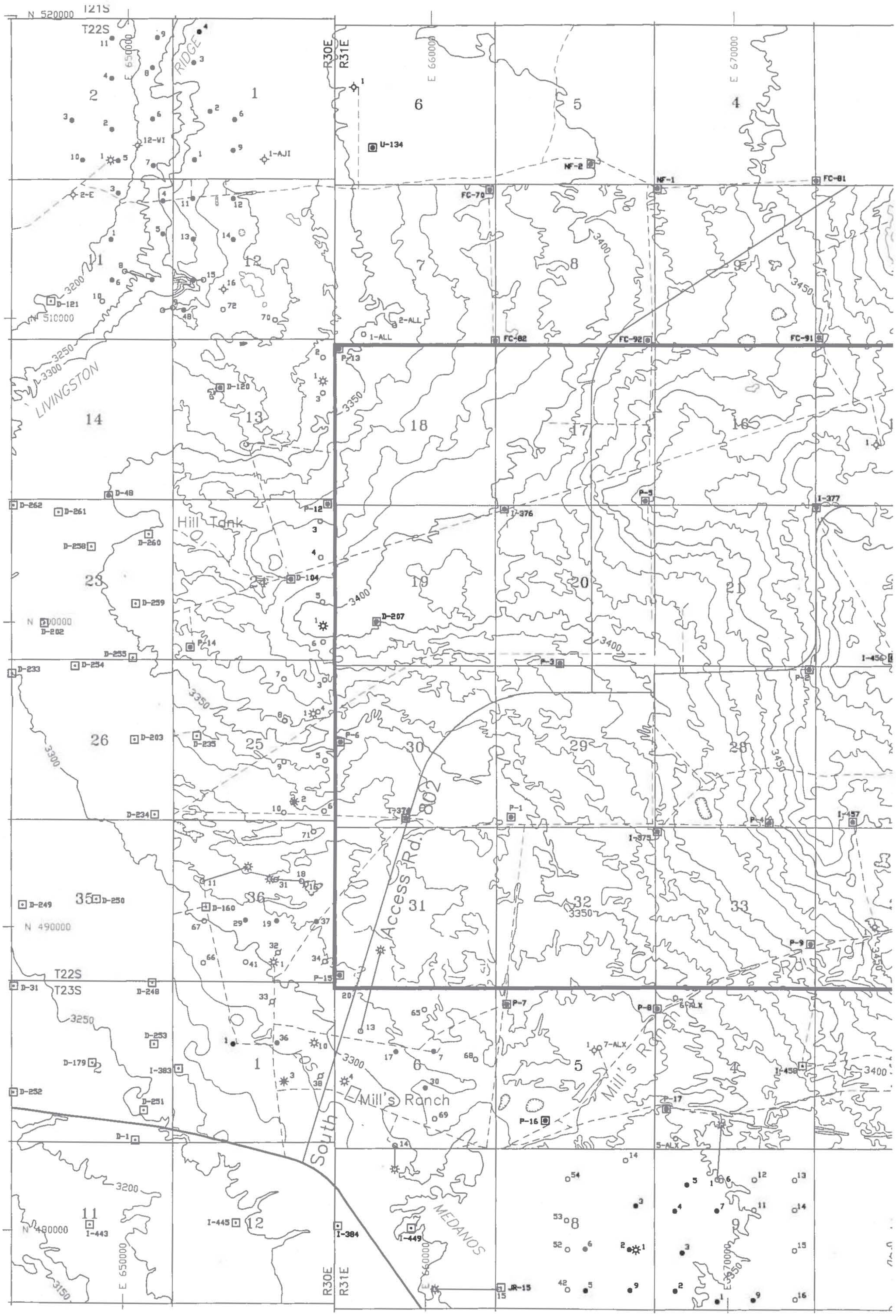
A complete listing of the 40 holes used in the reserve calculation is given in Table 5.1, and their locations are shown in Fig. 5.1.

Brief history of drill holes that constitute the database

In 1978 the USGS performed the first potash-reserve study at WIPP (John et al., 1978). In that report, the assay results of 37 of the 40 holes were given. The records of three industry drilled holes, I-377, I-456, and I-457, were obtained from the BLM. The assay records of these three holes became available to the public after the Department of Energy (DOE) bought the lease holdings of IMC Fertilizer, Inc. (then IMC Global, Inc., now IMC Kalium).

Special note is made of hole D-123 at the eastern edge of sec. 34 in the southeast corner of the WIPP site. This hole was drilled to a depth of 1,880 ft, deep enough to penetrate all the ore zones, but no assay records were provided to the BLM. The company that drilled the hole in 1953 (Duval Sulphur and Potash) apparently thought the core revealed no commercial potash. This hole was eliminated from our database. It had little effect on resource calculation.

As mentioned in the introduction, additional potash core holes have been drilled in the area by mining or exploration companies, mostly to the west. However, the detailed records, including chemical analyses of suspected ore intercepts, have not been released to the public at the request of the companies. This restriction applies so long as the company holds the mineral lease on which the holes were drilled. The 34 such holes that exist in the map area are shown in Fig. 5.1 but are not listed in Table 5.1. It is noteworthy that all holes drilled within the existing WIPP site have been avail-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FC-70
2-E
12-WI
1-AJI
D-121
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FC-82
FC-92
FC-91
P-13
D-120
LIVINGSTON
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3350
3400
3450
D-48
D-262
D-261
P-12
I-376
P-5
I-377
Hill Tank
D-258
D-260
D-104
D-259
D-207
N 500000
D-202
P-14
D-255
D-233
D-254
P-3
I-456
P-2
D-235
D-203
P-6
Access Rd. 802
D-234
I-374
P-1
P-4
I-457
I-375
D-249
D-250
D-160
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P-9
P-15
T22S
T23S
D-31
D-248
P-7
P-8
6-ALX
7-ALX
D-253
D-179
I-383
I-458
D-252
D-251
Mill's Ranch
P-17
P-16
Mill's Ranch Rd.
South Loop
D-1
5-ALX
MEDANOS
3200
N 480000
I-443
I-445
I-384
I-449
E 650000
3150
JR-15

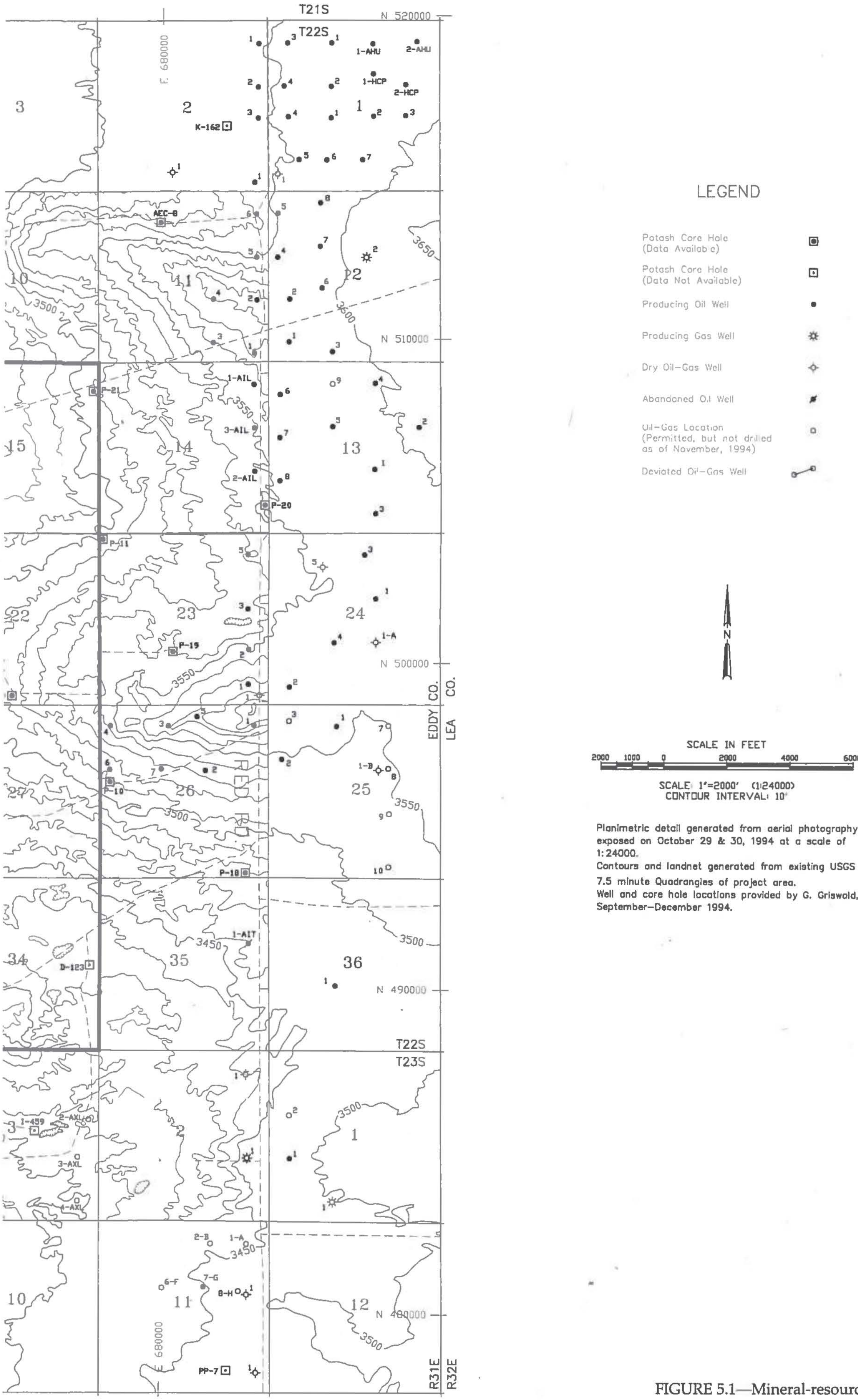

FIGURE 5.1—Mineral-resource drill holes.

TABLE 5.1—Ore zone data from USGS Open-file Report 78-828 (John et al., 1978).

Hole	North	East	Surface	2nd	3rd	4th	5th	8th	9th	10th	11th
AEC8	513579	679936	3532			X	X			X	
NF-1	514352	667501	3419	X		X				X	
NF-2	515149	665289	3401			X				X	
1	493668	662748	3346			X				X	
2	498545	672593	3481			X				X	
3	498716	664353	3384	X		X				X	
4	493519	671306	3443			X				X	
5	504060	667156	3467			X				X	
6	496110	657109	3355			X				X	
7	487526	662639	3333			X				X	X
8	487407	667633	3340	X		X			X	X	X
9	489558	672686	3413	X	X	X		X		X	
10	496361	678401	3510		X	X		X	X	X	
11	503799	678165	3505			X	X			X	
12	503918	656661	3375	X		X				X	
13	509024	657013	3347	X		X				X	
14	499194	652152	3360	X		X				X	
15	488451	657128	3309			X				X	
16	483712	663927	3319	X		X				X	
17	484122	667950	3336	X		X				X	
18	493580	682611	3479			X		X		X	
19	500353	680347	3542			X				X	
20	504866	683180	3554			X	X	X	X	X	
21	508358	677851	3510	X		X		X			
48	504173	649421	3349	X		X					
70	514285	661946	3380	X		X	X	X			
81	514622	672738	3469			X					
82	509315	662154	3379			X					
91	509453	672861	3448			X				X	
92	509346	667207	3418			X				X	
104	501442	655464	3388			X				X	
120	507722	653102	3329			X	X			X	
134	515656	658085	3361			X		X			
207	500079	658297	3400			X		X		X	
374	493614	659279	3343			X		X		X	
375	493213	667609	3384			X				X	
376	503777	662488	3404	X	X		X			X	
377	503868	672806	3492	X	X	X		X		X	
456	498952	675348	3516		X	X		X		X	
457	493566	674053	3453		X	X				X	

NOTES:
1. X denotes that assay information for that zone was available.
2. Holes AEC 8 and 1 through 21 drilled by the USGS during site study.
3. Holes NF-1 and NF-2 drilled by National Farmers Union.
4. Holes 70, 81, 82, 91, and 92 drilled by National Farmers Union.
5. Holes 104, 120, and 207 drilled by Duval Sulphur and Potash Co.
6. Holes 374, 375, 376, 377, 456, and 457 drilled by IMC Fertilizer, Inc.. (then IMC Global, Inc., now IMC Kalium).
7. Hole 134 drilled by U.S. Potash Co.

able to us. For this reason the calculations within the WIPP site should be considered as valid.

Hole locations

The locations of most of the 40 holes used in the reserve calculation are shown on the most current 7.5-minute USGS topographic quadrangle maps of the area. These locations were digitized using the New Mexico (East Zone) coordinates. In the few cases where the holes were not shown on the maps, the locations were first posted on the appropriate quadrangle map using the survey description shown on the written drill records filed with the BLM Carlsbad office, and then their positions were digitized using a Calcomp Drawing Board Two. This phase of the work was done by Thomas R. Mann & Associates, Inc. under contract. That company also compiled the graphics for Fig. 5.1.

Drill-hole elevations

The written drill record gives the elevation of the hole. The records then report formation changes, ore-zone intercepts, assays, etc. referenced as depths below the surface. These holes were drilled from the early 1950s to the late 1970s, and the surface elevations were surveyed from a variety of benchmarks. To further complicate matters, some records are to "drill-rig floor" and others to surface elevations.

The surface elevation was picked at each hole based on the current USGS 7.5-minute quadrangle maps in order to eliminate any survey errors. In cases where the depth measuring point was the drill-rig floor, a slight error may have been induced. However, potash drilling rigs are small units compared to oil-field rotaries, and the floor probably would be only 2 to 3 ft above ground level. For the purpose of compiling structure maps, the error would thus be insignificant.

Formation and ore-zone depths

The depths to ore came from the John et al., (1978) report for all holes except I-377, I-456, and I-457, for which the data came from records at BLM Carlsbad. Formation depths (marker beds) came from Jones (1978) for the "P-series" of 21 holes drilled by SNL-USGS in 1977 plus AEC No. 8. Formation depths for all of the remaining 18 holes came from records at BLM Carlsbad office.

Calculated mineral content and K_2O percentage of ore minerals

The calculation of the percentage K_2O as sylvite or langbeinite is not a simple process. First, the suspected ore-bearing interval is selected by visual examination of the recovered core. Once the intervals are selected, the core is then split longitudinally with one half saved for reference and the other half sent for chemical analysis. In addition to the two ore minerals, sylvite (KCl) and langbeinite ($K_2SO_4{\cdot}2MgSO_4$), the ore beds in the Carlsbad potash mining district typically are a mixture of halite, anhydrite, polyhalite, a variety of other gangue minerals including potassium-bearing minerals (such as carnallite) and magnesium sulfates (such as kieserite), and "insolubles" (mostly clay).

These ore and mineral calculations were performed by the USGS for the P-Series (1–21) and AEC No. 8 and by the individual mining companies when they reported drilling results to the BLM. Therefore, the assay information entered into the database has been adjusted for the mineral suite present at each specific ore intercept. A few spot checks of these calculations were made and found to be correct.

What then was entered into the database was the percentage in K_2O units for sylvite or langbeinite. These are considered to be the only two economic minerals present. The use of percent K_2O rather than the true chemical equivalent of potassium (KCl for sylvite or $K_2SO_4{\cdot}2MgSO_4$ for langbeinite) is a custom of the potassium fertilizer industry.

Ore intercepts

There are 11 known potash-bearing horizons in the Carlsbad potash mining district. They are numbered in sequence upward. The 40 drill-hole cores that form the database showed potash mineralization in all but the 1st, 6th, and 7th of these horizons. Although the principal economic deposits are only in the 4th and 10th ore zones, all known mineral intercepts were entered into the database, and the in-place tons and grade were computed for each.

The drill records report the depths to tops, bottoms, and resulting thicknesses of each ore intercept. This information was placed into the database. In a few instances, John et al. (1978) reported double intercepts for a single ore bed when a lens of barren halite divided the bed into two layers. Most notably this occurred in the 4th ore zone intercept in hole P-21. This particular intercept was combined and corrected so that the data input was 7.35 ft of 5.88% K_2O as langbeinite. In all other cases the thicker reported intercepts were always selected.

Mixed ores

It is common in this area of the Carlsbad potash mining district to find ore that is a mixture of both sylvite and langbeinite. This is true for both the 4th and 10th ore zones in the vicinity of the WIPP site. These mixed ores are being mined and processed with economic success by one of the mining companies, IMC Kalium, a few miles west and south of the WIPP site.

The BLM has used "Equivalent Grade" for such ore mixtures. The calculation is as follows:

- langbeinite-dominant ores;
- equiv. K_2O = % K_2O as langbeinite + 0.4 × % K_2O as sylvite;
- sylvite-dominant ores;
- equiv. K_2O = % K_2O as sylvite + 2.5 × % K_2O as langbeinite.

This 0.4:2.5 ratio is based on a balance of percentage of K_2O between the two minerals and their sales value. The reserves of both the 4th and 10th ore zones were calculated using the equivalent grade: langbeinite-dominant for the 4th and sylvite-dominant for the 10th.

DEFINITIONS OF ORE RESERVES VERSUS ORE RESOURCES

The mining industry and the U.S. Bureau of Mines (USBM) maintain a rather restricted interpretation of what can be called reserves. In short, this means that the ore in-place can be mined under current economics and technology. Others, particularly the USGS, will use the term resource to define in-place mineral-bearing bodies that have the potential to be mined, which is a more liberal interpretation. A full discussion of these two terms can be found in USGS-USBM (1980).

Much of the in-place potash-bearing 4th and 10th ore zones that were quantified meet the more restrictive definition of reserve because they would provide reasonable profits at current market values for potash products and they can be extracted with currently available mining and processing methods. In addition, most of the 4th and 10th ore zones would be classified as ore reserves by order of the Secretary of the Interior dated October 21, 1986, according to which *four feet of 10 percent K_2O as sylvite or four feet of 4 percent K_2O as langbeinite or equivalent combination of the two minerals* defines *potash reserves*. The term *Lease Grade Reserves* was used to define those resources that meet or exceed the above criteria and thereby become reserves.

On the other hand, the reserves quantified for the 2nd, 3rd, 5th, 8th, 9th, and 11th ore zones should be considered resources. The resources may become minable if new thin-seam mechanical miners are developed. Solution mining might be applied to those that are sylvite bearing, but not to those containing the relatively insoluble langbeinite.

To be classified as an ore reserve also means that the geometry of the in-place ore is well defined by either reliable drilling or actual sampled exposures, whether it be from outcroppings or mine faces underground. In case of WIPP the reserves must be regarded as drill-defined only.

The spacing of drill holes within the WIPP boundary is approximately on one-mile centers. This meets current BLM requirements to define ore reserves, which allows a projection of three-quarters of a mile outward from an existing hole (or 1.5-mile spacing). However, it is common for some of the nearby mining companies to close up the drill spacing to 2,000 or even 1,000 ft to define better ore-bearing areas in advance of developing detailed mining plans. Nonetheless, the potash industry probably would agree that the spacing within the WIPP boundary meets their criteria for defining ore reserves and certainly is adequate to define their life-of-mine reserves.

Outside the WIPP boundary a clear-cut line cannot be drawn between what is to be classed as ore reserve or ore resource. Drilling information is incomplete, particularly to the west, and there is no subsurface information whatsoever on the immediate south and east boundaries of the WIPP site. More discussion of the validity of the estimates of reserves and resources adjacent to the WIPP site accompanies the following descriptions of individual ore zones.

COMPUTATION OF ORE-IN-PLACE RESOURCES

The term resources was used during the process of determining the areal extent, thickness, and K_2O grade of the in-place potash mineralization for each of the sampled ore zones. Afterward, determination was made of what could be called Lease Grade Reserve followed by determining what part of that reserve would meet the criterion of Higher Grade Reserve.

Brief review of previous estimates

The original in-place reserve estimates for the WIPP site were done by the USGS (John et al., 1978). All subsequent economic analyses by Weisner et al. (1980) appear to have used the USGS-generated data. The method used was based on the time-honored triangular method for calculating in-place tonnages and grade. The method was briefly described by John et al. (1978, p. 29):

> ...The weighted-volume estimate method (Forrester, 1946, p. 560-562) was used for calculating ore reserves. Triangular networks among drill holes were constructed for each ore zone, and ore grade: types and thicknesses were posted at the apices of the triangles and(or) cutoff points. The weighted-average grade and average thickness were determined for each triangle and these and other data were entered into an electronic graphics calculator. Then, the perimeter of the triangle was scaled by the calculator cursor and the tons of potash ore electronically calculated.

The method produced reliable results. However, in recent years digitally based computer methods have been developed that make the task both easier and more accurate.

The USGS report did not present separate maps showing the in-place reserves for each ore zone. Instead, only tabular information was given for each ore zone, and the maps were a composite (stacking) of ore zones that presented only the outer bounds for three definitions of reserves: lower cutoff (>3% K_2O as langbeinite or >8% K_2O as sylvite), lease grade (>4% K_2O as langbeinite or 10% K_2O as sylvite), and higher grade (>8% K_2O as langbeinite or 14% K_2O as sylvite), all at a thickness of 4 ft or more.

An essential conclusion of the USGS study was given on p. 28:

> ...Although the potash ore is not as high a grade, nor are the thicknesses and continuity as great as some of the ore currently mined in the Carlsbad Mining District, at U.S. Geological Survey lease grade, an estimated 353.3 million tons of ore (315.7 million tons measured and 37.6 million tons of indicated ore) is present in the WIPP Area. ...

It will be shown below that evaluation presented here is in essential agreement with the USGS resource-reserve calculation made some 17 years ago.

The reserves were apparently recalculated by Seedorff (1978). They used a method of contouring between holes and then used a planimeter to determine areas. The areas were converted to volumes based on the average thicknesses reported in the drill-hole records. That method can produce reliable estimates except in one important step: Seedorff contoured "isopleths" of the product of grade and thickness *at each drill hole.* Grade and thickness are not correlative in the Carlsbad potash mining district, and thus that method will induce error. The Seedorff study did include maps of each ore bed that were useful in comparing this evaluation to theirs.

Computer programs to calculate in-place volumes and grades

There are a number of geology-oriented computer programs that could be used to determine ore resources in place based on drill-hole intercepts. One of the more widely used programs is MacGridzo marketed by RockWare Earth Science Software. This particular program was selected because of its ease of use, the ability to readily perform mathematical calculations on individual grids (cells), perform summations of selected areas, etc. In addition, experience existed in applying the MacGridzo program to determine ore reserves at a nearby potash mine. In that study computer-generated data based on simple drill-hole information was compared to actual results from mining that reserve. This provided confidence in the MacGridzo program as a useful tool in estimating potash reserves.

A separate spreadsheet program was used for inputting the drill-hole information, and another program was used to compile histograms and charts of output data generated within the MacGridzo program. Fig. 5.2 diagrams the method used to input, calculate, and output data using the MacGridzo program.

Brief description of the MacGridzo program

MacGridzo places a rectangular grid over a set of randomly spaced information data points (in our case the selected ore intercept information: depth, thickness, and grade). This increment of the hole data can be considered the "Z" component, while the hole location provides the "X" and "Y" of a three-dimensional array.

The program then calculates a unique value for the Z-component at the center of each grid based on interpolation of the Z-component values of nearby holes. To accomplish these calculations, the program can be set on either a "radial search" or simply a method based on the nearest set of drill-hole information. The radial search mode was used to avoid emphasis on a cluster of holes.

Once the grid values are determined for any parameter such as grade or thickness, they can be recalculated using simple algorithms. For example, the grade can be adjusted for thickness to obtain the adjusted grade based on an increase in mining height. Similarly, the tons in that grid can be determined for the new thickness using a "tonnage factor". In the case of langbeinite ores, the tonnage factor was also adjusted per grid based on the percent langbeinite in the ore. An important capability is that the thickness values can be assigned independent of the grade values. This is a distinct advantage over the method used by Seedorff (1978). Another advantage of the MacGridzo program is contour plots, whether it be grade, ratio of sylvite to langbeinite, thickness, products of thickness and grade, or structure of the top or bottoms of an ore zone, that can be readily produced to assist in visualization of the data files.

The size of the cells selected was 571.90 ft in the east–west (X) direction and 510.28 ft in the north–south (Y) direction. This particular grid size was selected to coincide with the exact position of the north and east sidelines of the WIPP site. This assisted in partitioning the reserve summations to determine tonnages inside and outside the WIPP boundaries. The cell size selected resulted in the assignment of 60 cells in the east–west direction and 63 in the north–south direction, for a total of 3,780 cells. The dimensions of an individual cell results in the ability to assign individual thickness and grade to 58,000-ton blocks of in-place ore 3 ft thick (a typical thickness).

Gridded (study) area and WIPP area

A feature of the MacGridzo program is the placement of a rectangular boundary based on the extremity coordinates of the data set. Hole U-134 determined the north, Hole P-20 the east, Hole P-16 the south, and Hole D-48 the west boundaries of the gridded area. Resource tonnages and grades could be estimated within that rectangle. Therefore, on labels for maps and tables the term "Entire Gridded Area" was used to define calculations within that boundary. In the text, this is referred to as the "Study Area."

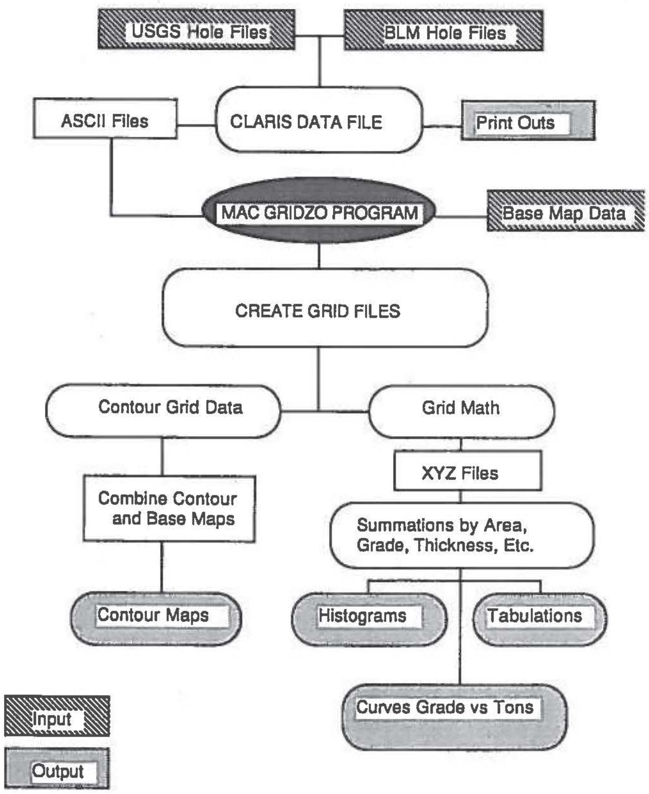

FIGURE 5.2—Method of potash reserve calculation.

It was then a simple procedure to clip the gridded cell information along the WIPP boundaries. This allowed the calculation of resources for the entire study area and the WIPP boundary area. The simple difference in the two resulted in defining resources outside of WIPP.

Initial calculation of in-place resources

The resources were calculated from the actual in-place tonnages in grade ranges using only the actual thicknesses and assays for each ore intercept reported in the drill-hole records. First, determine the thicknesses for each cell using the radial search method. Second, in a similar manner, assign assay results for percentage of K_2O as langbeinite or sylvite (or equivalent mixture using the 2.5:1 ratio) to each cell. Third, determine the thickness × grade product. Once these three steps are completed, a contour map can be produced for: thickness, grade, and product of thickness × grade. These maps give a visual presentation of the actual ore resources in place without consideration for the need to correct for mining height—a step that would be needed to determine the viability of mining.

The product maps (thickness × grade) provided an essential element for determining what part of the resources would become reserves. To illustrate, BLM uses the criterion of 4 ft of 10% K_2O as sylvite to determine Lease Grade Reserves. Therefore, the product of thickness × grade is 40. This criterion is not dependent on thickness or grade but the product of the two. Of course one always has to consider the criterion that the grade will be at least 10% K_2O for sylvite (or 4% for langbeinite) if the thickness is less than 4 ft. This latter criterion was readily determined by examination of the contour map of grade. The advantage of the product contour maps is that one can readily determine the outer boundaries for any specific definition of reserves, e.g., the 40 contour is the boundary for Lease Grade Sylvite Reserve.

The resource tonnages could then be determined by calculating the volume of each cell multiplied by the tonnage factor. For sylvite ores we used a constant tonnage factor equal to 14.8 ft^3/ton. For langbeinite ores we used:

$$\text{Tonnage factor} = 14.8 - (0.152 \times \%\ K_2O \text{ as langbeinite}).$$

This correction was rather small, but it was easily accomplished by the computer.

The last step in resource calculation was to perform summations of all the cell data. For ease in presentation of the results, the in-place tonnages were calculated in step ranges of 0.5% K_2O of the ore mineral (sylvite, langbeinite, or equivalent grade mixture), which were then compiled into histograms. Finally, tables and graphs were made from the histogram data to determine in-place resource tonnages versus grade using weighted averages.

Adjustment of in-place resources to mining height

Most of the in-place resources are in beds thinner than can be currently mined. For example, seam mining of sylvite is done by drum-type machines that can mine at no less than 4 ft. In the case of langbeinite ores, the current method is to undercut the mine face, drill, blast, and load using mechanical-arm machines. For that type of mining, headroom is normally no less than 5 ft.

Therefore, to determine what part of the in-place resources could be considered minable reserves we had to include a factor for diluting (lowering) the grade to allow for current mining technology. This was a simple task for the computer. The grade of each cell was reduced in linear proportion to the ratio of the in-place thickness to the desired mining height. This procedure reduced the grade but increased the tonnage.

The term "Adjusted Mining Height" was used when recomputing the in-place resources to determine what resources would meet the definition of reserves. The mining height was adjusted in 0.5-ft steps from the in-place thickness up to a mining height of 7 ft. Because the product contour maps indicated that only the 4th and 10th ore zones would meet Lease Grade Reserves, this exercise of thickness adjustment was done only for those two ore zones.

The results of the grade adjustment of the 4th and 10th ore zones for mining thickness formed the database for all subsequent economic evaluations.

RESULTS OF ORE RESOURCE AND RESERVE CALCULATIONS

4th ore zone

Economic analysis (*see* Chapter 6, this circular) has shown that much of this ore could be mined at a profit, which transforms much of the resource into reserve. It was concluded that economic mining could be conducted in the 4th langbeinite ore zone even using the Higher Grade Reserve criterion where the cutoff grade was set at 6.25% K_2O equivalent langbeinite and the minimum mining height increased to 6 ft.

Figs. 5.3, 5.4, and 5.5 are contour maps of the in-place thickness, grade, and grade × thickness product. This ore zone is mostly langbeinite, but it does contain recoverable amounts of sylvite. Therefore, Figs. 5.4 and 5.5 are for equivalent langbeinite, i.e. the percentage K_2O grade of langbeinite is adjusted upward by adding 0.4 × % K_2O as sylvite where present. Please note the position of the "16" contour in Fig. 5.5. The material inside that contour meets the BLM Lease Grade reserve criterion of 4% K_2O (or equivalent) langbeinite at a 4-ft mining height. Also note the approximate position of the "37.5" contour that represents the criterion for economic mining.

(Text continues on p. 43.)

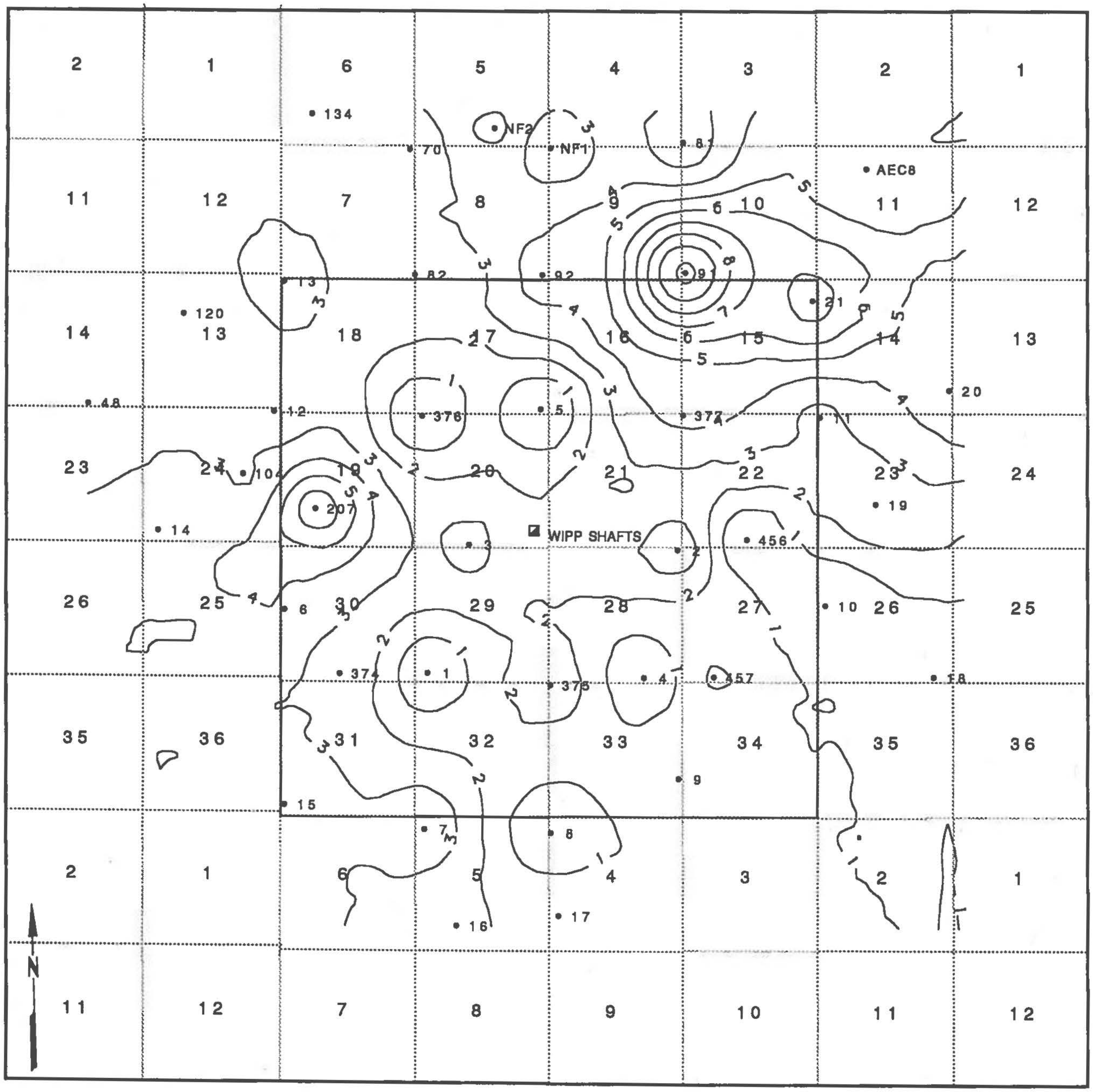

FIGURE 5.3—Thickness of the 4th ore zone. Contour interval 1.0 ft.

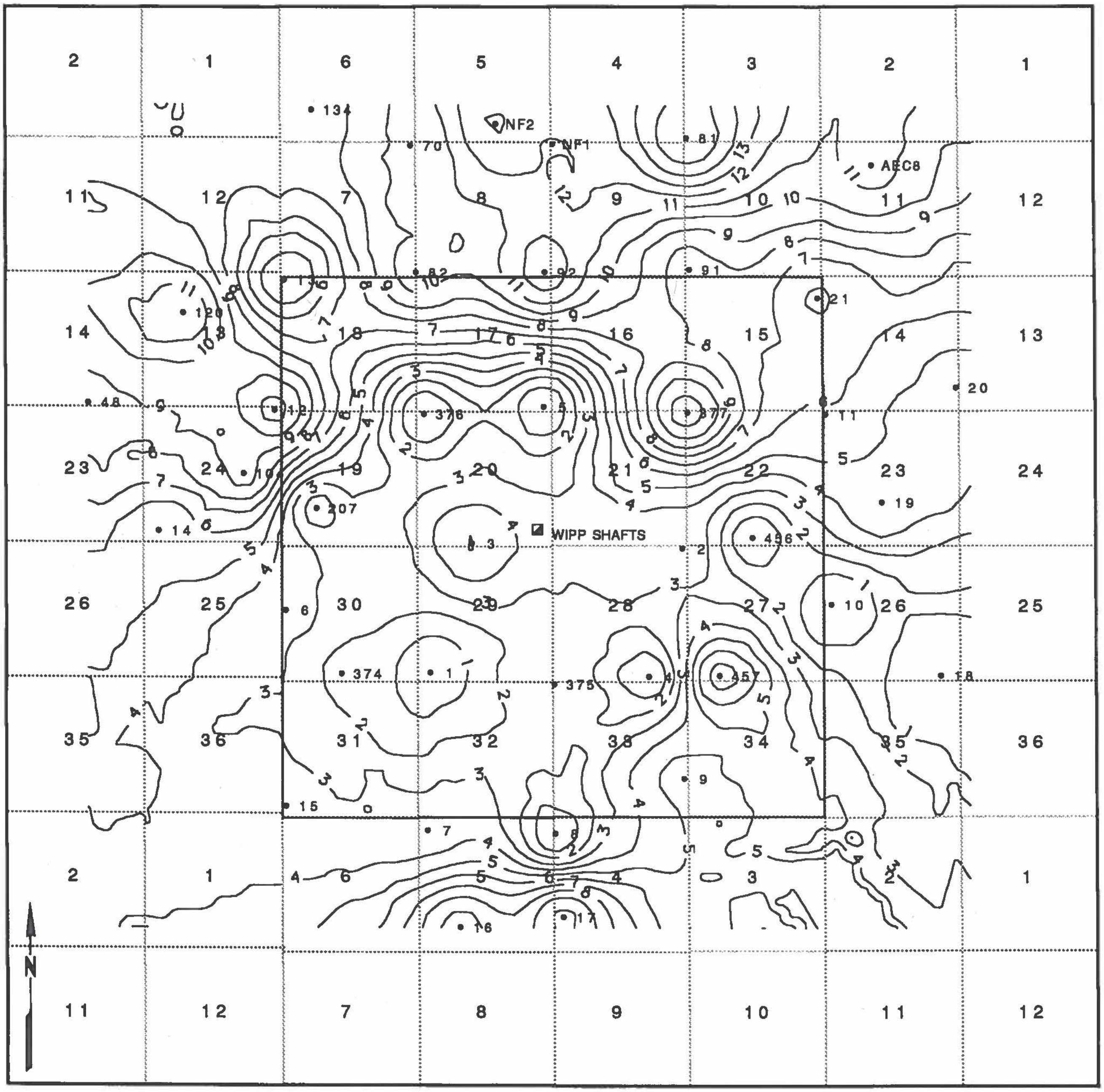

FIGURE 5.4—4th ore zone—% K_2O as equivalent langbeinite. Contour interval 1.0% K_2O.

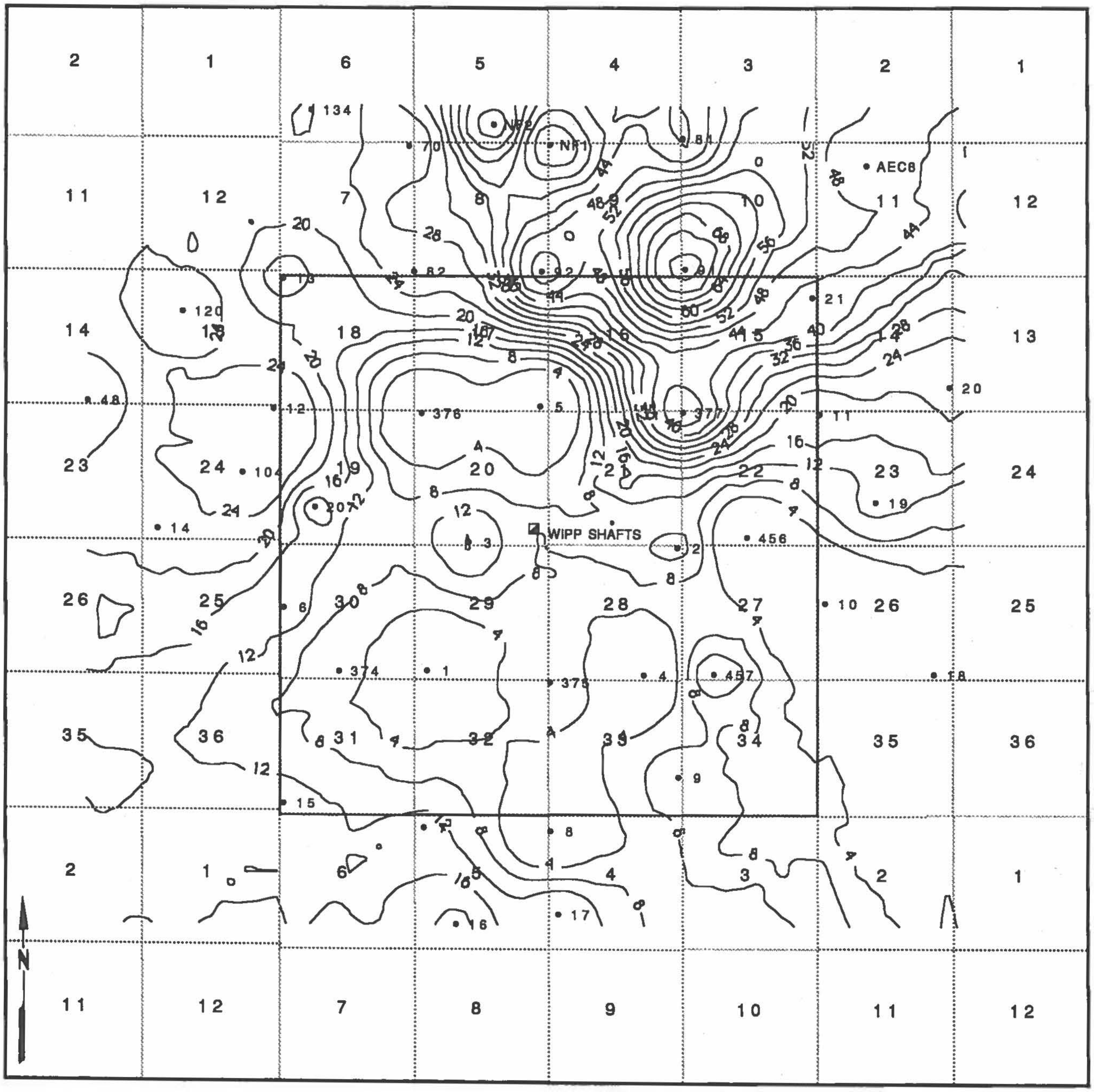

FIGURE 5.5—4th ore zone—% K_2O equivalent langbeinite × thickness. Contour interval 4.0% K_2O × feet.

TABLE 5.2—Resources and reserves of the 4th langbeinite ore zone.

Area	Tonnage (millions)	Avg. % K_2O (equiv. lang.)
Entire study area		
In-place resource (>4% K_2O and actual thickness)	168.7	8.02
BLM Lease Grade reserve (>4% K_2O at 4 ft mining height)	166.5	7.22
Higher grade reserve (>6.25% K_2O and 6 ft mining height)	72.4	7.95
(>6.25% K_2O and 4.5 ft mining height)	75.4	9.07
Inside WIPP boundary		
In-place resource (>4% K_2O and actual thickness)	47.0	7.21
BLM Lease Grade reserve (>4% K_2O at 4 ft mining height)	40.5	6.99
Higher grade reserve (>6.25% K_2O and 6 ft mining height)	18.0	7.59
(>6.24% K_2O and 4.5 ft mining height)	20.9	8.24
Outside of the WIPP boundary (about one mile)		
In-place resource (>4% K_2O and actual thickness)	121.7	8.33
BLM Lease Grade reserve (>4% K_2O at 4 ft mining height)	126.0	7.30
Higher grade reserve (>6.25% K_2O and 6 ft mining height)	54.4	8.07
(>6.25% K_2O and 4.5 ft mining height)	54.5	9.40

Fig. 5.6 is a histogram of the resources that are in place for the entire study (gridded) area, and Fig. 5.7 is the histogram for the same data within the WIPP boundary. Figs. 5.8–5.11 illustrate data in tonnage-summation-curve formats to determine reserves as a function of cutoff grade or as a function of the average grade for varying mining heights, again for the entire study area and also within the WIPP boundary. Calculation of the reserves outside the WIPP boundary is a simple matter of subtraction.

A summation of the cell data for the 4th ore zone was made of the three significant criteria and partitioned by areas. The results are in Table 5.2.

The resource and reserve estimates are valid within the WIPP boundary because all drill-hole information within that boundary was available and the spacing of the holes was approximately one mile on center.

The tonnages and grade outside of the WIPP boundary were estimated in accordance with the grid generated by the MacGridzo computer program that extended out to the farthest drill holes in all cardinal directions. Referring to Fig. 5.5, note that the "16" contour, which determined the BLM Lease Grade reserve, defines a large reserve that extends north and east of the WIPP site. Also note there was a sufficient number of holes in that area to justify classification as drill-defined reserves. The same held true for our estimate of Higher Grade Reserves (defined by the "37.5" contour) for that area.

BLM Lease Grade reserve in a separate location was evident on the west, defined by holes 12, 14, 48, 104, and 120. However, the information base did not include several industry-drilled holes along the west flank of the WIPP site (see Fig. 5.1 for the locations of these holes because they are not shown elsewhere), which would have improved the estimate of reserve in that area. Nonetheless, the estimate of BLM Lease Grade reserve appears to be reasonable within one mile west of the WIPP boundary. It is important to note that Higher Grade Reserve (defined by the "42" contour in Fig. 5.5) does not exist within one mile of the WIPP boundary on the west. Similarly, the 4th ore zone boundaries are well defined, but potential for additional discoveries exists in the southwest part of the study area where few exploratory holes exist.

Figs. 5.12 and 5.13 were used to measure the degree to which the 4th ore zone contained mixed ore. It was apparent that the northeast part of the mineralized area was simply langbeinite and contained most of the resources and reserves for that ore bed. Therefore, exclusion of the sylvite part for determination of equivalent percentage of K_2O had little effect on the determination of reserves in the northeast. However, the presence of sylvite was important in defining BLM Lease Grade reserves in the northwest. Fig. 5.14 is a structure contour map of the top of the 4th ore zone. The map is consistent with the known structure of the Salado Formation in the WIPP site area.

(Text continues on p. 50.)

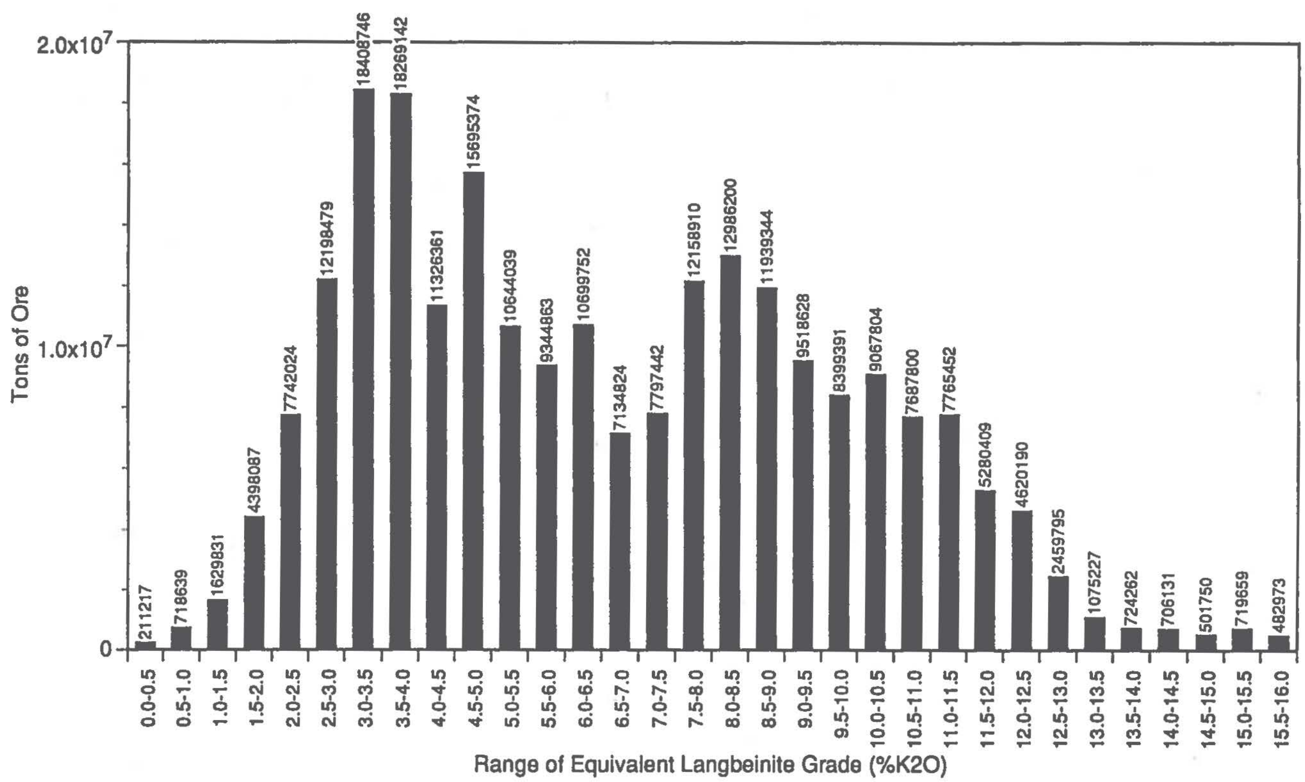

FIGURE 5.6—4th ore zone equivalent langbeinite reserves (in place) for entire gridded area.

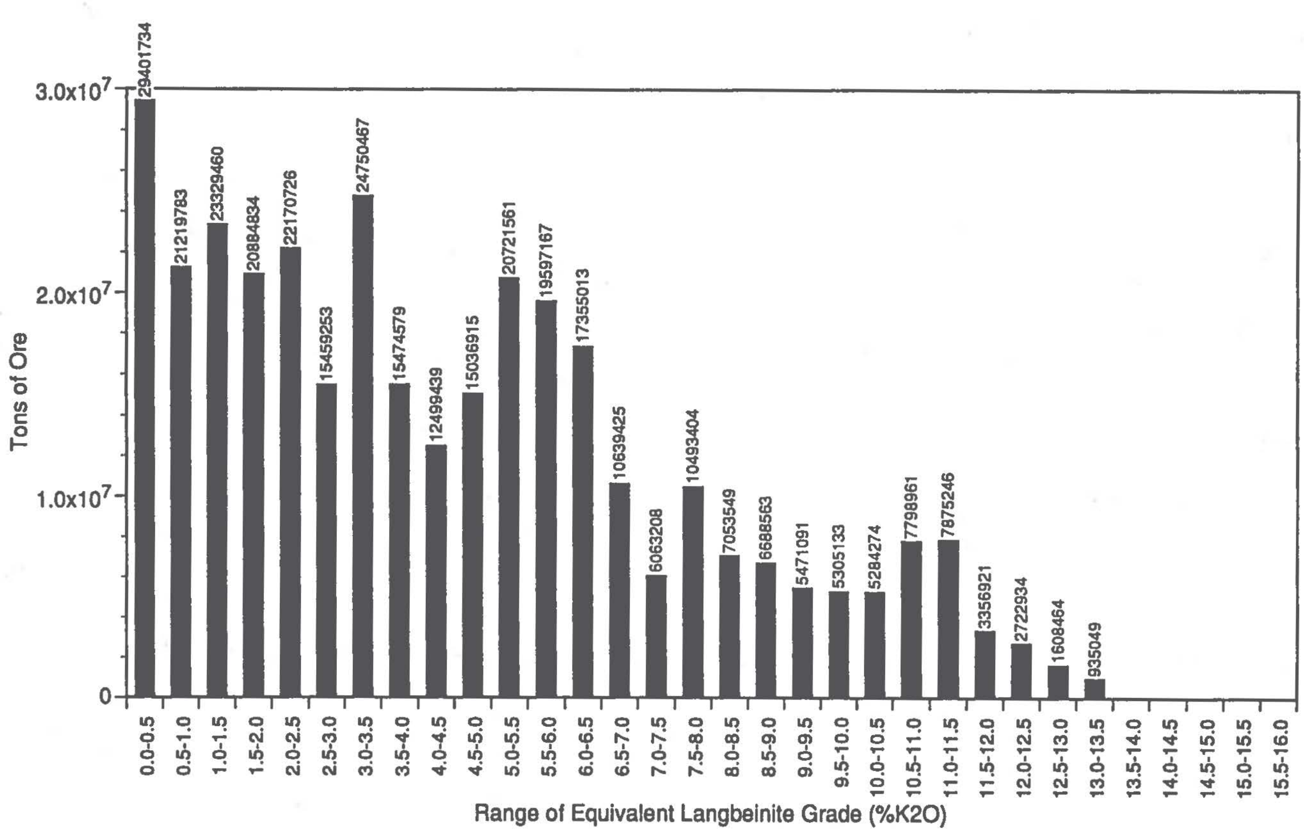

FIGURE 5.7—4th ore zone equivalent langbeinite reserves (in place) within WIPP boundary.

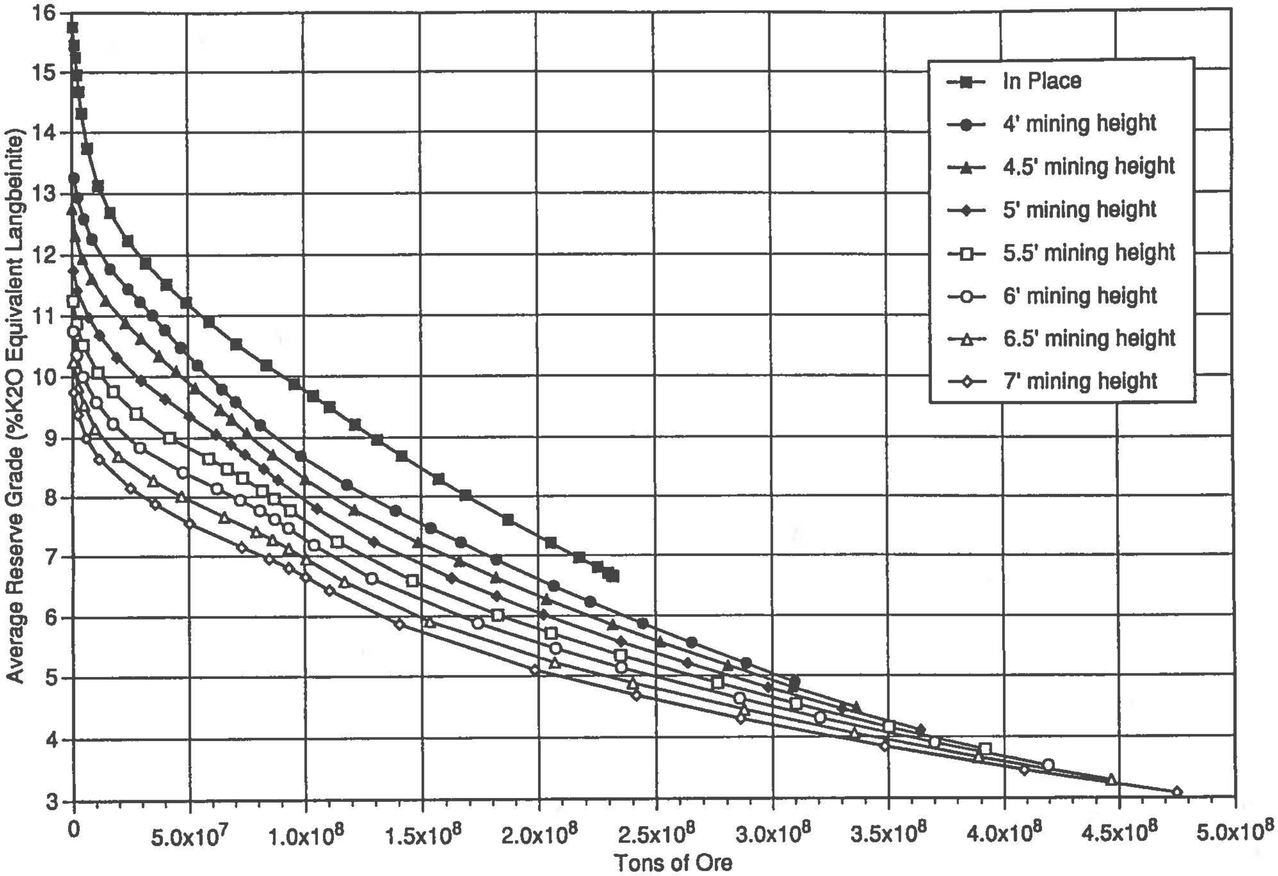

FIGURE 5.8—4th ore zone langbeinite reserves (reserve grade) for entire gridded area.

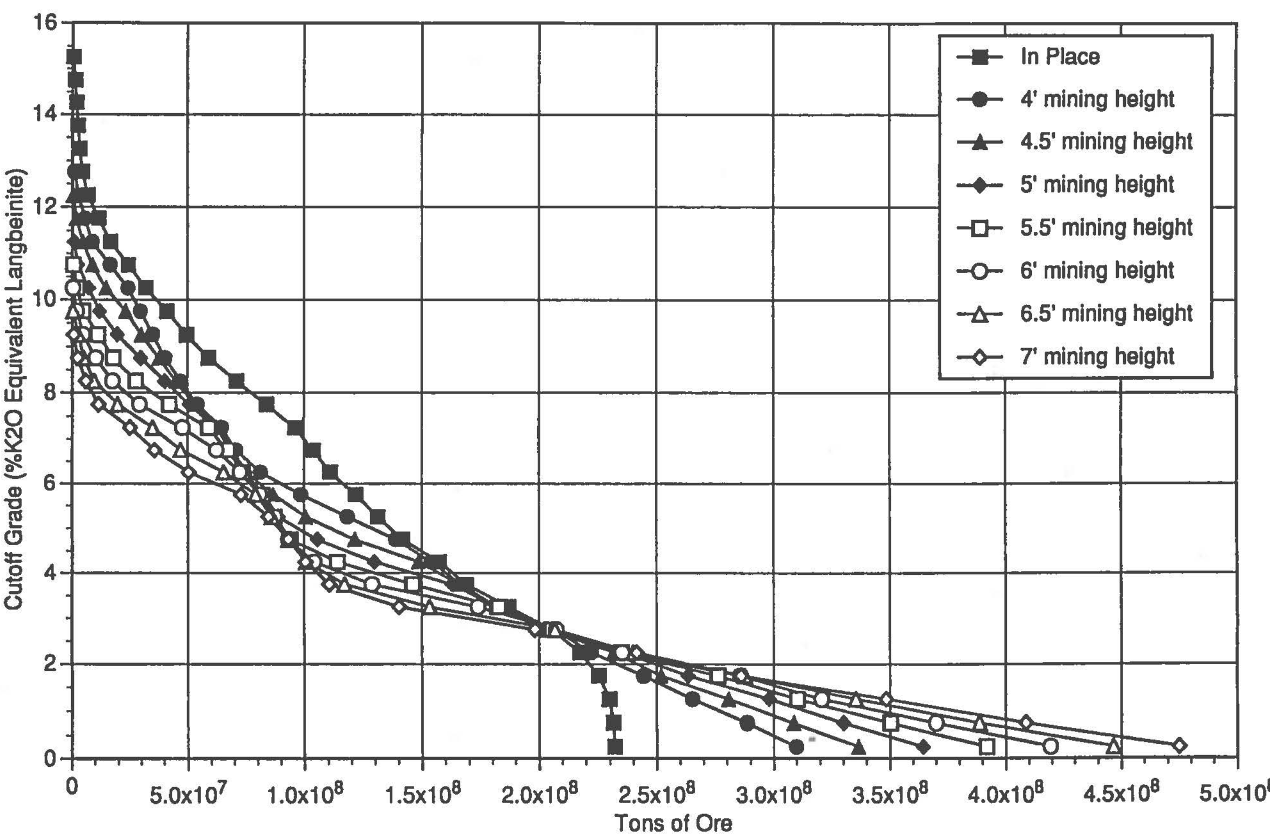

FIGURE 5.9—4th ore zone langbeinite reserves (cutoff grade) for entire gridded area.

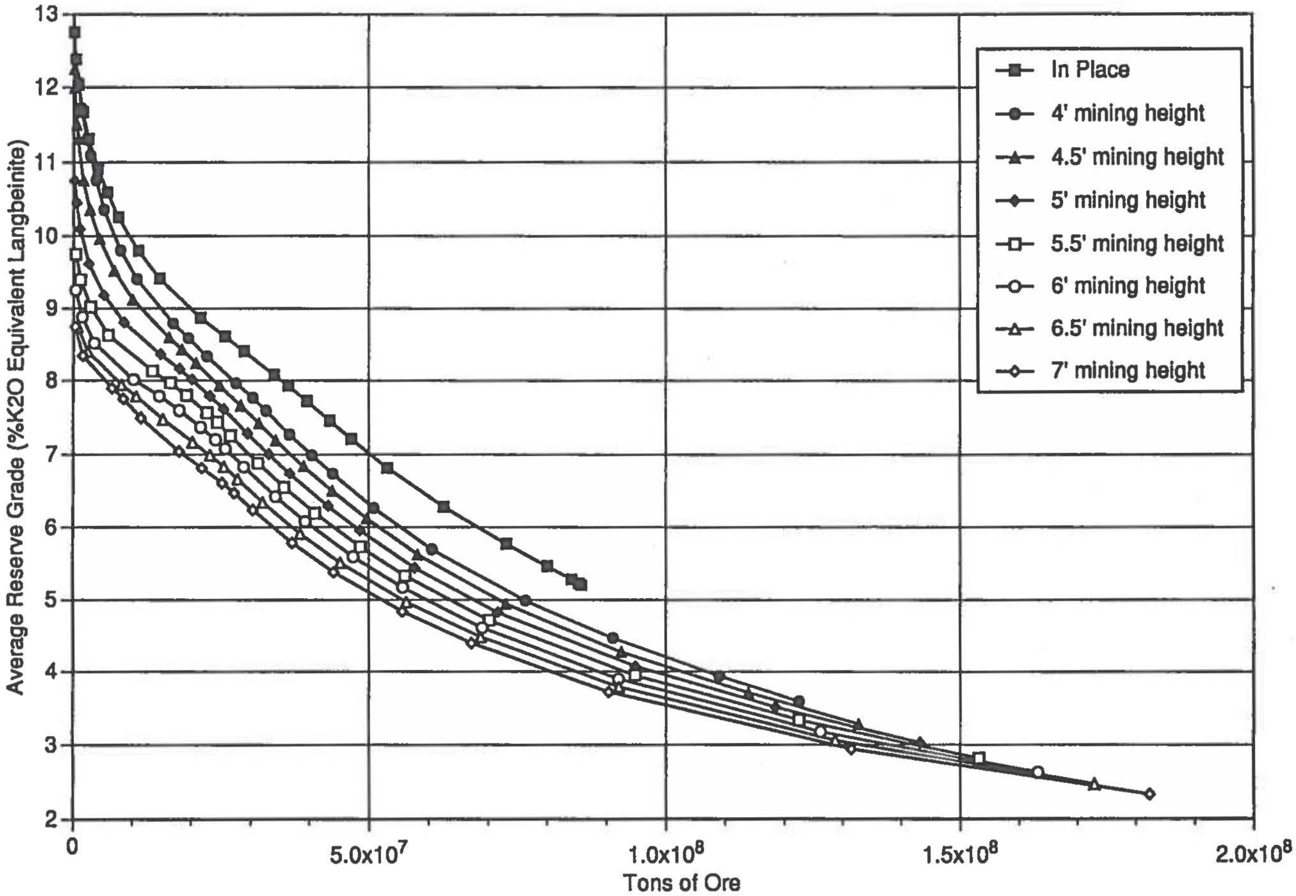

FIGURE 5.10—4th ore zone langbeinite reserves (reserve grade) within WIPP boundary.

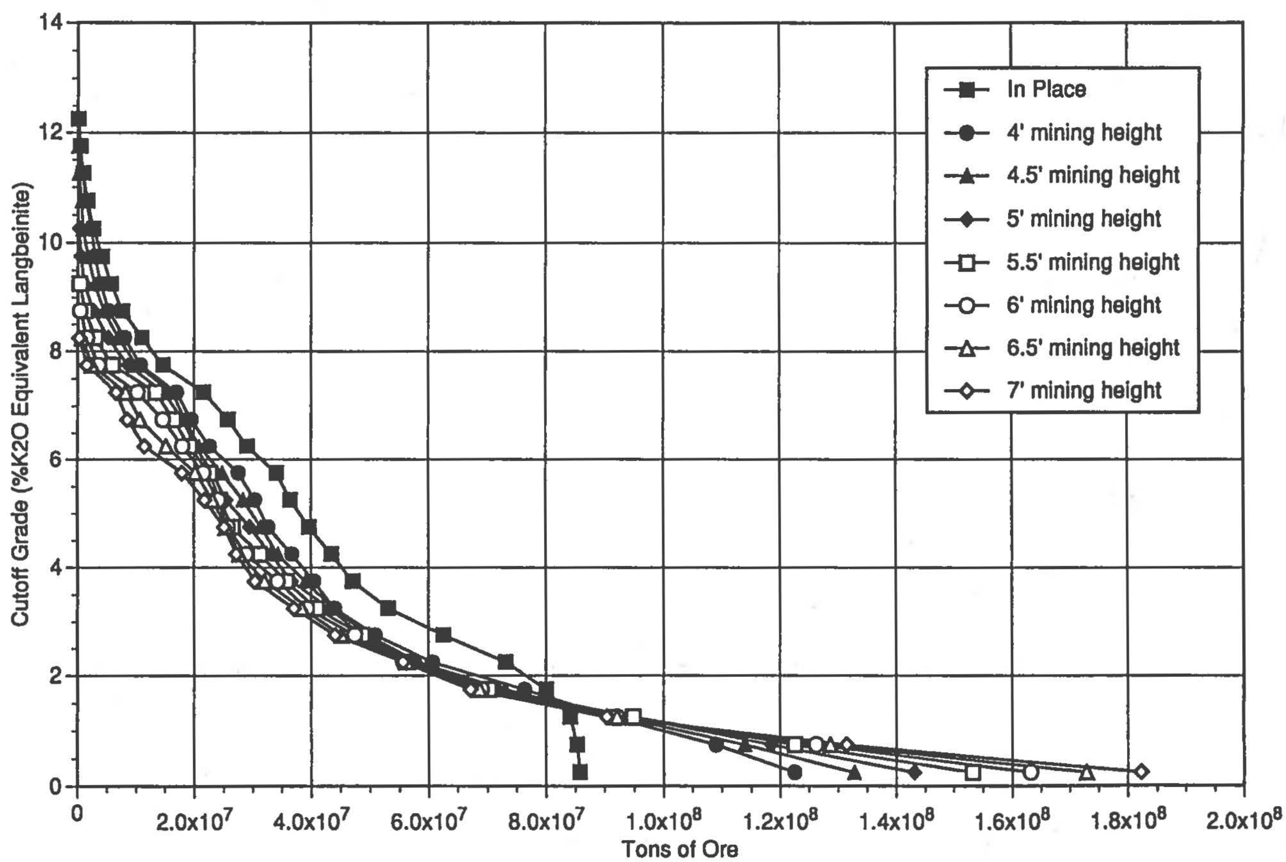

FIGURE 5.11—4th ore zone langbeinite reserves (cutoff grade) within WIPP boundary.

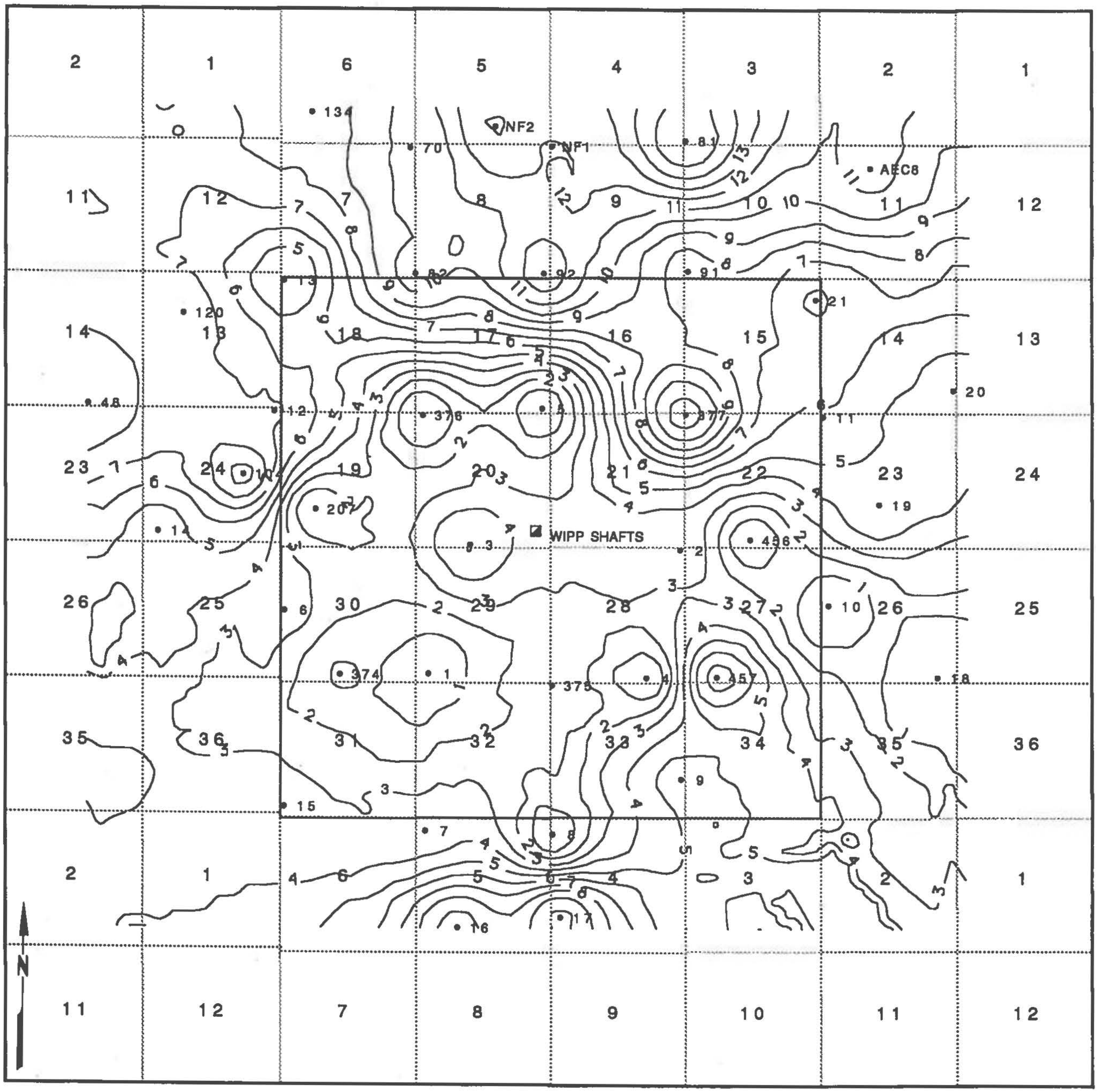

FIGURE 5.12—4th ore zone % K_2O langbeinite only. Contour interval 1.0% K_2O.

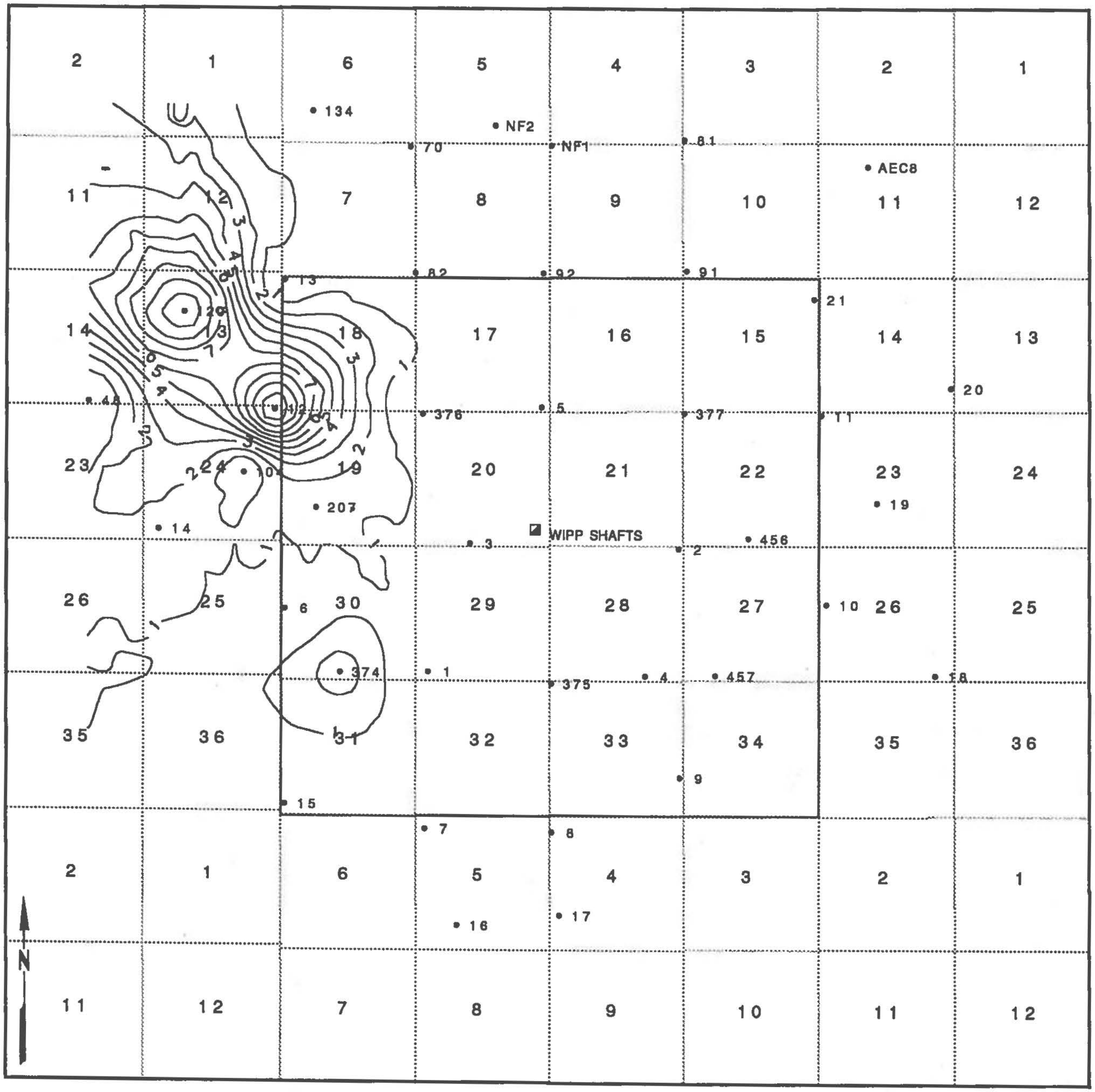

FIGURE 5.13—4th ore zone % K_2O sylvite only. Contour interval 1.0% K_2O.

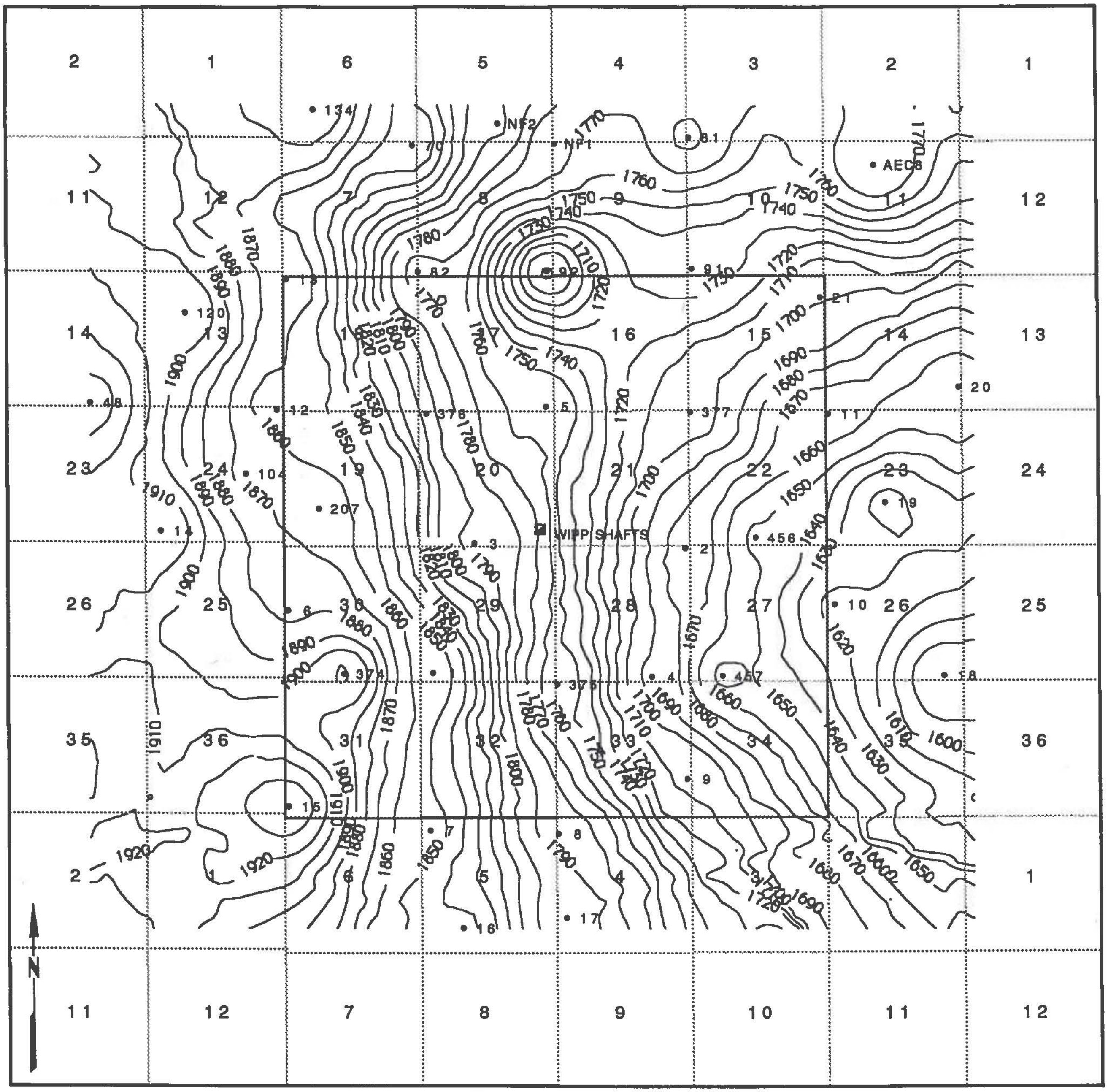

FIGURE 5.14—Structure of the top of the 4th ore zone. Contour interval 10 ft.

10th ore zone

As with the 4th ore zone, economic analysis has shown that much of this resource could be mined at a profit, which transforms much of the resource into reserve. The 10th ore zone is dominantly sylvite, in contrast with the dominantly langbeinite ores of the 4th ore zone. The Higher Grade Reserve of the 10th langbeinite ore zone are those resources that meet a cutoff grade of 12.25% K_2O equivalent sylvite using a minimum mining height of 4.5 ft.

Figs. 5.15, 5.16, and 5.17 are contour maps of the in-place thickness, grade, and grade × thickness product. Although this ore zone is mostly sylvite, it does contain recoverable amounts of langbeinite. Therefore, Figs. 5.16 and 5.17 are for equivalent sylvite, i.e. the percentage K_2O grade of sylvite is adjusted upward by adding 2.5 × % K_2O as langbeinite where present. Please note the position of the "40" contour in Fig. 5.17. The material inside that contour meets the BLM Lease Grade reserve criterion of 10% K_2O (or equivalent) sylvite at a 4-ft mining height. Also note that the approximate position of the "55" contour that represents the criterion for Higher Grade economic mining. The "55" contour lies between the 50 and 60, but the scale of the map is too small to show its exact position. However, when summations of cell values were done by computer, the tonnages were quite precise.

A summation of the cell data for the 10th ore zone was made of the three significant criteria and partitioned by areas. The results are in Table 5.3.

Fig. 5.18 is a histogram of the resources for a range of mining thicknesses for the entire study (gridded) area, and Fig. 5.19 is a histogram for the same data within the WIPP boundary. Figs. 5.20–5.23 present the histogram data in tonnage-summation-curve-formats to determine reserves as a function of cutoff grade and as a function of the average grade, again for the entire study area and for within the WIPP boundary. To calculate the reserves outside of the WIPP boundary was a simple matter of subtraction.

As with the 4th ore zone, the 10th ore zone resource and reserve estimates are valid within the WIPP boundary because all drill-hole information within that boundary was available to us and the spacing of the holes was approximately one mile on center.

The tonnages and grade outside of the WIPP boundary were estimated in accordance with the grid generated by the MacGridzo computer program that extended out to the farthest drill holes in all cardinal directions. Referring to Fig. 5.17, note that the "40" contour, which determines the BLM Lease Grade reserve, defines a reserve that extends over much of the east half of the WIPP site and continues to the northeast. The BLM Lease Grade boundary also extends southward from the WIPP site. On the west, leasable reserves enter into the northwestern edges of the WIPP site.

A sufficient number of holes are in secs. 10, 11, 14, 23, and 26 to adequately define reserves, both at the BLM and Higher Grade Reserve definitions, and to justify classification as defined reserves for about one mile outward from the WIPP boundary to the northeast.

The estimate of reserves on the south is hampered by a lack of drill-hole information. It is worthy of note that the computer-generated "40" contour passes in the vicinity of hole D-123 (shown only in Fig. 5.1), the core of which was not assayed by the Duval Sulphur and Potash Company because it appeared to be subeconomic. The reserves in the E½ sec. 34 may be overestimated within the WIPP boundary and in a small part of sec. 35 outside of the WIPP site. However, the estimates are reasonable for a mile-long extension southward from the WIPP boundary into secs. 3, 4, and 5 because the outline of the boundary for defined reserves closely matches that of the outline for reserves shown on the current BLM map.

BLM Lease Grade reserves are present in the west part of the study area on the basis of both the spacing of holes with assayed ore intercepts and agreement with the current BLM map. The BLM Lease Grade reserve would meet the conditions of proven reserve. Note that the leasehold in that area (Western Ag-Minerals Company) has done relatively close-spaced drilling in secs. 23 and 26 and less in secs. 24 and 25. The drilling implied that the 10th ore zone becomes lower in quality as it approaches the WIPP boundary from the west, which is in agreement with our computer-generated contours.

The potash deposits of the 10th ore zone are mixes of sylvite and langbeinite, more so than in the 4th ore zone, with the sylvite being dominant. Figs. 5.24 and 5.25 present contours of the percentage of K_2O content as separate minerals. The 10th ore zone is mixed ore over much of its central and southeast mass within the WIPP boundary. On the west it is sylvite only. Mixed ore continues northeastward from within the WIPP site into the one-mile zone outside it, and commercial ore extends perhaps an additional half mile to the north on the basis of current BLM maps. Fig. 5.26 is a structure map contoured at the top of the 10th ore zone. It reflects the same structure as the underlying 4th ore zone.

(Text continues on p. 60.)

TABLE 5.3—Resources and reserves of the 10th sylvite ore zone.

Area	Tonnage (millions)	Avg. % K_2O (equiv. sylvite)
Entire study area		
In-place resource (>10% K_2O and actual thickness)	168.2	14.61
BLM Lease Grade reserve (>10% K_2O at 4 ft mining)	157.3	14.64
Higher grade reserve (>12.25% K_2O and 4.5 ft mining)	107.8	15.33
Inside WIPP boundary		
In-place resource (>10% K_2O and actual thickness)	53.7	14.26
BLM Lease Grade reserve (>10% K_2O at 4 ft mining)	52.3	13.99
Higher grade reserve (>12.25% K_2O and 4.5 ft mining)	30.6	15.00
Outside of the WIPP boundary (about one mile)		
In-place resource (>10% K_2O and actual thickness)	114.5	14.77
BLM Lease Grade reserve (>10% K_2O at 4 ft mining)	105.0	14.96
Higher grade reserve (>12.25% K_2O and 4.5 ft mining)	77.2	15.46

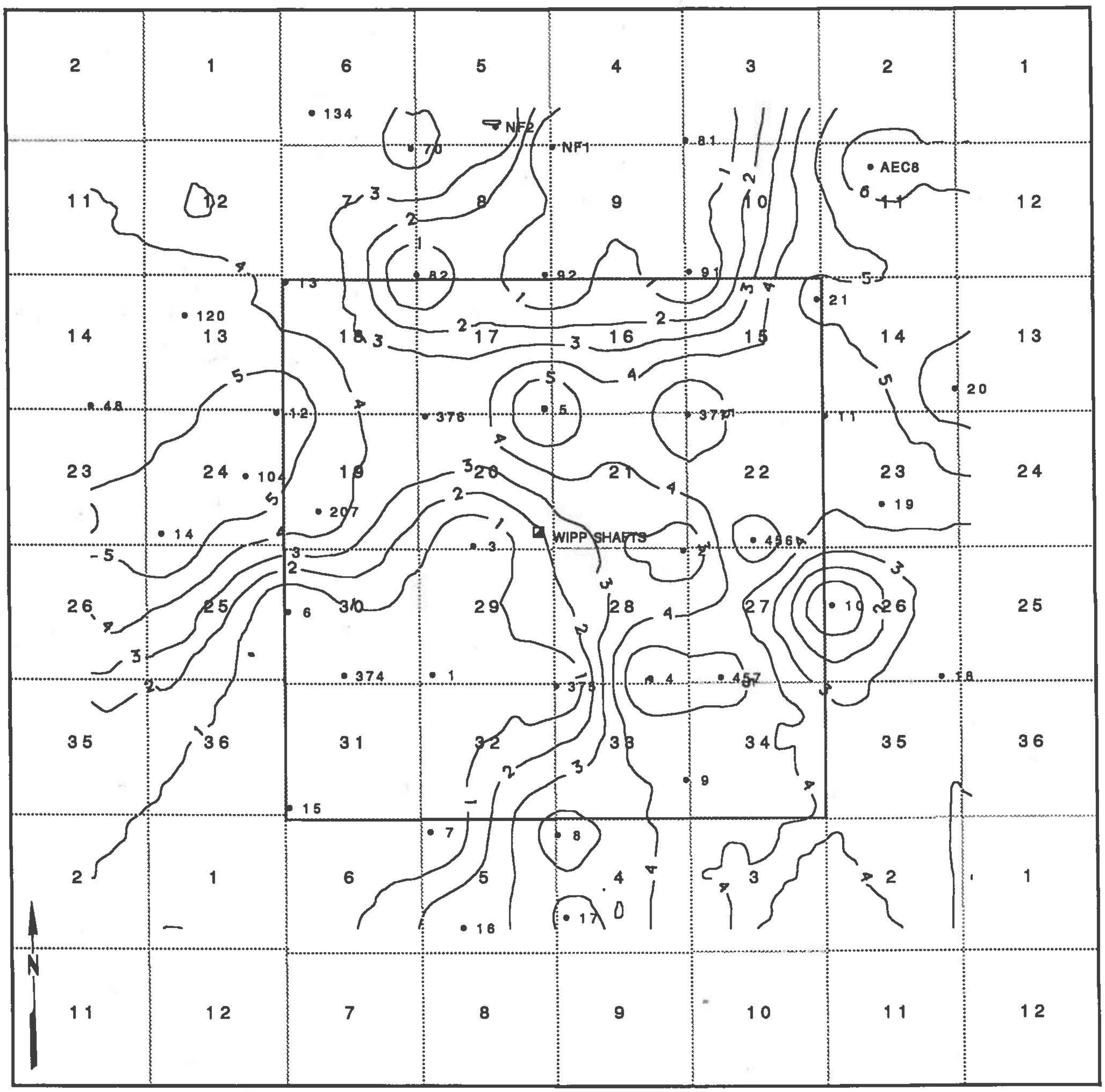

FIGURE 5.15—Thickness of the 10th ore zone. Contour interval 1.0 ft.

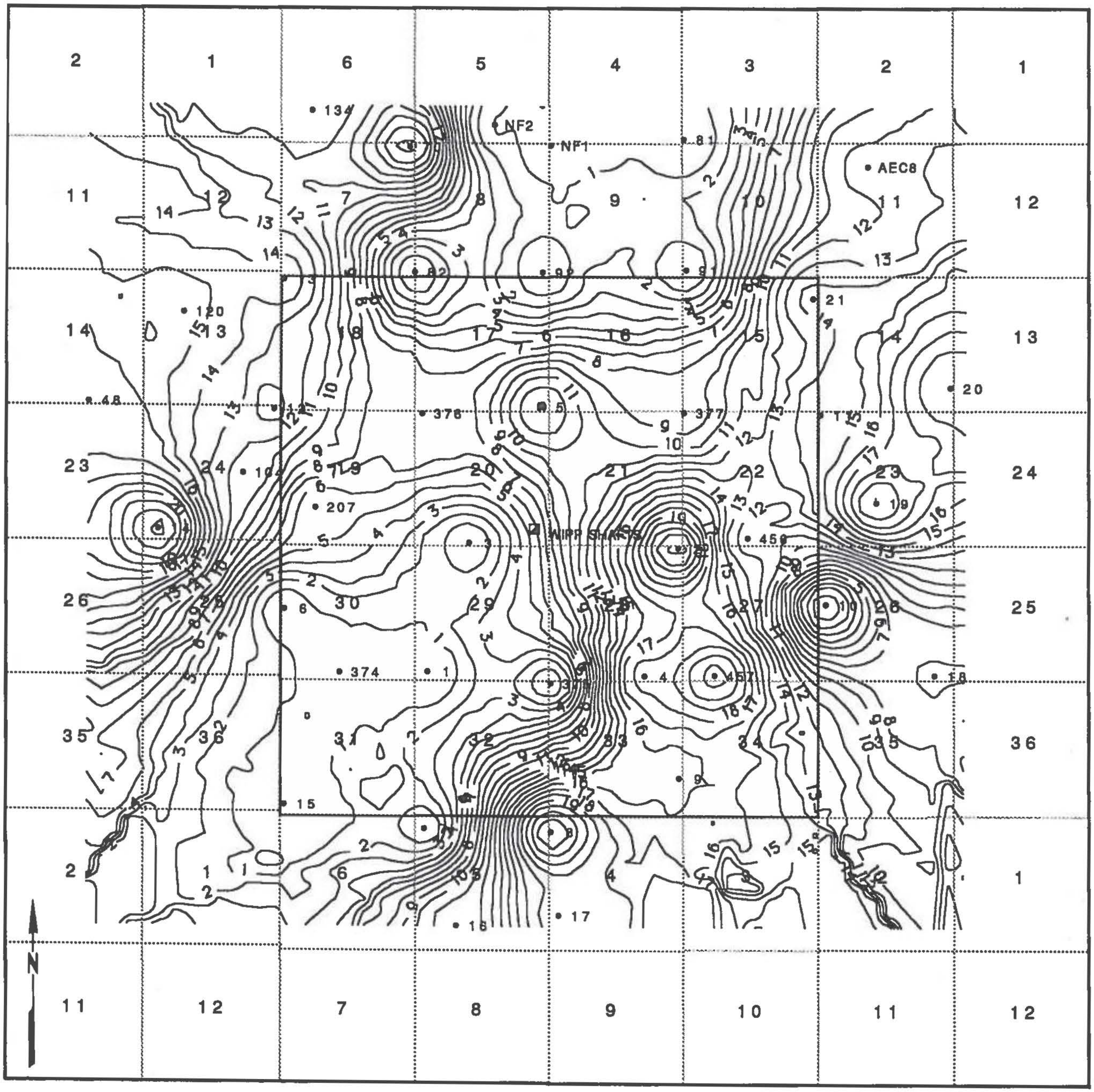

FIGURE 5.16—10th ore zone % K_2O as equivalent sylvite. Contour interval 1.0% K_2O.

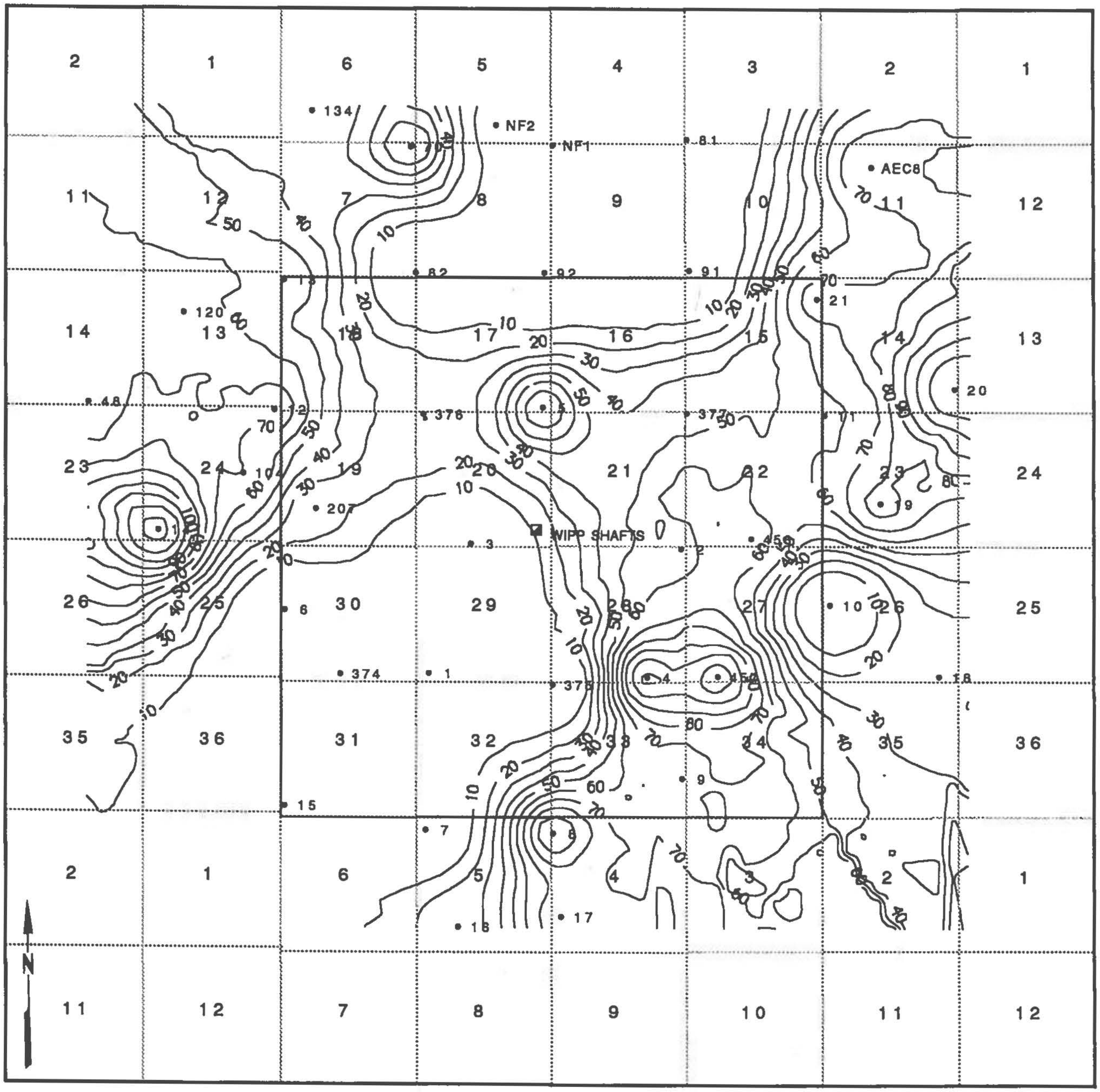

FIGURE 5.17—10th ore zone % K_2O equivalent sylvite × thickness. Contour interval 10% K_2O × feet.

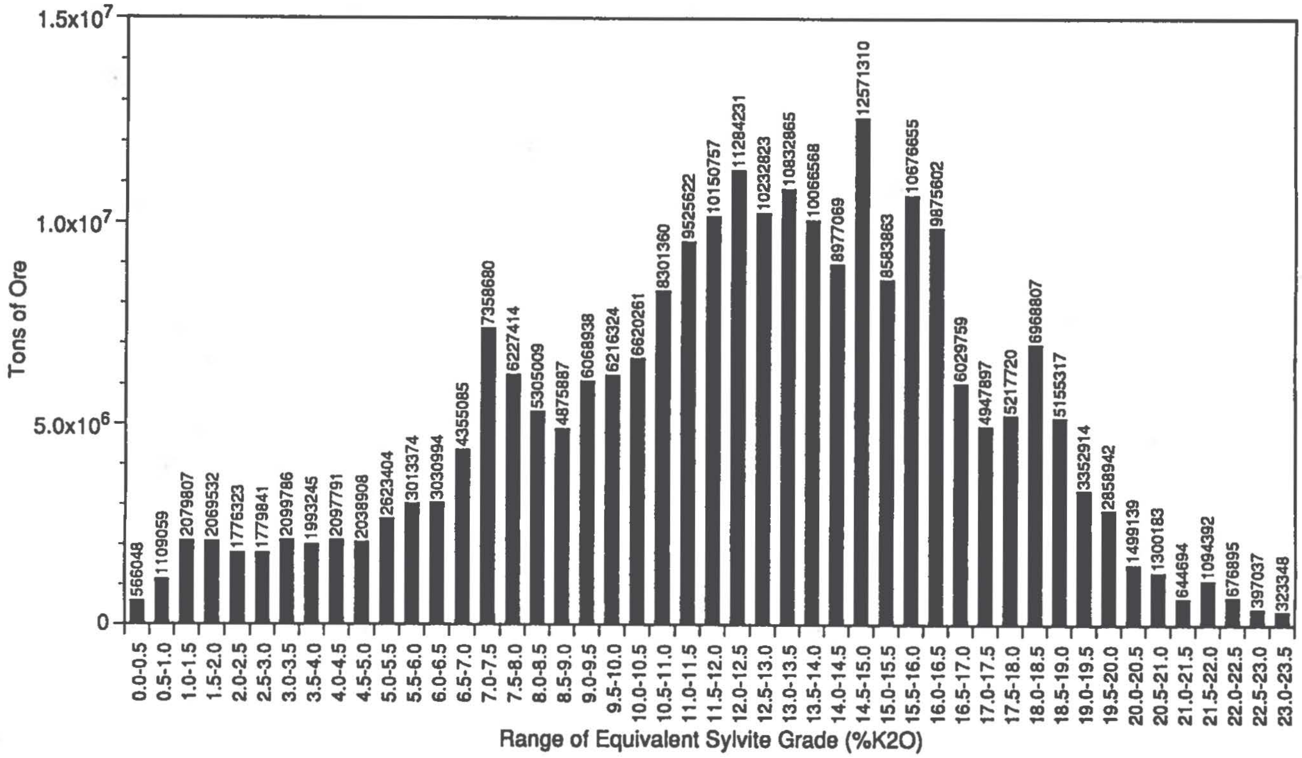

FIGURE 5.18—10th ore zone equivalent sylvite reserves (in place) for entire gridded area

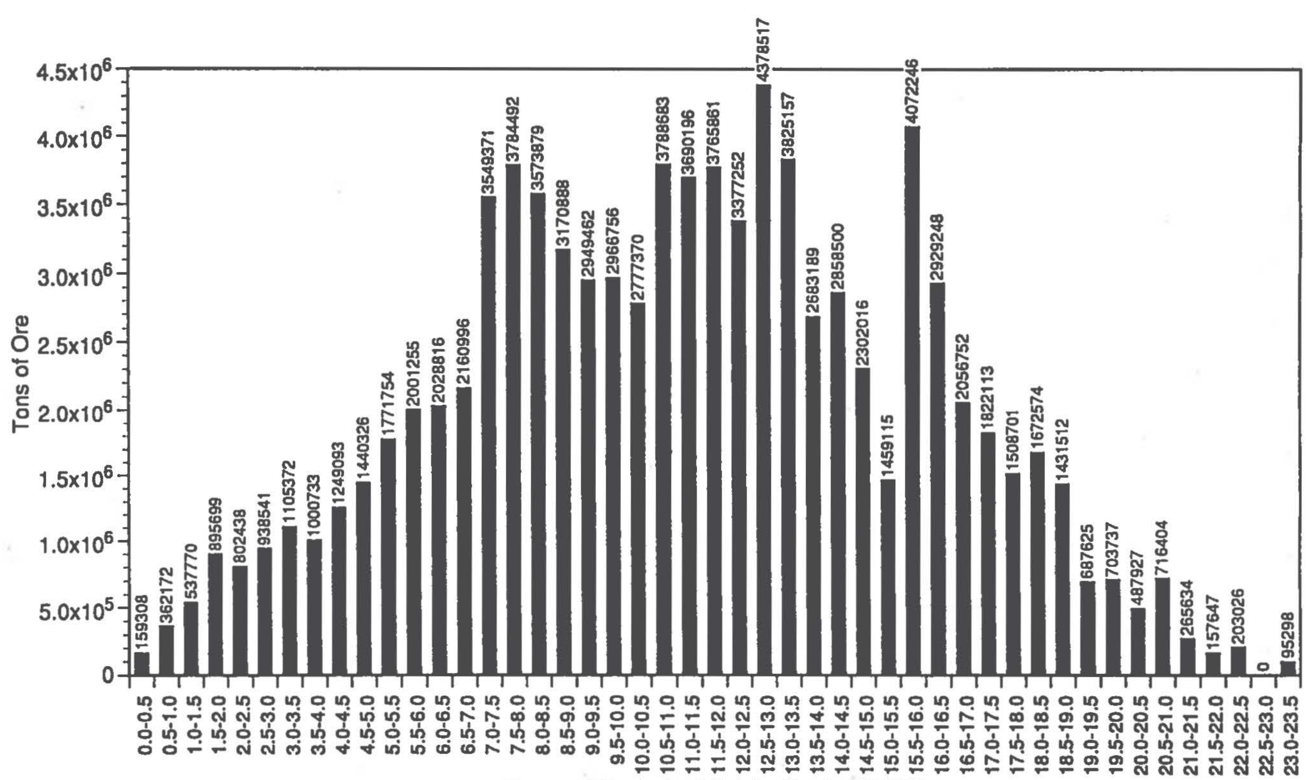

FIGURE 5.19—10th ore zone equivalent sylvite reserves (in place) within WIPP boundary.

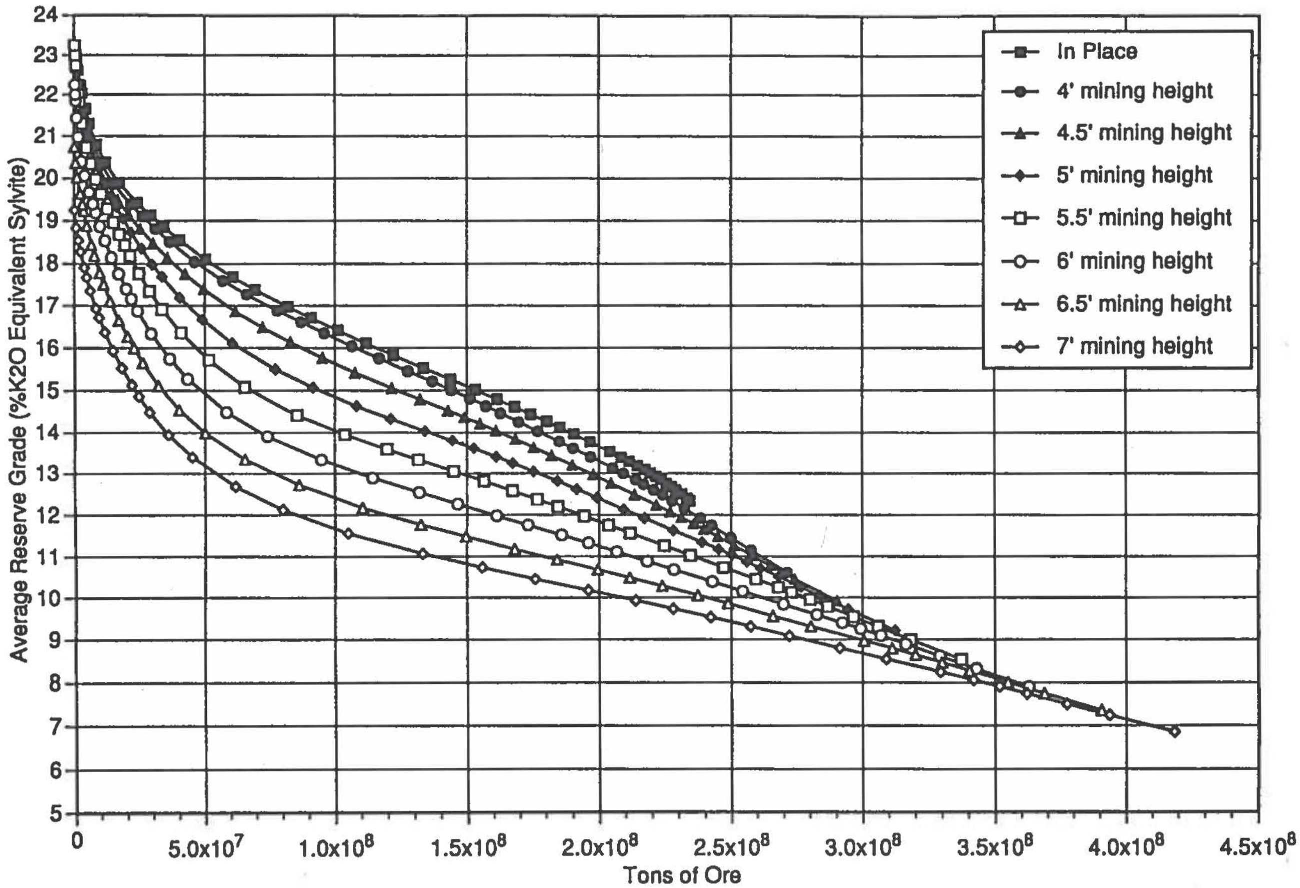

FIGURE 5.20—10th ore zone sylvite reserves (reserve grade) for entire gridded area.

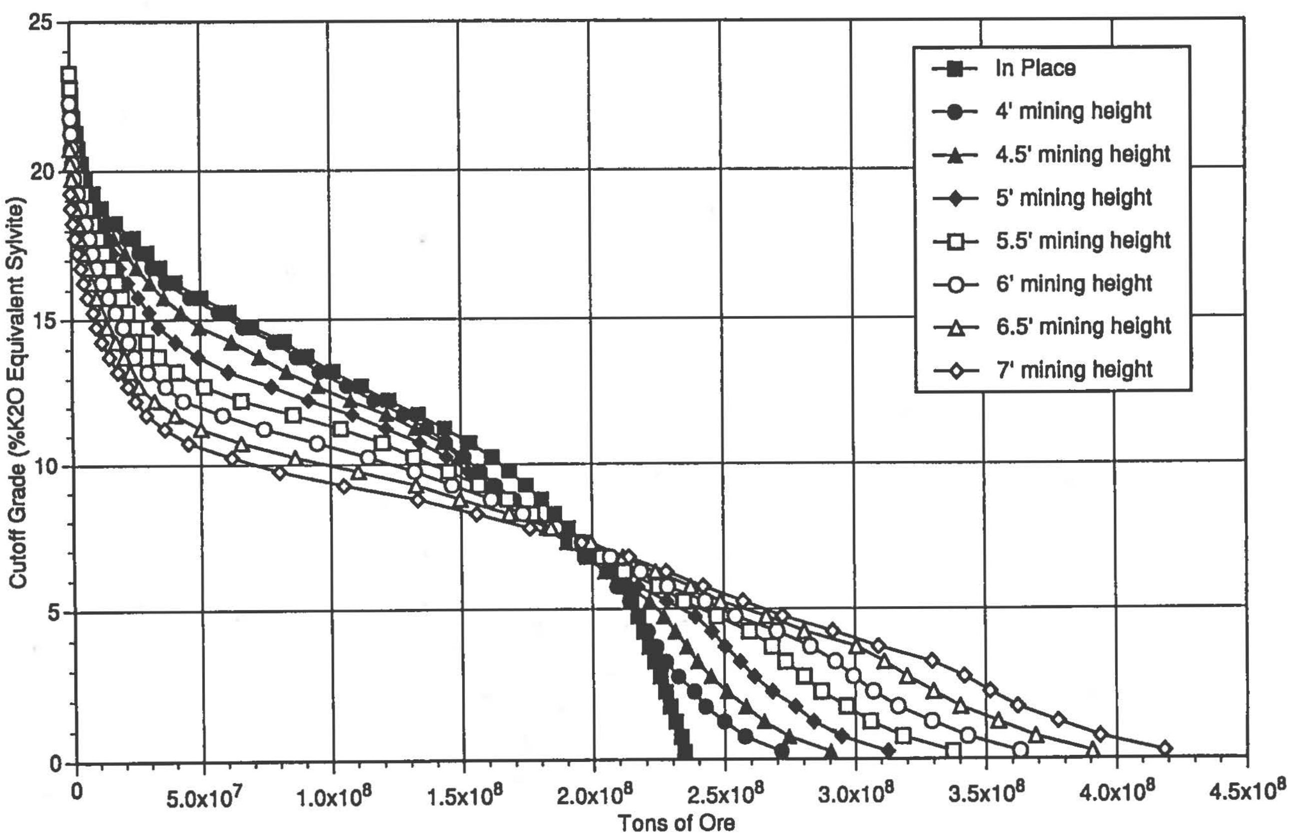

FIGURE 5.21—10th ore zone sylvite reserves (cutoff grade) for entire gridded area.

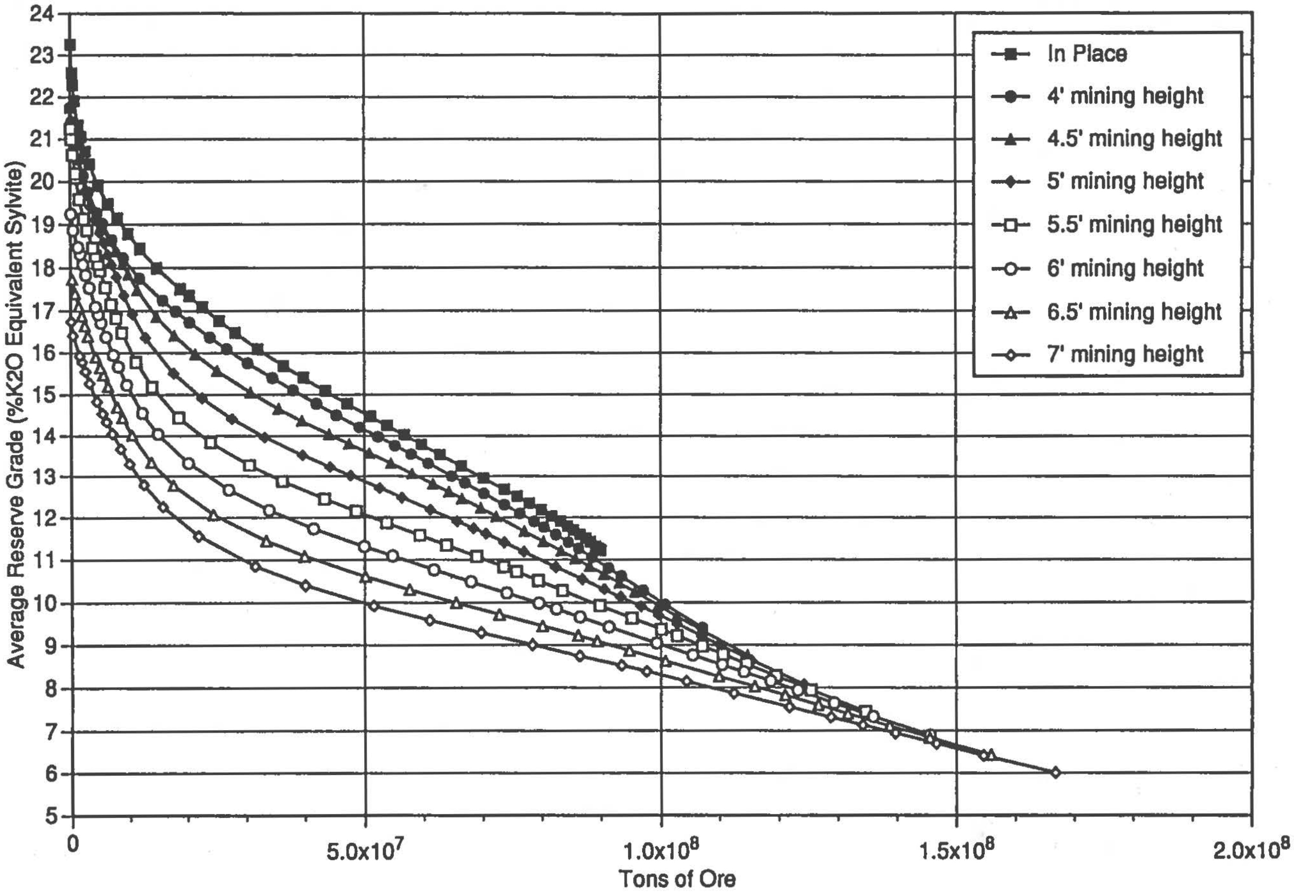

FIGURE 5.22—10th ore zone sylvite reserves (reserve grade) within WIPP boundary.

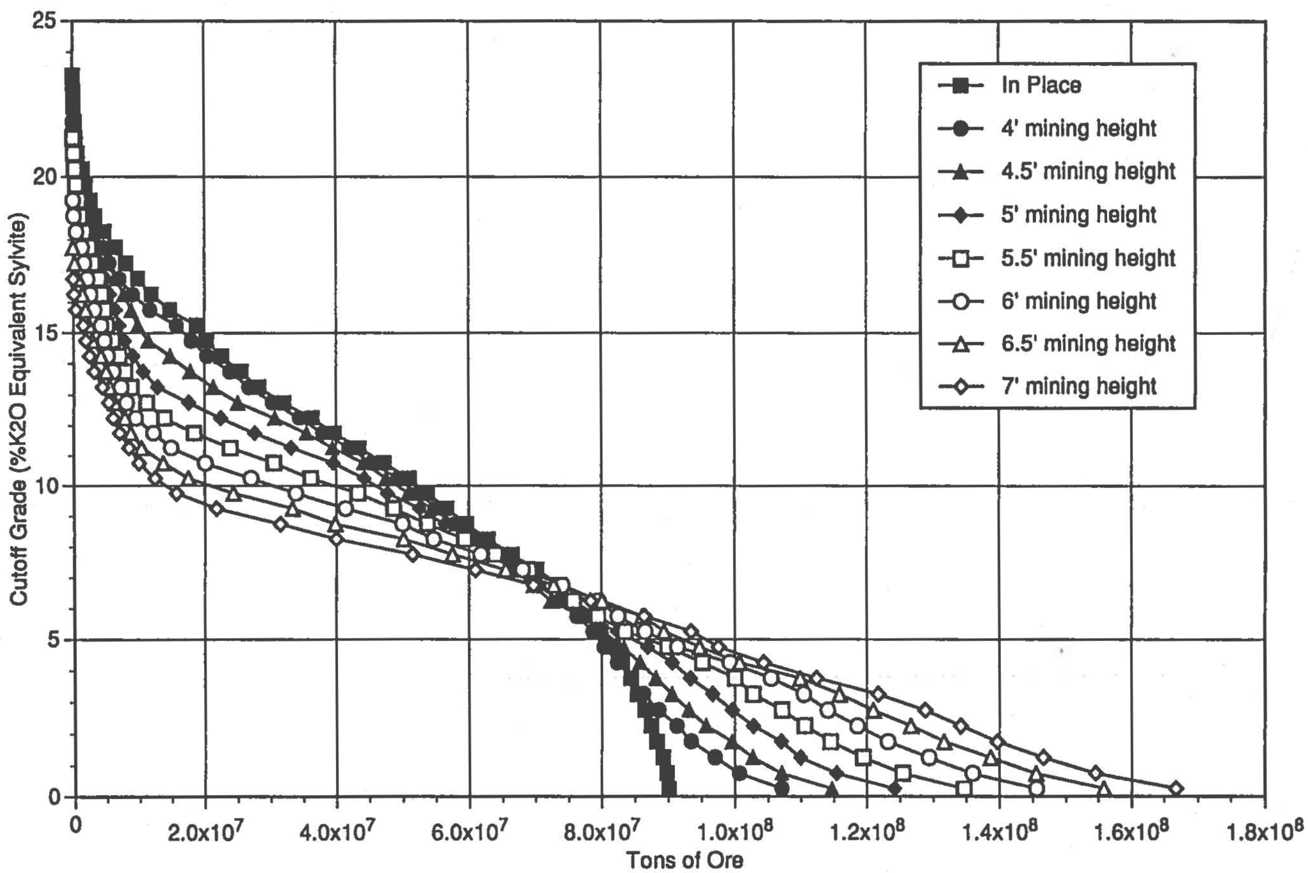

FIGURE 5.23—10th ore zone sylvite reserves (cutoff grade) within WIPP boundary.

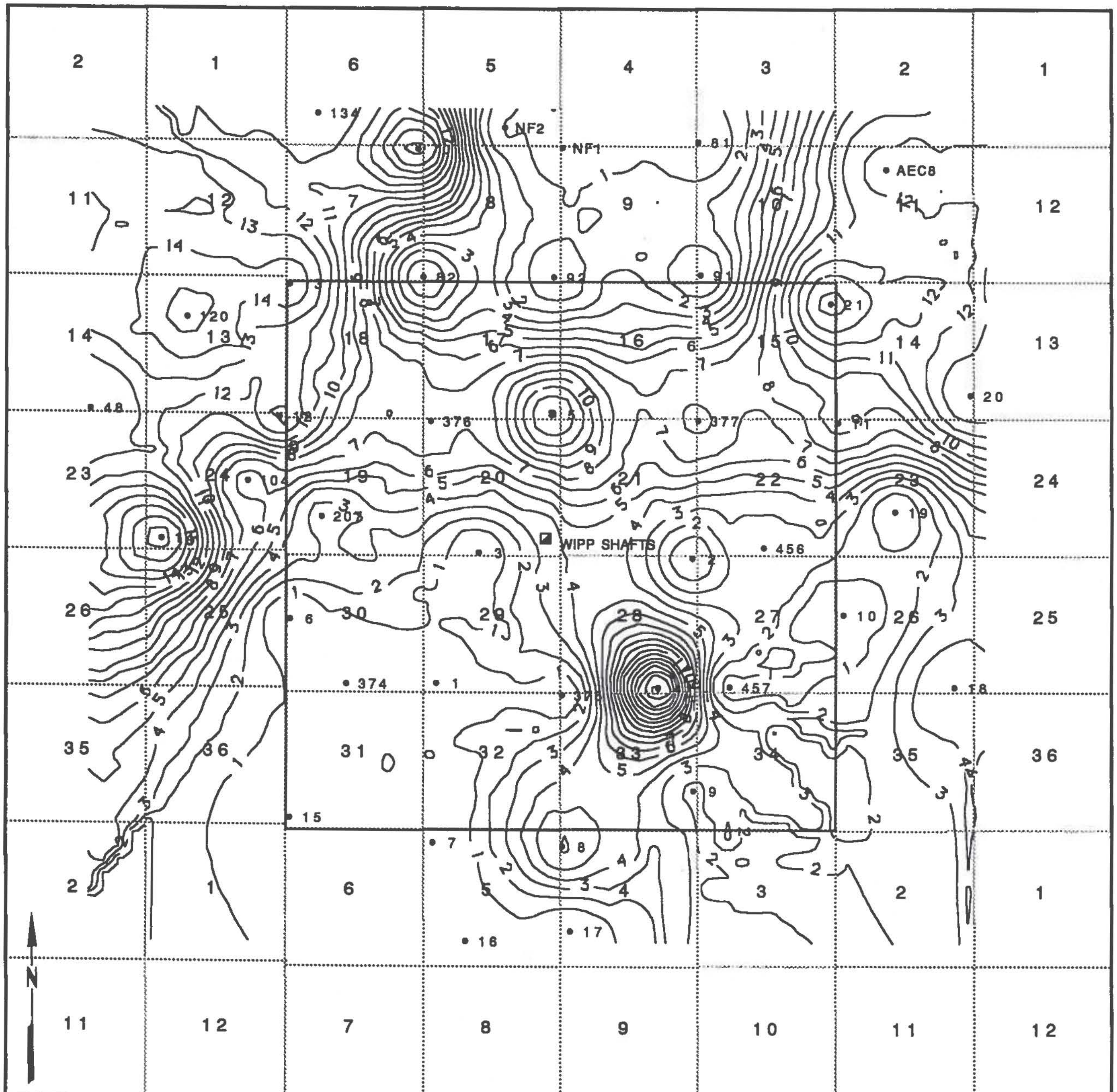

FIGURE 5.24—10th ore zone % K_2O sylvite only. Contour interval 1.0% K_2O.

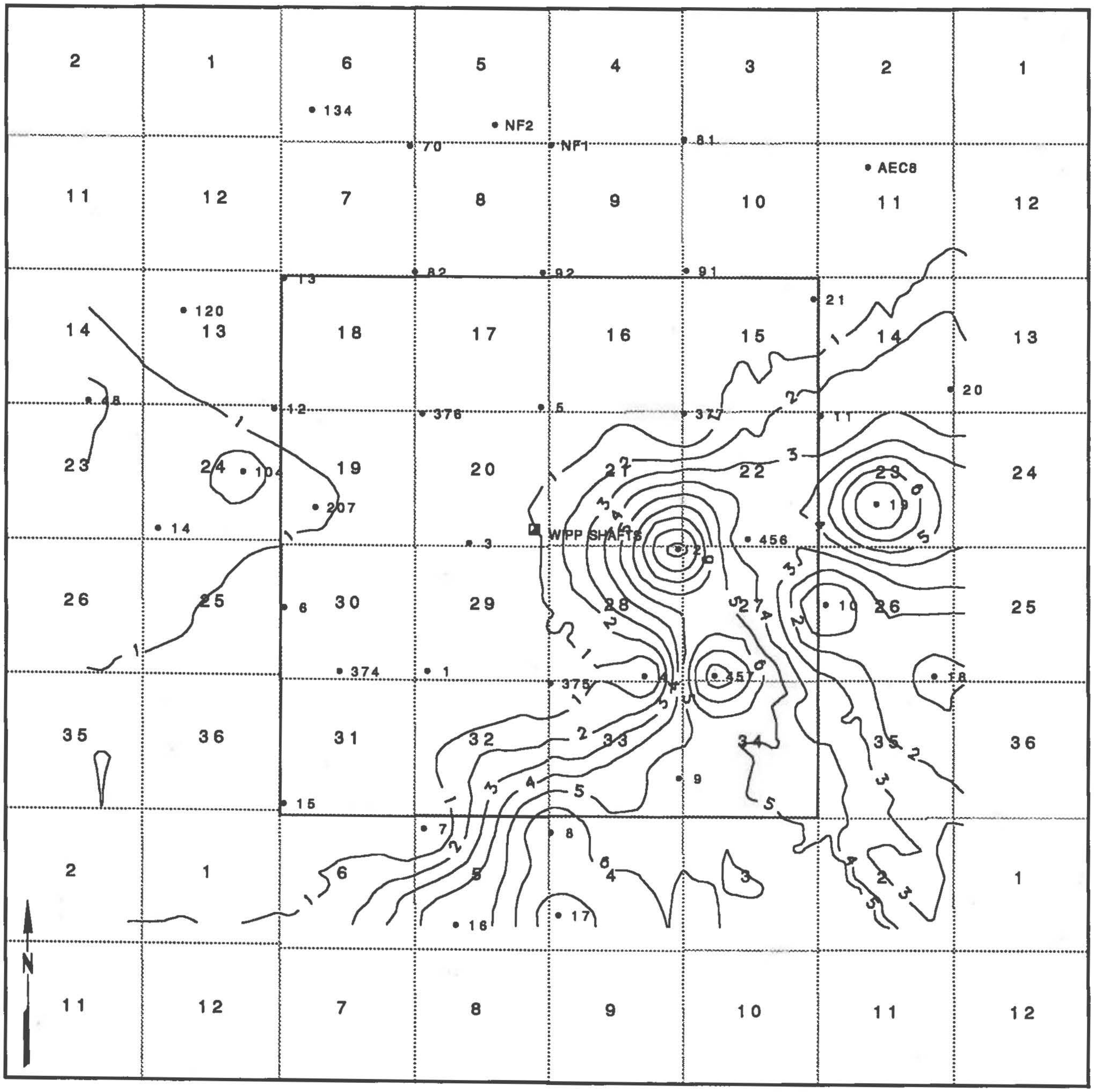

FIGURE 5.25—10th ore zone % K_2O langbeinite only. Contour interval 1.0% K_2O.

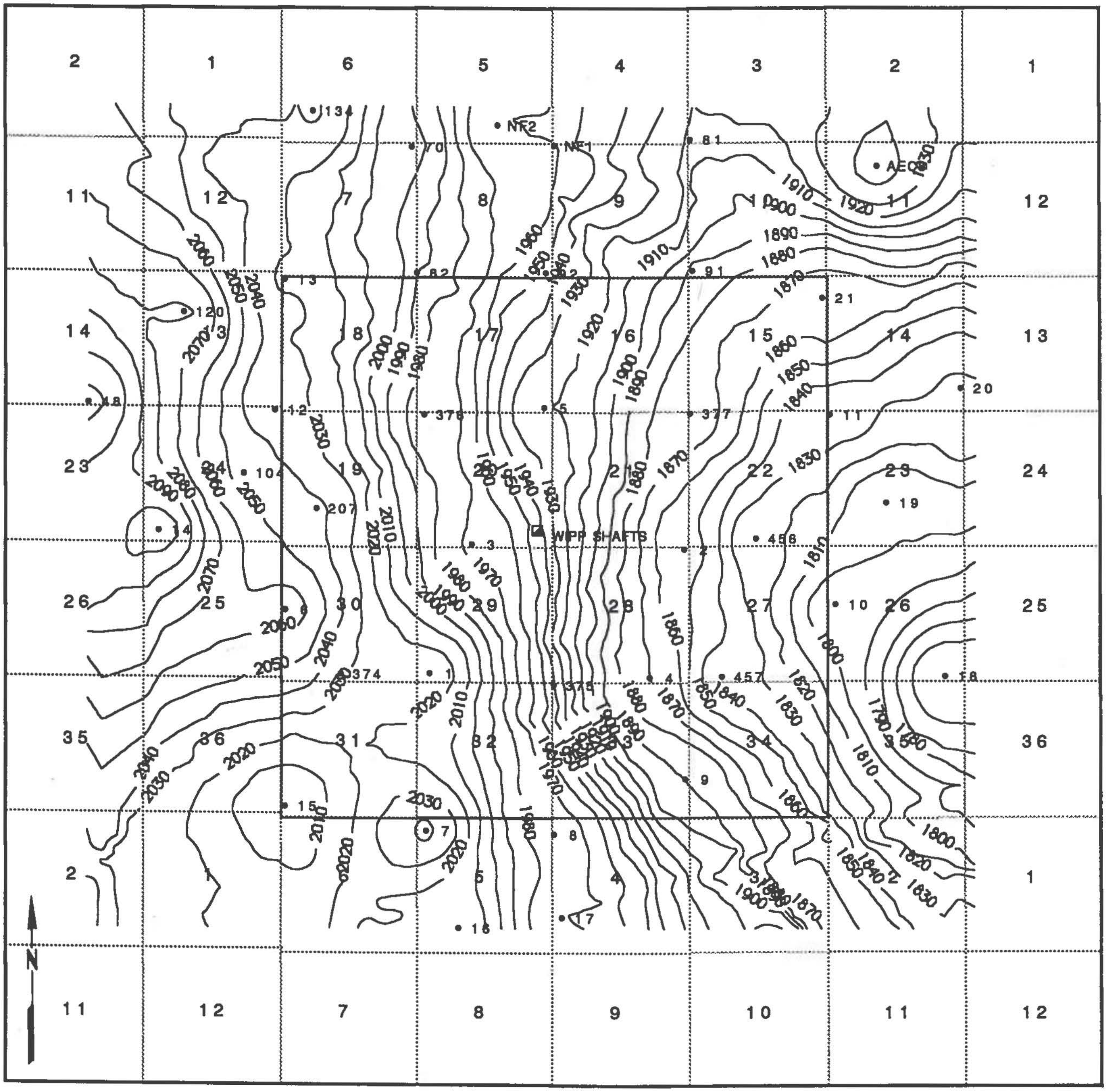

FIGURE 5.26—Structure of the top of the 10th ore zone. Contour interval 10 ft.

TABLE 5.4.—In-place resources for other ore zones (tons in millions).

Ore zone	Entire study area		Within WIPP		Outside of WIPP	
	Tons	% K_2O	Tons	% K_2O	Tons	% K_2O
2 (langbeinite >4% K_2O)	4.2	6.32	2.3	6.34	1.9	6.30
3 (equivalent langbeinite >4% K_2O)	16.2	5.93	8.9	6.20	7.3	5.60
5 (langbeinite >4% K_2O)	17.8	6.81	4.9	5.74	12.9	7.22
8 (sylvite >10% K_2O)	18.0	14.29	1.8	15.71	16.2	14.13
9 (sylvite >10% K_2O)	1.8	12.37	0.5	11.70	1.3	12.63
11 (sylvite >10% K_2O)	none		none			

Other ore zones

It was concluded that the intercepts of all other ore zones within the WIPP site that meet the criteria for BLM Lease Grade reserve are so small that they truly should be termed resources. If and when they would be mined will depend on the development of new methods for thin-seam mining. Only the in-place resources were calculated for these zones and are given in Table 5.4.

Figs. 5.27–5.32 are contour maps of the grade × thickness product for each of these subeconomic resources. Finally, Figs. 5.33 and 5.34 are the same sets of data presented in summations of tonnages versus weighted-average in-place grade, again one for the entire study (gridded) area and one for the WIPP site.

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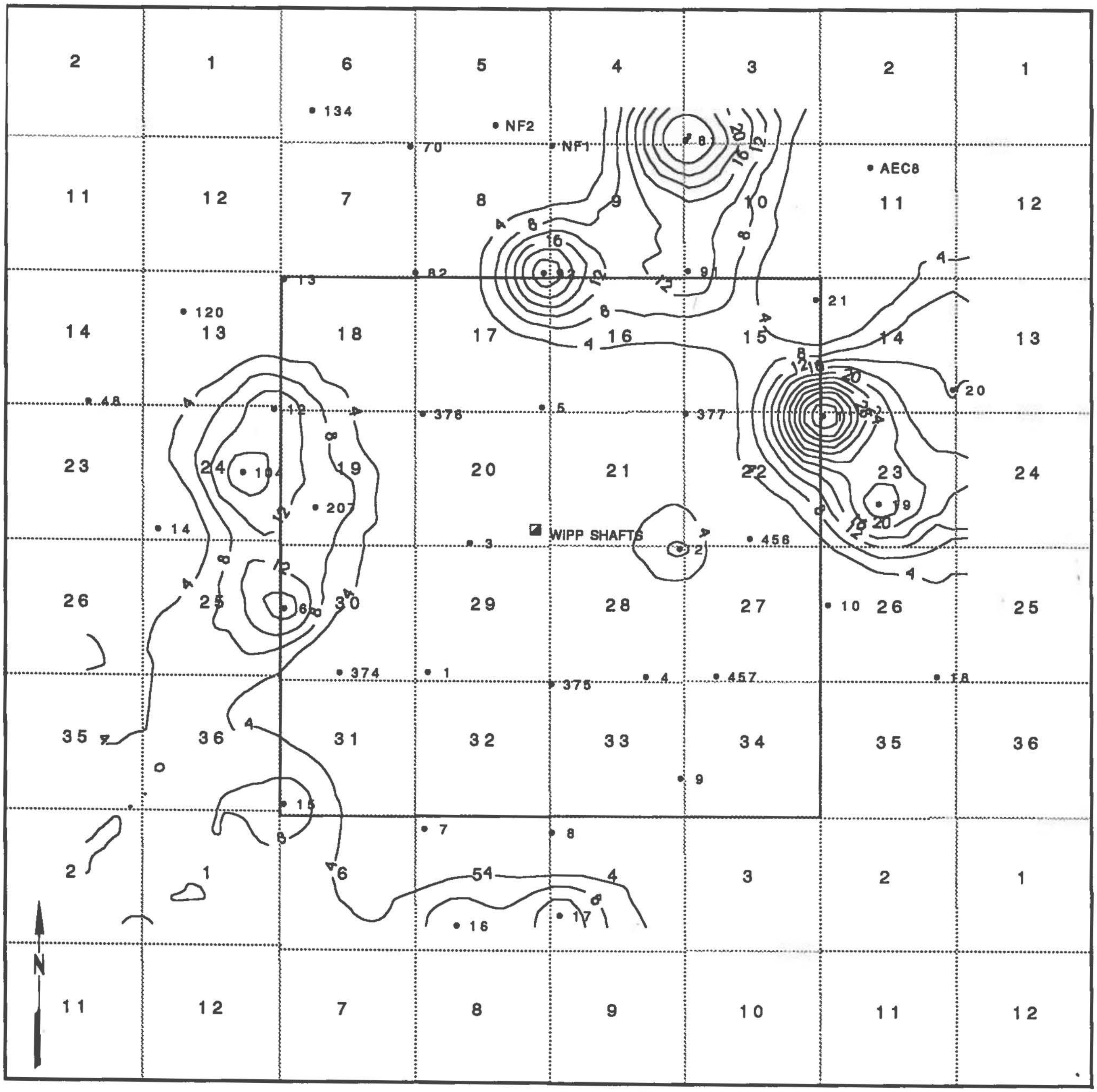

FIGURE 5.27—2nd ore zone % K_2O equivalent langbeinite × thickness. Contour interval 4.0% K_2O × feet.

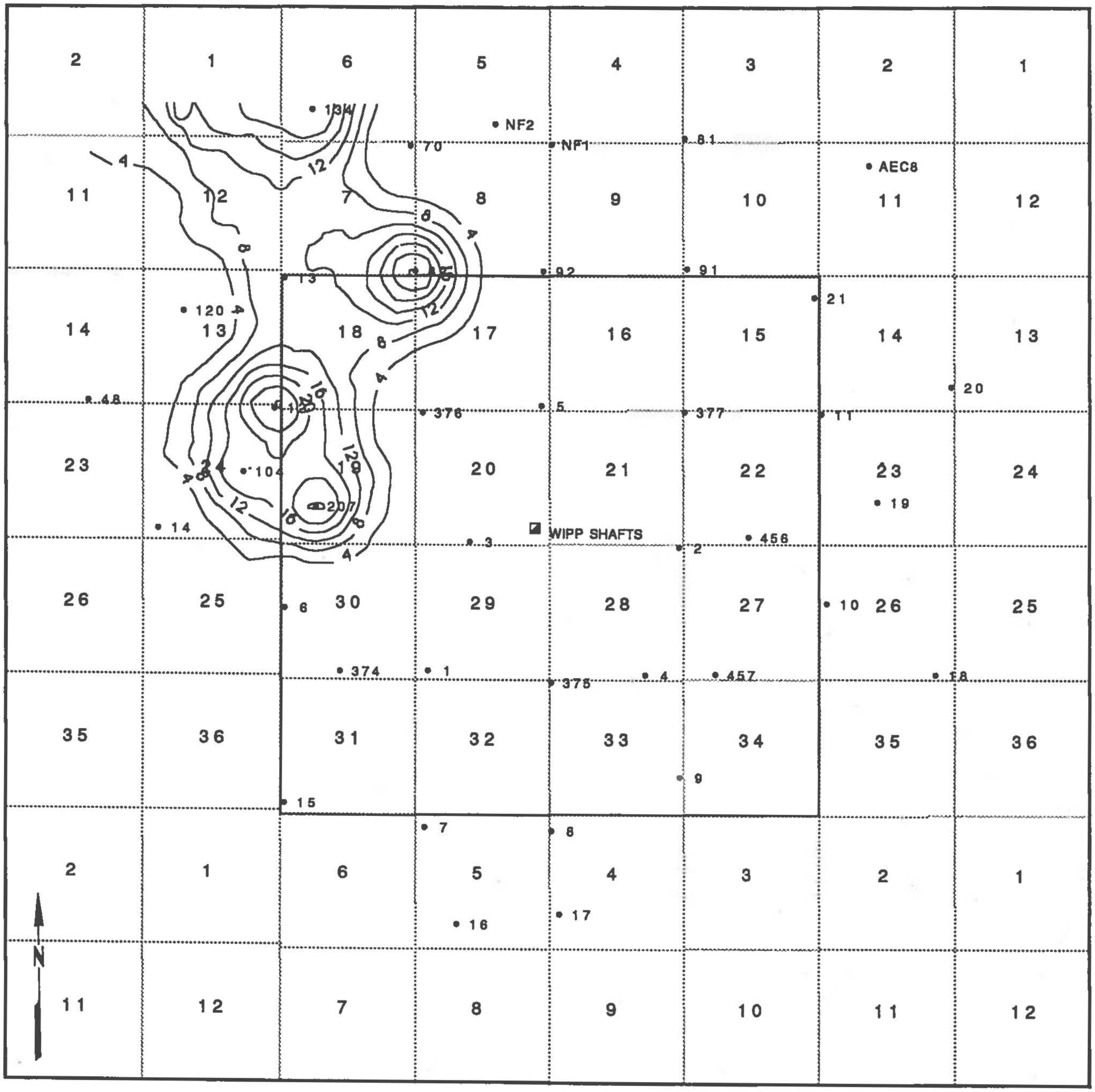

FIGURE 5.28—3rd ore zone % K_2O equivalent langbeinite × thickness. Contour interval 4.0% K_2O × feet.

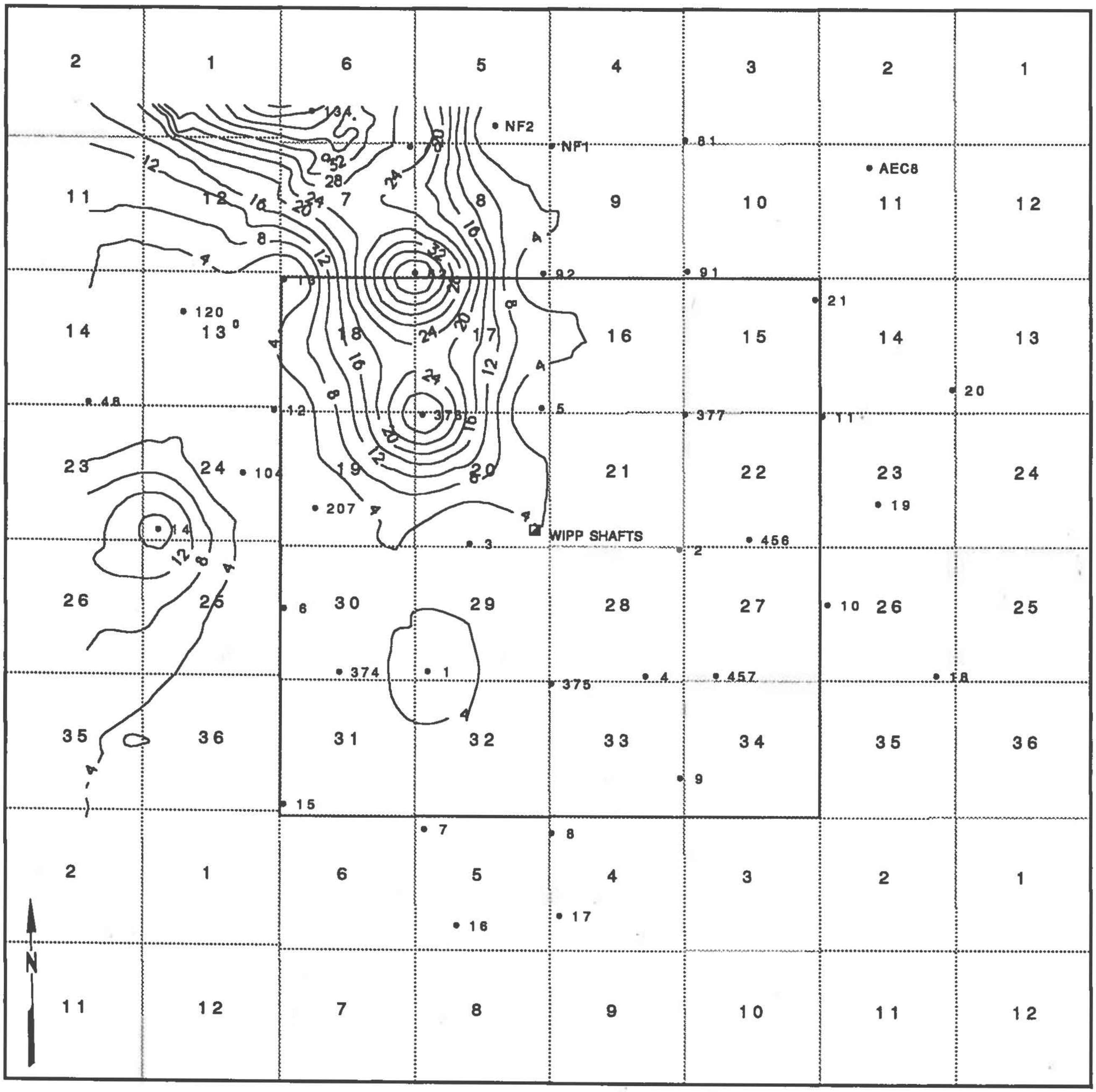

FIGURE 5.29—5th ore zone % K_2O equivalent langbeinite × thickness. Contour interval 4.0% K_2O × feet.

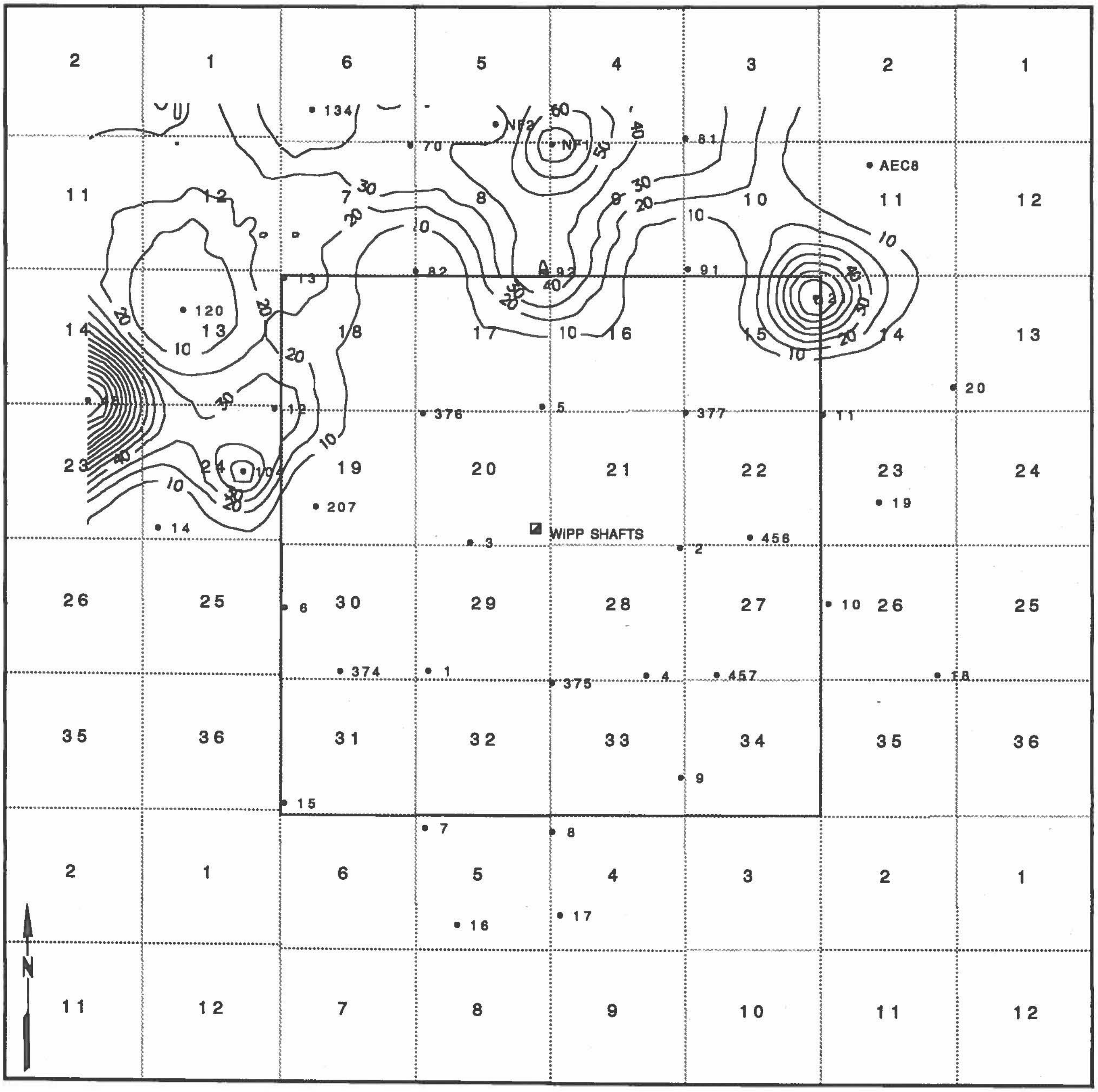

FIGURE 5.30—8th ore zone % K_2O equivalent sylvite × thickness. Contour interval 10.0% K_2O × feet.

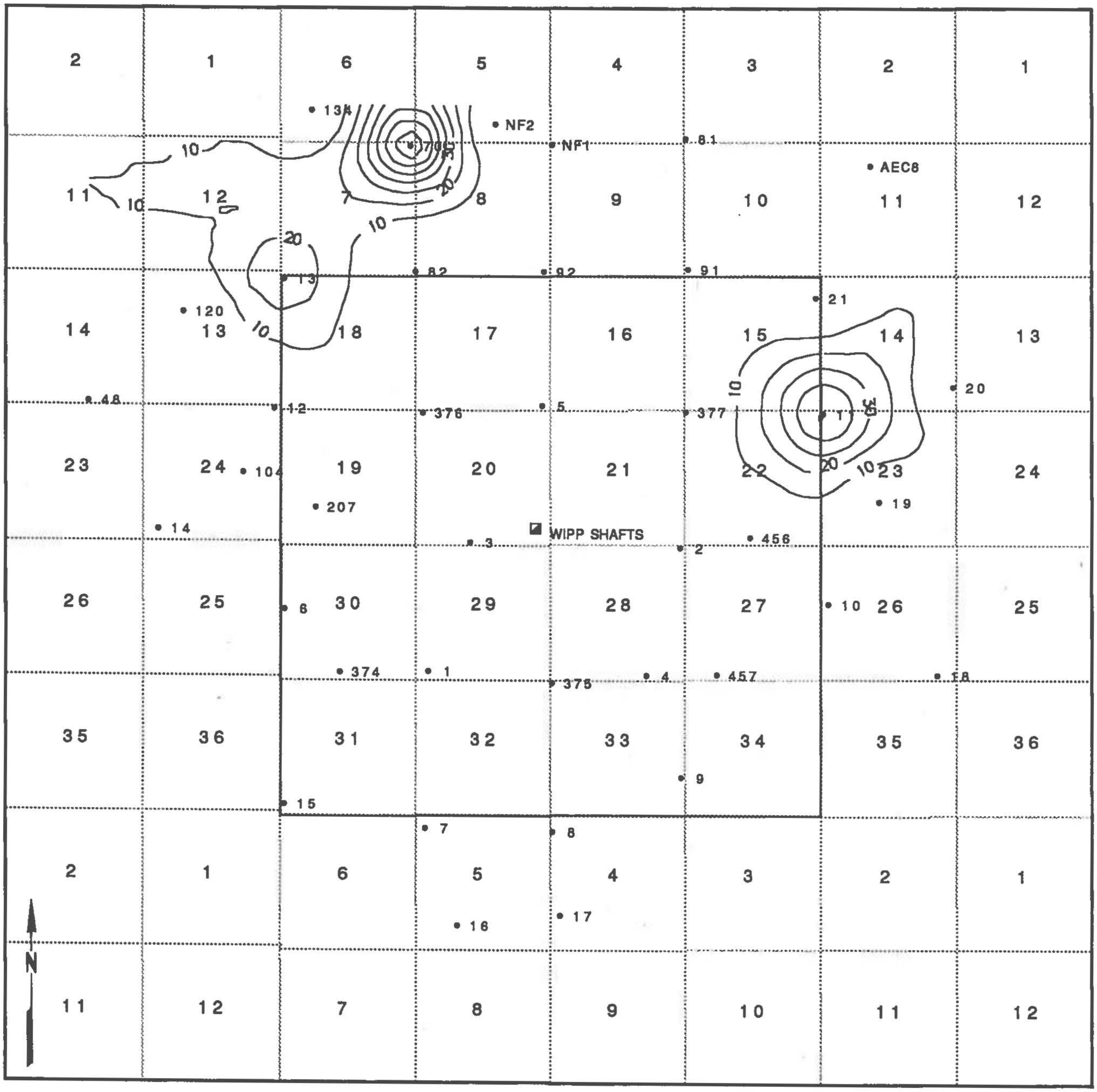

FIGURE 5.31—9th ore zone % K_2O equivalent sylvite × thickness. Contour interval 10.0% K_2O × feet.

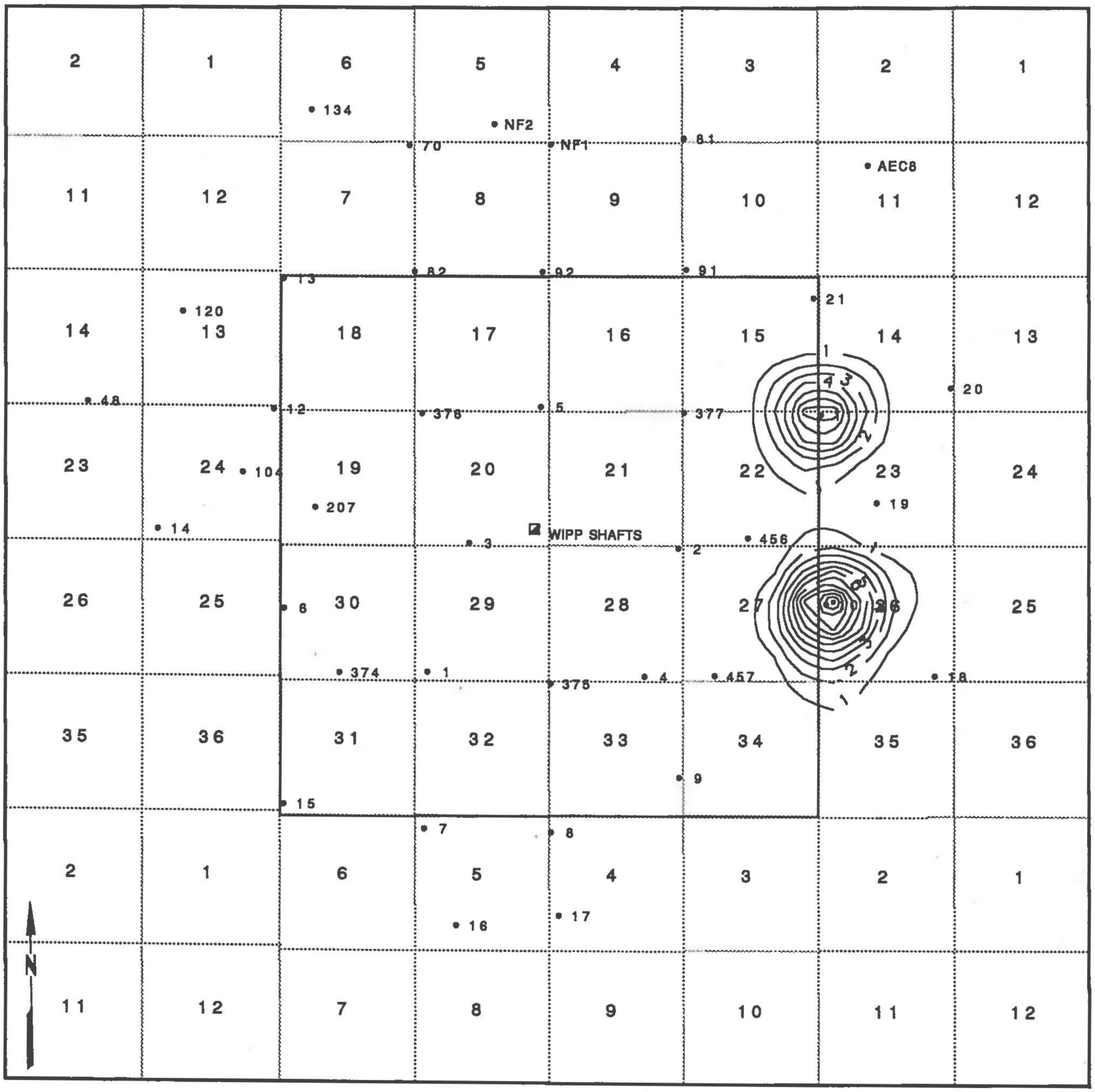

FIGURE 5.32—11th ore zone % K_2O equivalent sylvite × thickness. Contour interval 10.0% K_2O × feet.

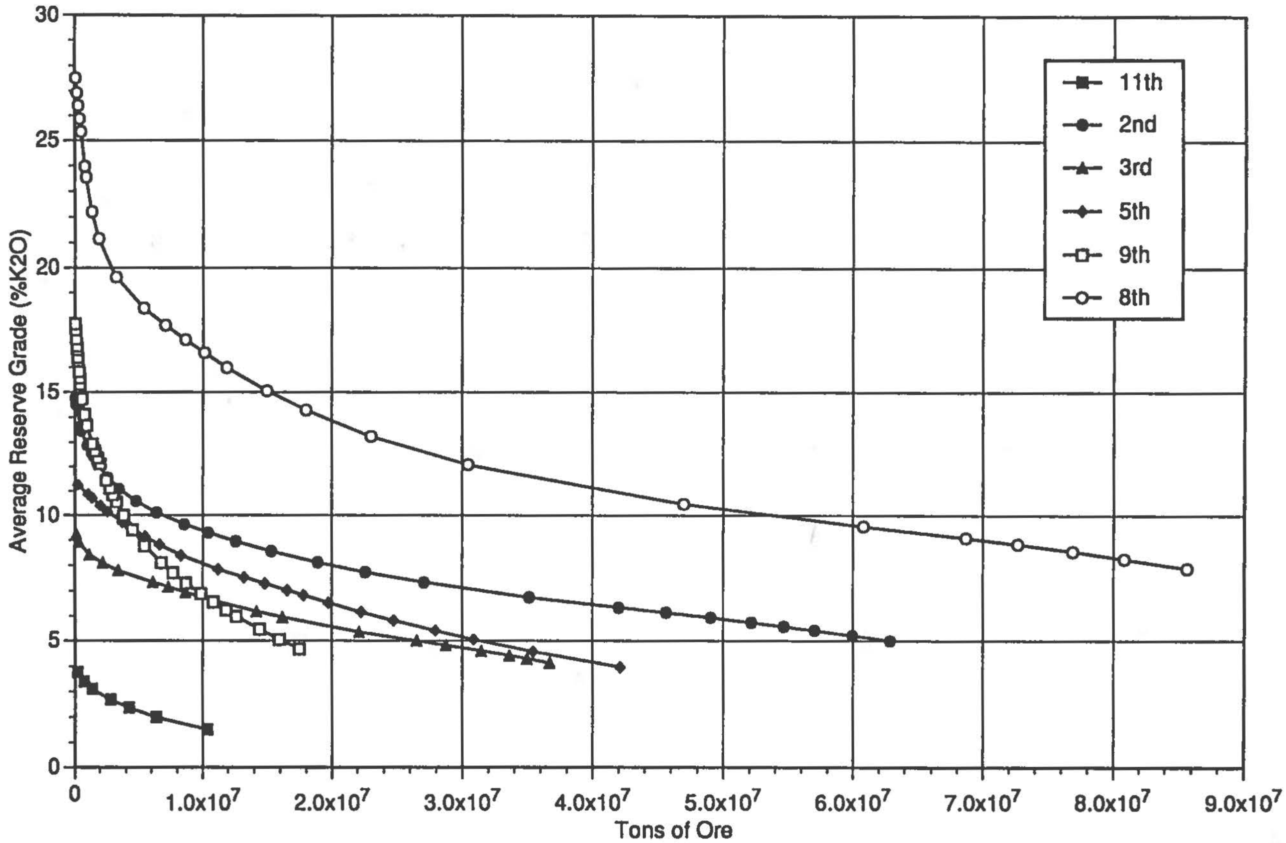

FIGURE 5.33—Multiple ore zone in-place reserves (reserve grade) for entire gridded area.

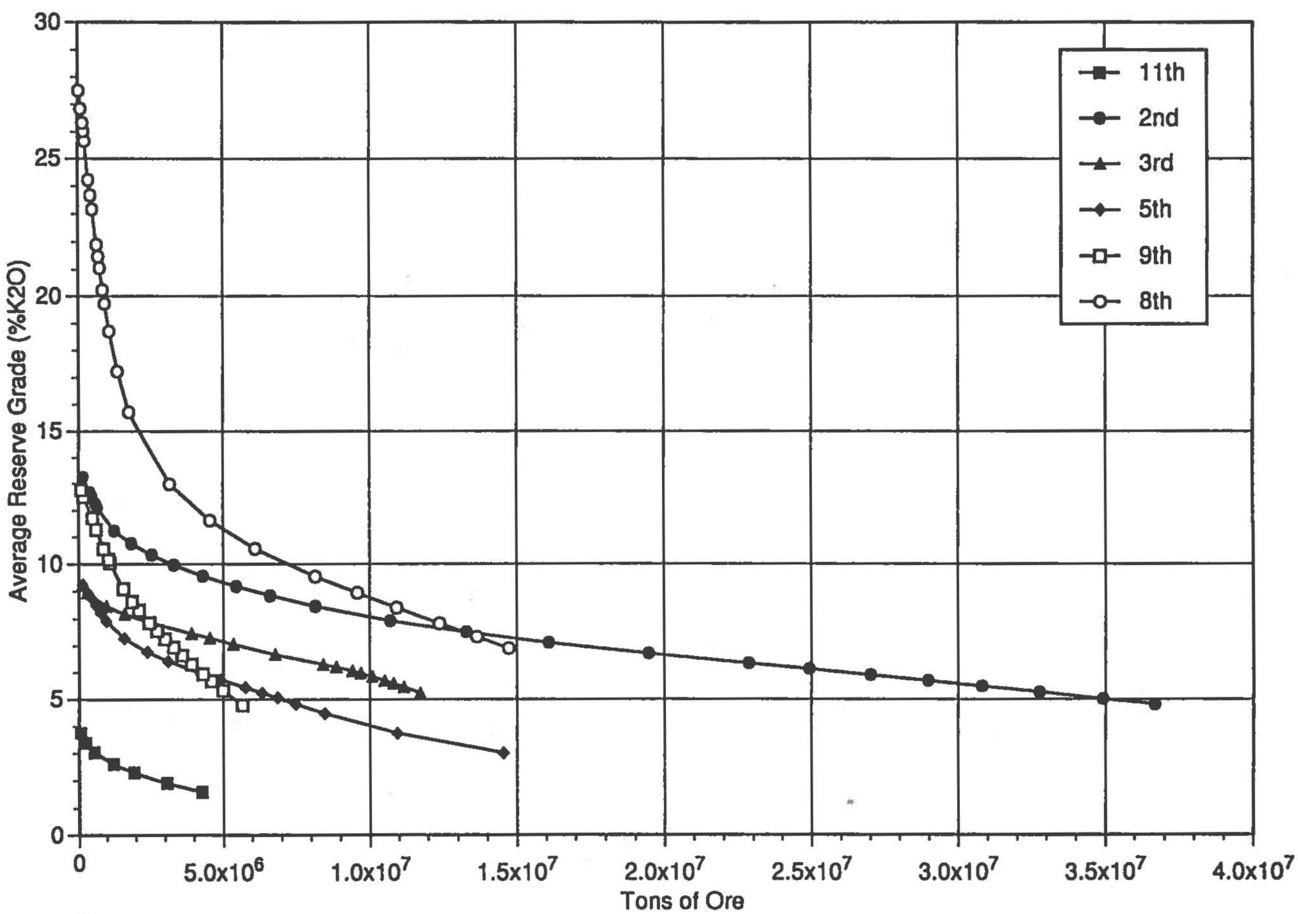

FIGURE 5.34—Multiple ore zone in-place reserves (reserve grade) within WIPP boundary.

6. Valuation of potash reserves at the WIPP site combined area

Peter C. Anselmo

Dept. of Management, New Mexico Institute of Mining & Technology, Socorro, NM 87801

ABSTRACT

Presented are valuation results and discussion of the method by which estimated potash reserves at the projected Waste Isolation Pilot Plant (WIPP) and the additional area around it were valued. The WIPP area and additional area form the combined area; total WIPP and additional area reserves (combined area reserves) are subjected to the procedure. Potash reserves in the form of both langbeinite and sylvite exist in the combined area. It was assumed that opening WIPP will make all potash reserves in this area unavailable for exploitation. A Monte Carlo sampling method was used to generate random-walk price and mining-cost data for the time period 1995–2030. The U.S. Bureau of Land Management criteria were used to establish cutoff mining grades, and three distinct development scenarios were evaluated from the perspective of a single firm. Sensitivity analyses of base-case variables are presented.

OVERVIEW

Potash deposits at the WIPP site and the surrounding one-mile-wide additional area (together known as the combined area) were valued via Monte Carlo simulation. Simulation input data included area raw-material reserves, market-price and operating-cost data, and other information obtained from potash operators, expert consultants, and the New Mexico Bureau of Mines & Mineral Resources (NMBMMR). Prices and production and processing costs were generated using random-walk techniques. A 15% discount rate was used for the base-case valuation of future cash flows and revenues from potash mining operations.

The overall objective was simulation-based derivation of probability distributions for six variables of interest. The six variables were revenues, cash flows, severance taxes, state taxes, corporate taxes, and royalties. Revenues and cash flows from mining operations were evaluated from the perspective of a single firm. Taxes and royalties were also estimated from this single-firm perspective. A 35-year timeframe was used in the study. These distributions were seen as opportunity-loss distributions, as opening of the WIPP will render the potash deposits within the 36-mi^2 combined area unavailable for exploitation.

Key input data were obtained from NMBMMR and an expert consultant. Because the amount and quality of potash deposits in the combined area are known with some degree of certainty, the amount of raw ore necessary to achieve various levels of final product was treated as a known quantity.

Sensitivity analyses were conduced on several key input variables, and distribution parameters (expectation, standard deviation, and skewness) were generated in all the analyses. Sensitivity analysis was conducted on the discount rate used on future cash flows, the amount of each potash product (langbeinite and sylvite) produced annually, and the cost per ton of mining and processing raw ore. Base-case values for these variables were

- Discount rate: 15%;
- Product tons: 350,000 (langbeinite);
  450,000 (sylvite);
- Cost/ton: $18 (langbeinite);
  $12 (sylvite).

Three mining scenarios were also considered. These were

- Scenario 1: Mining in the combined area begins in 1 year; No new development costs.
- Scenario 2: Mining in the combined area begins in 2 years; $5 million in development costs for each product.
- Scenario 3: Mining in the combined area begins in 4 years; $150 million in new plant-development costs (46.7% allocated to langbeinite and 53.3% allocated to sylvite).

Scenarios and base-case variables were, with the exception of the discount rate, provided by the expert consultant after extensive consultations with area operators. The cost per ton is an annual figure that includes the per-ton cost of mining and processing raw ore. Product tons refer to the amount of final potash product produced annually. Scenario 1 is based on the fact that current mining operations are occurring within a few miles of the combined area boundary, and if the WIPP does not come "on line," mining within the combined area would begin in about 1 year. Scenarios 2 and 3 are based on the possibility that development costs (a new shaft in the case of Scenario 2; a new processing plant in the case of Scenario 3) will be required for expansion of mining activities to the combined and surrounding areas.

RESULTS

Base-case expected values (all probability distributions were unimodal; some were more symmetrical than others) for the six variables of interest for all three mining scenarios are in Tables 6.1 and 6.2. Not surprisingly, immediate exploitation of combined-area potash resources is associated with the highest expected present values for all six financial variables of interest.

TABLE 6.1—Langbeinite expected values ($millions). Base case: 350,000 tons annual production; 15% discount rate; $18/ton cost.

Langbeinite	Scenario 1	Scenario 2	Scenario 3
PV (Revenues)	156	134	99.5
PV (Cash flows)	58.1	43.0	-59.2
PV (Severance tax)	1.9	1.7	1.2
PV (State tax)	2.7	2.2	0.46
PV (Corporate tax)	12.3	10.4	2.2
PV (Royalties)	3.9	3.4	2.5

TABLE 6.2—Sylvite expected values ($millions). Base case: 450,000 tons annual production; 15% discount rate; $12/ton cost.

Sylvite	Scenario 1	Scenario 2	Scenario 3
PV (Revenues)	193	166	123
PV (Cash flows)	52.0	37.4	-78.4
PV (Severance tax)	2.4	2.1	1.5
PV (State tax)	2.3	1.9	0.33
PV (Corporate tax)	10.9	8.9	1.6
PV (Royalties)	4.8	4.1	3.1

In Tables 6.1 and 6.2, PV (Revenues) refers to the expected present value of the revenue streams associated with mining langbeinite and sylvite over the 35-yr period considered, and it is a measure of the value of each resource. PV (Cash flows) is the expected net present value of the decision to exploit either potash resource from the perspective of a single firm. The other four values represent the expected present value of royalties and severance, state and corporate taxes paid as a result of potash mining operations within the combined area. As noted above, it is assumed that none of these cash flows would be realized by either mining firms or governments if the WIPP becomes operational.

The above numbers are expected values of probability distributions for each variable. Figs. 1–16 (in the Appendix) depict Scenario 1 probability distributions for expected revenue present values and expected cash-flow net present values with base-case costs at 15% for the four product-ton levels analyzed. Distributions for the expected present and net present values in Tables 6.1 and 6.2 may be seen in Figs. 2 (present value of langbeinite revenues), 6 (present value of sylvite revenues), 10 (present value of langbeinite cash flows), and 14 (present value of sylvite cash flows).

Prior to presentation and discussion of sensitivity-analysis results, the next section is devoted to the simulation method used.

SIMULATION METHOD

All data presented are the result of 1,560 simulation runs. An example of the spreadsheet simulation (years 1995–2000 for sylvite Scenario 1) is shown in Table 6.3.

Potash reserve estimates for the WIPP site, additional area, and combined area were provided by consultants and the specialists at NMBMMR. Product tons were held constant (at four levels for each product) over the simulation time frame. In the example in Table 6.3, 450,000 tons of sylvite product were assumed to be produced annually. The study was conducted presuming that reserves would be mined in order of quality. That is, the highest-grade raw ore (the ore with the highest product content) would be mined first, followed by the next highest grade and so on. Thus the amount of raw ore required to produce a given product tonnage will increase over time. This method ensures the most profitable years, on average, happening early in the 35-yr sequence.

Key model inputs, in addition to price, cost, and reserve data, included the price of the resource, the unit cost of extraction, severance-tax rates, state and federal corporate taxes, the depreciation schedule assumed for capital investments, and the discount rate. Development of a method to anticipate future market prices for potash was a key issue. Time units were years, and the time frame simulated was 1995–2030.

Confidential historical Eddy County potash prices were available from NMBMMR. Also available were various historical price databases and potash price indices. Where possible, time-series methods were used to model historical data. However, only 15 yrs of annual Eddy County price data were available. Several other sources of price data were considered, as were potash production indices. However, there was little correspondence across data sources, and the Eddy County data were deemed most appropriate for this project. These historical data limitations made use of time-series forecasts for the 35-yr-study time frame difficult to justify.

TABLE 6.3—Potash simulation example for sylvite Scenario 1.

	1995	1996	1997	1998	1999	2000
Net invest	0	0	0	0	0	0
Tons mined		1734288	1734288	1734288	1734288	1750897
Tons product	0	450000	450000	450000	450000	450000
Price/ton	75	74.81105039	75.79938253	75.13275348	75.77829148	72.36407079
Annual rev	0	33664972.68	34109722.14	33809739.06	34100231.16	32563831.86
Cost/ton	12	11.19015078	11.72916992	10.68161521	9.718915963	8.819637708
Annual cost	0	19406944.22	20341758.65	18524997.07	16855399.33	15442277.2
Severance tax	0	488142.1038	494590.971	490241.2164	494453.3519	472175.5619
Depreciation	0	0	0	0	0	0
Royalties	0	841624.3169	852743.0535	845243.4766	852505.7791	814095.7964
NI bef depl	0	12928262.03	12420629.47	13949257.3	15897872.71	15835283.29
Depletion	0	5049746	5116458	5071461	5115035	4884575
Taxable inc	0	7878516.034	7304171.466	8877796.296	10782837.71	10950708.29
State tax	0	1158767	1115117	1234713	1379496	1392254
Corp tax	0	2678695	2483418	3018451	3666165	3723241
Net income	0	4041054.034	3705636.466	4624632.296	5737176.706	5835213.294
Cash flow	0	9090800.034	8822094.466	9696093.296	10852211.71	10719788.29
Monthly PV	11.07931197	9.544922546	8.223032863	7.084213533	6.103110886	5.257882518
Quarterly PV	3.651384127	3.1514114	2.719898392	2.347471124	2.026039169	1.748619896
PV rev	0	26777463	23373781	19959618	17343124	14268067
PV cash flow	0	7230915	6045364	5724100	5519354	4696949
PV sev tax	0	384584	336309	287707	250445	206414
PV state tax	0	912938	758251	724613	698728	608631
PV corp tax	0	2110417	1688661	1771432	1856948	1627633
PV royalties	0	663076	579844	496046	431803	355886

Forecasting is as much an inexact art as a science, particularly when the forecasting horizon is 35 yrs, which will always make the use of time-series-based price predictions quite risky. Thus, although historical prices for Eddy County potash were modeled using time-series methods, a simulation approach was used to value these resources. Annual market prices were simulated using a random-walk methodology (an excellent reference is Karlin and Taylor, 1975), which is discussed below.

Key assumptions and features associated with the potash revenues and cash flows used in the simulation include

- All calculations are performed from 1 January 1995. Potash extraction activity in the three zones of interest is treated as a capital project that was evaluated from 1 January 1995 and undertaken either 1 January 1996, 1 January 1997, or 1 January 1999. However, the decision to go forward with any potash mining and development venture was considered from the perspective of 1 January 1995.
- Mine shaft and/or new plant capital expenditures are recovered using a 10-yr Accelerated Cost Recovery System depreciation method (Stermole and Stermole, 1993).
- Revenues are treated as if realized monthly, and taxes and royalties are treated as if paid on a quarterly basis.
- Each simulation run, summarized as an individual data set in the attached appendix, consisted of 35 simulated potash price and cost "paths" from 1995 to 2030. The Monte Carlo simulations generated numbers for each year for the present value of the market value of the reserves and the present value of the total cash flow for each simulation run. As is standard practice in financial analysis (for example see Levy and Sarnat, 1994), cash flows attributable to the decision to mine potash are the sum of income after taxes, depreciation, and depletion. Data were also generated for expected present values for severance taxes, state and corporate taxes, and royalties. The possibility of partial or complete debt financing for either a new shaft (Scenario 2) or new plant (Scenario 3) was not considered.

Specifics regarding simulated input variables are provided below.

Market prices

Annual prices per ton for both potash products under the various scenarios were generated using a random-walk method known as a Wiener process. Historical, confidential langbeinite and sylvite prices were analyzed using time-series techniques to show that these historical prices may be modeled as a random process. An estimate for the end of 1994 market price for both products was obtained from area operators and was used as the 1995 market price and the point of departure for the price simulations.

Use of random-walk methods to forecast future prices is partially predicated on the idea that future prices may not be directly predicted from current and historical data. Presumably, all past and current market and commodity information is included in current market prices. A Wiener process is attractive in this situation because an estimation of the variance of the historical price path is not required. Also, a Wiener process is attractive in situations such as this one, particularly in the case of a commodity like potash, because the uncertainty associated with the commodity-market price estimate in a given year is an increasing function of the forecast time horizon. So, as price forecasts move away from 1995, the uncertainty associated with those forecasts increases (Dixit and Pindyck, 1994).

The price model used was

$$P_t = P_{t-1} + z_t \sqrt{dt}$$

where P_t and P_{t-1} denote the current and previous years' prices for either langbeinite or sylvite, z_t is a random variable with expectation 0 and standard deviation 1 generated [These values were generated in MSExcel as the sum of 12 uniform random variables less 6. This variable is known to have a distribution that approaches a normal distribution with mean 0 and standard deviation 1 (Clemen, 1996).] for each new annual price in each simulation run, and dt is the number of years between 1995 and year t. Thus, for the year 2000, dt=5. This Weiner process (also known as Brownian motion) does not include a drift parameter (the expected price in any single year is the price the previous year) because the expected value for z_t is 0. This point is discussed later in this chapter.

Wiener processes are less sophisticated than other stochastic-process techniques and are grounded in three major assumptions. (1) The Markov property states that only current information is useful for forecasting future price paths. Thus, predicting future prices on the basis of historical price data will not enable speculators to "beat the market." The fact that potash is a commodity much like other mineral commodities, and is therefore subject to many of the same politically and/or macroeconomically based price shocks, makes the first assumption reasonable. (2) Each (in this case, annual) price change is independent of all other annual price changes. This assumption may not be as easily defended, though in the longer term (over a 35-yr period, for instance) it probably holds. (3) Annual price changes are normally distributed. On the basis of the analysis of historical annual price data conducted for this study, we cannot refute this assumption. The trouble with the assumption is that very large price swings are possible. In fact, negative prices are theoretically possible. However, because all data reported are the result of (at least) 1,560 simulation runs, potential negative-price impacts are negated.

Appendix Fig. 17 contains an example of three sylvite price paths from 1995 to 2000. Individual price paths have a tendency to wander and vary considerably, although the price process used in the study does not permit significant year-to-year price movements (except, possibly, for years near the end of the 1995–2030 study period). However, the number of runs conducted resulted in an average potash price nearly identical to the beginning (1995) price. Regardless of the data set examined, historical potash prices have shown an inflation-adjusted return of about 0% over the last (approximately) 20 yrs. The discount rate used in this study is therefore a real (as opposed to nominal) rate because of the historical (geometric) average real rates of change in potash prices. This real return over the last 20 yrs is also the reason for exclusion of a drift parameter in the price model used in the study.

It is important to reiterate that the Wiener process approach was selected after analysis of Eddy County historical, confidential potash price data provided by NMBMMR. Historical data were not available for machinery, new plant or operating costs, so cost data had to be obtained from area potash operators.

Capital and operating costs

Capital costs used in this report for a new shaft or plant were provided to NMBMMR by area operators via the expert consultant, as were data concerning per-ton annual operating costs. As noted above, operating costs encompassed both mining and processing costs. These data were used as simulation inputs. After much discussion (in the absence of historical data), the uncertainty associated with annual operating costs was expressed as ±10% of the previous year's per-ton operating cost. Thus, a uniform distribution was used for annual operating costs, with the mean for any one year the cost generated for the previous year. The range for potential operating costs in any year was ±10% of the expected cost, which in the simulation was the previous year's operating cost. All non-capital annual costs were aggregated into the operating cost figures provided by consultants and area operators.

More specifically, the cost model used was

$$C_t = C_{t-1}(0.9 + 0.2y_t)$$

where C_t and C_{t-1} represent the current and previous years' annual operating costs, and y_t is a random variable with a uniform distribution over the interval [0,1] generated for each annual cost in each simulation run.

No inflation factor was built into the cost projections. Although mine productivity (in terms of tons produced per potash-mine worker) has been essentially flat since 1965 (Economic Report of the President to Congress, 1994), technological advances that will enable mining companies to offset the effects of inflation on operating costs are likely in both the near and distant future. Also, because no positive inflation factor was built into the price model, a balanced approach dictated that a zero-drift cost model be used in conjunction with the price model.

The sensitivity of the generated probability distributions for the six variables of interest to this price/cost model combination was examined by Anselmo (1996). In that study, the price/cost model combination used in this study was compared with two other (zero inflation) price/cost models. As one might guess, expected values for revenues and cash flows were about the same; distribution standard deviations varied considerably. The heuristic, variance-based rationale for selection of the price/cost combination used in this study and in Anselmo (1995) was also discussed.

Taxes and royalties

The State of New Mexico assesses severance taxes on revenues attributable to minerals extracted within the state. Rather than attempt to predict factors that might contribute to alterations in the severance tax rate, a rate of 1.25% (based on current tax law and expert input) of potash revenues was used for the study period. A royalty rate of 2.5% of revenues, provided as a current estimate by experts in this area, was used in the simulations for similar reasons.

Capital investment and other tax incentives that mining companies may periodically receive from political entities were likewise ignored in this work. In addition to presenting a major limited data prediction problem, consideration of tax incentives would involve acquisition of additional proprietary data from area producers. An average corporate tax rate of 34% was therefore used.

All taxable income (listed as Taxable Inc in Table 6.3) is assumed to be New Mexico income for state-tax purposes. New Mexico tax rates are 4.8% of taxable income under $500,000; $24,000 plus 6.4% of the excess over $500,000 for amounts between $500,000 and $1,000,000; and $56,000 plus 7.6% of the excess over $1,000,000 for taxable income over $1,000,000.

Discount rate

Results are presented above for a 15% discount rate, which also was used by Weisner, Lemons, and Coppa in 1980. Estimation of discount rates for risky investment projects (the perspective taken in this study was one of viewing potash-exploration activity in the zones of interest as risky investment projects) is generally a difficult and inexact process. Though there is detailed knowledge regarding the location and grade of potash deposits in the area, there is some uncertainty (as noted above) regarding the future market price of potash products. Along with the long time horizon, price uncertainty may be considered a major source of potash mining operation risk.

The primary use of Eddy County potash product is in fertilizer for various foodstuffs and other consumer products such as tobacco. There is little doubt that global demand for food, fueled by both the large and expanding global population and the rapid industrialization occurring in areas where much of the world's population lives, will be increasing for the foreseeable future. Demand for food will not decline in the near or distant future unless a global catastrophe occurs. However, as Searls (1992) notes, near-term demand for potash products as food-producing fertilizer is far from certain.

Additionally, farm productivity in the United States has been increasing slowly but steadily since 1965 along with the use of agricultural inputs. However, the use of agricultural inputs relative to all other inputs in the United States agricultural process (e.g., labor and capital equipment such as farm machinery) has remained steady since 1985 (Economic Report of the President to Congress, 1994). Stable domestic demand for potash-based fertilizer products is a likely feature of the potash market for the (at least) near future. Searls (1992) notes that future demand increases are likely to come from outside the U.S.

Although the world population is rapidly increasing, albeit at a decreasing rate, passage of international and regional treaties such as the General Agreement on Tariffs and Trade (GATT) and the North American Free Trade Agreement (NAFTA) may have a negative impact on agriculture subsidies around the world. Stabilization or rolling back of agricultural subsidies in countries such as Japan may have a levelling (or, in the short term, negative) impact on global demand for potash-based fertilizer products. Certainly, the near future for potash prices (despite the historical upward trend in per-ton product prices) is uncertain; the more distant future is uncertain by definition.

This is not to say that potash operations are not profitable. On the contrary, all available evidence at the time of this study seems to indicate that potash operations in the Carlsbad area have been profitable over the years. However, the circumstances summarized above point to the notion that prediction of an upward trend in potash prices is difficult to substantiate given current market conditions.

The 15% real rate used as the base case for this study is therefore reasonable in light of the long-term market uncertainties faced by potash producers. Although the development risk associated with potash deposits in the combined area is low, there is a significant long-term market-price risk that is faced by operators. Although langbeinite is essentially unique to the Carlsbad/Eddy County area, extensive sylvite deposits in various stages of development exist around the world. Furthermore, any investment situation as long term as a potash mining operation faces considerable interest-rate risk—the risk that more favorable return opportunities will arise over the life of a project.

A precise discount rate for different firms operating in the WIPP area is difficult to estimate (particularly in the absence of debt/equity ratio data for said firms). So, although pinpointing a discount rate for a 35-yr project is quite risky in and of itself, current levels of activity in the region and market factors point to a 15% discount rate for Carlsbad area potash operations. Numbers associated with a 10% rate are presented in the tables in the Appendix; and the numbers in the Appendix are discussed in the next section.

SENSITIVITY ANALYSIS

Sensitivity analyses were conducted for all combinations of the following levels of the following input variables.

- Annual product tons:
  Langbeinite: 200,000, 350,000, 500,000, and 1,000,000;
  Sylvite: 300,000, 450,000, 600,000, and 1,000,000;
- Discount rate: 15% and 10%;
- Cost/ton:
  Langbeinite: $18, $16, and $12;
  Sylvite: $12 and $10;
- All three scenarios.

Figs. 18 and 19 contain expected revenue present values for all three scenarios (indicated as Sc 1, 2, or 3 in the legends) and both discount rates for langbeinite (Fig. 18) and sylvite (Fig. 19). As one might expect, the most favorable valuation combination for either product is Scenario 1, 1 million product tons and a 10% discount rate. The least favorable valuations are associated with minimum production levels, Scenario 3, and 15% discount rate.

Expected cash-flow net present values for langbeinite for all three scenarios and operating costs of $18 and $12/ton are presented in Fig. 20. Expected cash-flow net present values for sylvite in all three scenarios with per-ton operating costs of $12 and $10 are presented in Fig. 21. In both Figs. 20 and 21, the discount rate used was 15%. As may be seen from the figures, the feasibility of construction of a new plant (Scenario 3) is questionable at best. For both products, the new plant is only feasible at the highest production level considered (1 million product tons of each product), the low discount rate, and the lowest production cost. Although the new processing plant is feasible for langbeinite at 1 million tons annual production or at 500,000 tons annual production if langbeinite operating costs are $12/ton, it was assumed that the new plant would be built to process both products. Also, the plant is feasible for neither product at base-case production levels at 15% discount rate.

Tables A1-A120 in the Appendix contain probability distribution data for all variable combinations. Tables are organized by production level and scenario. Within each production level and scenario, data are reported for all discount-rate and operating-cost combinations. In each of the 120 tables, Ave. denotes the distribution expected value, Max. and Min. refer to maximum and minimum values generated, Med. is the distribution median, St. Dev. is the distribution standard deviation, and Skew denotes the distribution skewness.

All distributions for all variables were unimodal. In general, revenue present-value distributions were less skewed than net present-value distributions, though exceptions may be found in the tables. Trends in all distribution expected values may be seen in Figs. 1–16 and 18–21. Tables A1–A120 provide distribution data associated with the expectations provided and discussed in the body of this report.

CONCLUSION

As part of the process of assessing the viability and feasibility of the WIPP, the New Mexico Bureau of Mines & Mineral Resources was charged with assessment and valuation of the mineral resources within the region known as the WIPP site combined area. This study was completed in March 1995.

In response to several issues raised by area operators regarding the valuation of potash reserves reported in the original work, this study was undertaken. The objective was determination of present-value probability distributions for the six financial variables of interest (revenues from potash products; the net present value of potash mining operations; royalties; and severance, corporate, and state taxes) associated with a hypothetical single firm conducting potash mining operations in the combined area. The generated distributions may be seen as opportunity cost (or loss) distributions from the perspectives of the single firm and various governmental entities, as operation of the WIPP will cause combined-area potash reserves to be inaccessible for about 10,000 years.

Many of the issues associated with this study were unclear, and judgment was used throughout the process of generating the data reported here. With respect to input variables, cost and price data were provided by area operators via the expert consultant. The price/cost model combination used and the discount rate were both selected after much data analysis and consideration of very relevant qualitative factors, such as the anticipated worldwide demand for Eddy County potash over the next 35 yrs. However, the actual method used to select these critical variables was heuristic in nature.

Because of the extensive use of judgment in the base-case analysis, the extensive sensitivity analyses reported in this work were conducted. Though there is considerable variation in the distribution parameters under various variable and scenario combinations, the base case remains just that—the basis for comparison and our best estimate of the relevant variables associated with potential potash production within the Eddy County, New Mexico, combined area.

ACKNOWLEDGMENT—Data-collection assistance provided by Jennie Wong is gratefully acknowledged.

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APPENDIX

Figure 1
Langbeinite 200K Annual Production

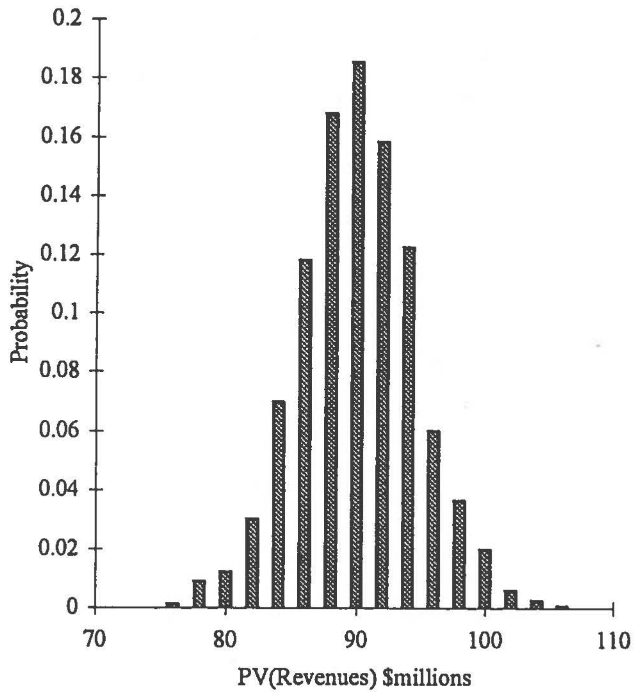


Figure 2
Langbeinite 350K Annual Production

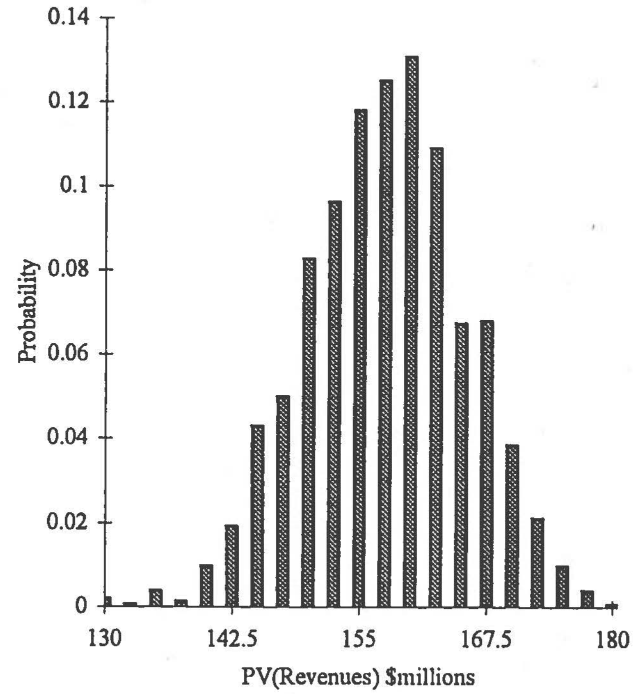


Figure 3
Langbeinite 500K Annual Production

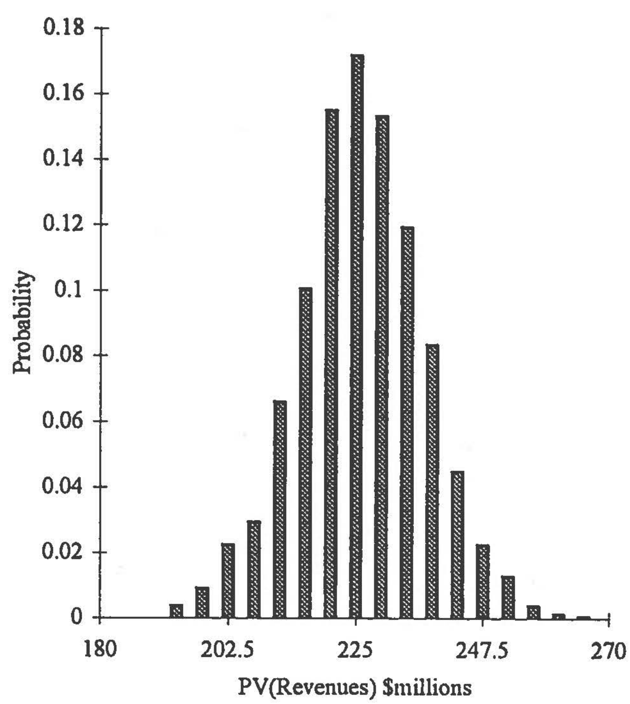


Figure 4
Langbeinite 1000K Annual Production

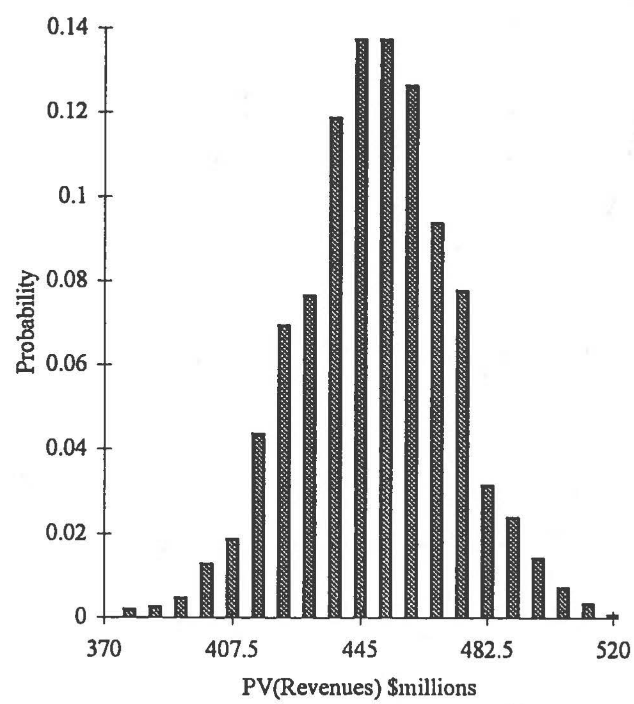


Figure 5
Sylvite 300K Annual Production

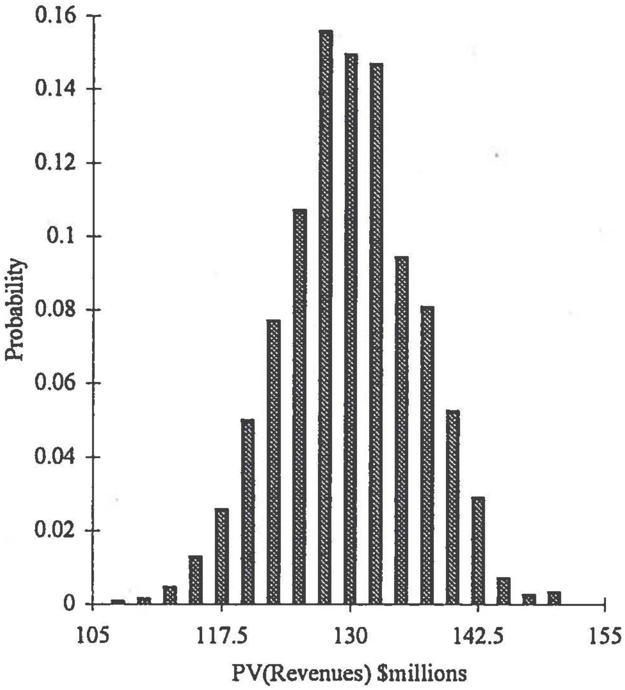


Figure 6
Sylvite 450K Annual Production

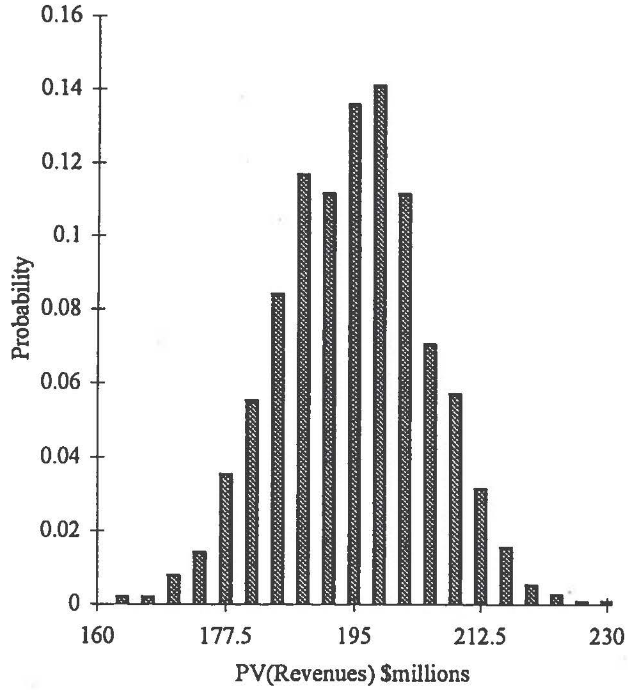


Figure 7
Sylvite 600K Annual Production

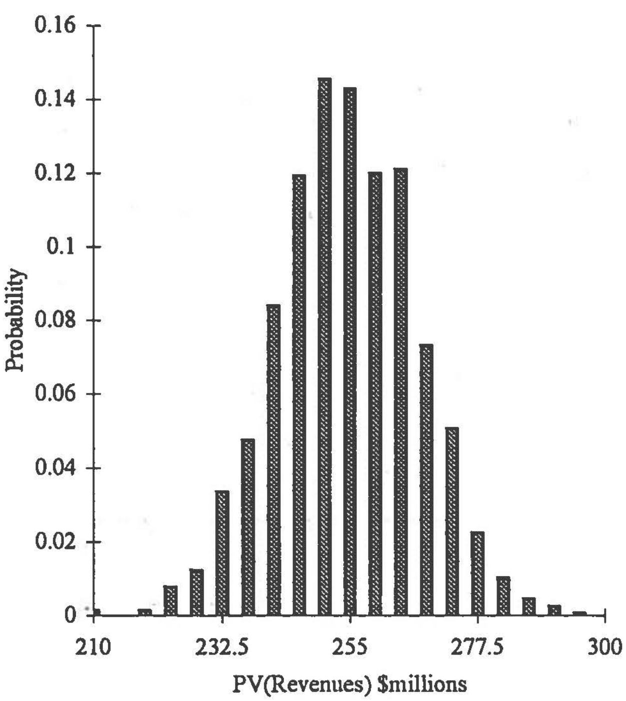


Figure 8
Sylvite 1000K Annual Production

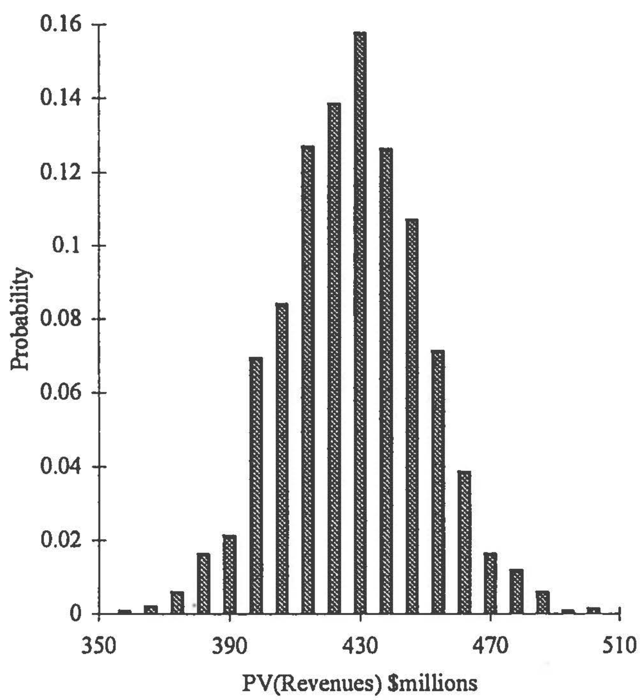


Figure 9
Langbeinite 200K Annual Production

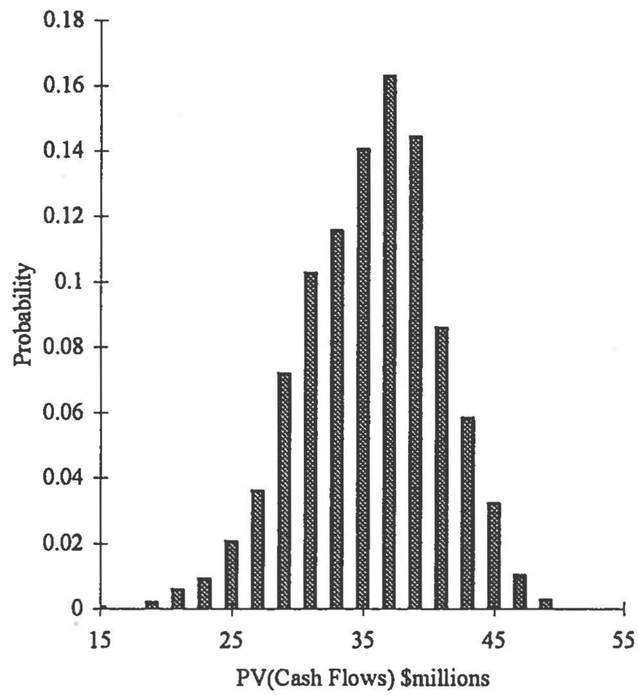


Figure 10
Langbeinite 350K Annual Production

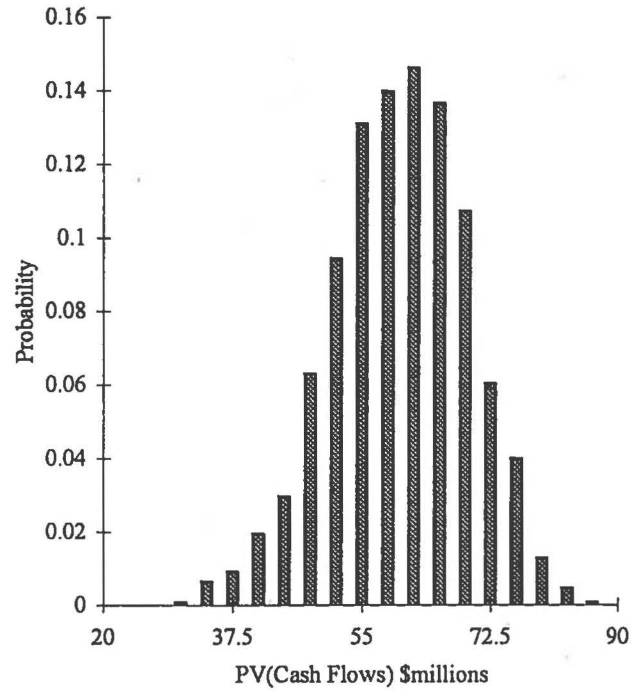


Figure 11
Langbeinite 500K Annual Production

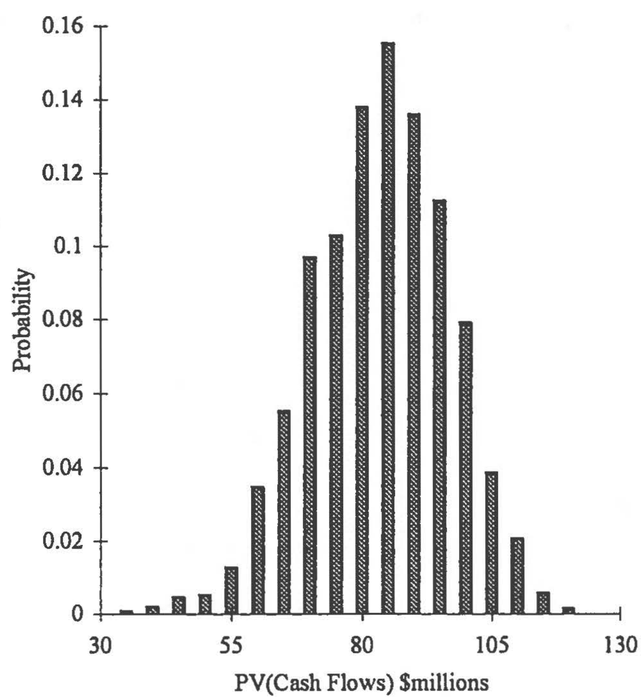


Figure 12
Langbeinite 1000K Annual Production

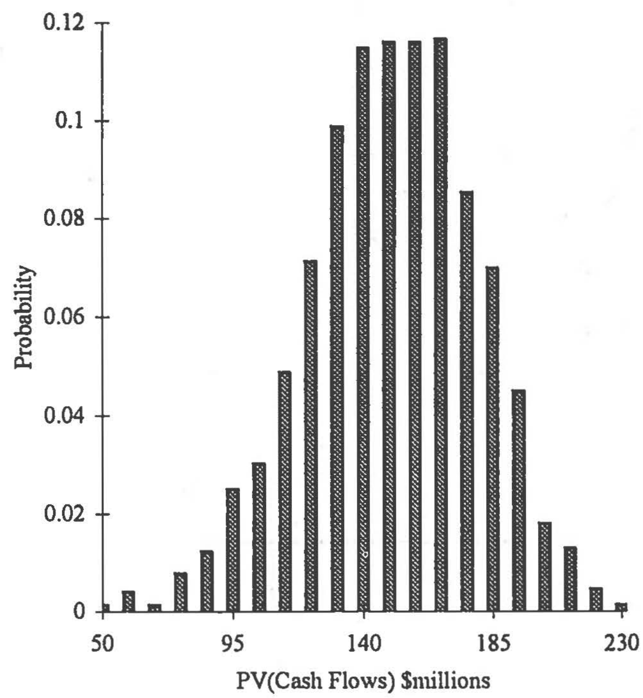


Figure 13
Sylvite 300K Annual Production

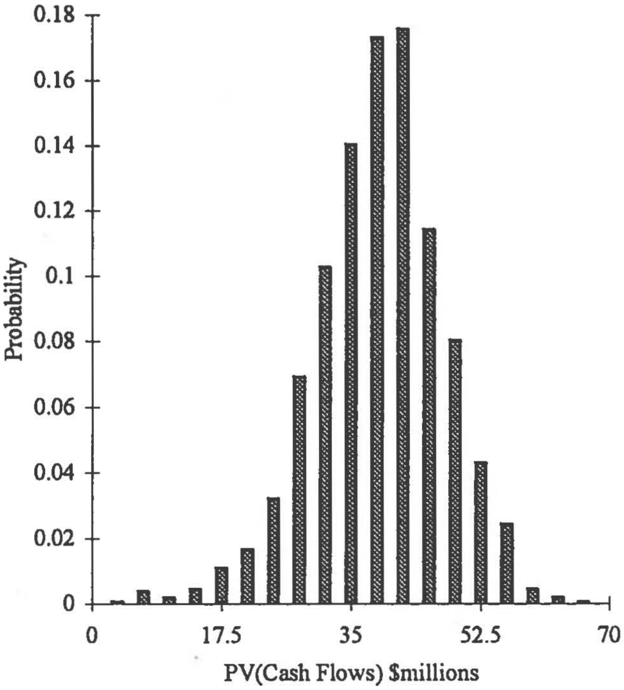


Figure 14
Sylvite 450K Annual Production

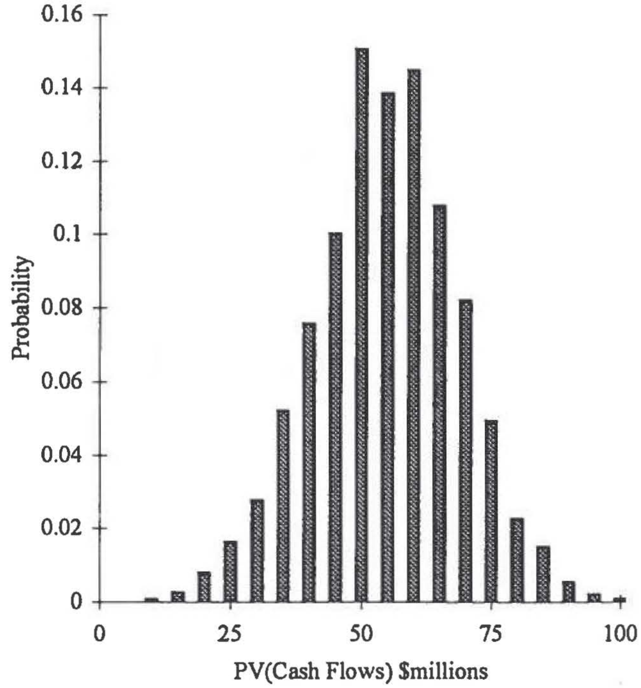


Figure 15
Sylvite 600K Annual Production

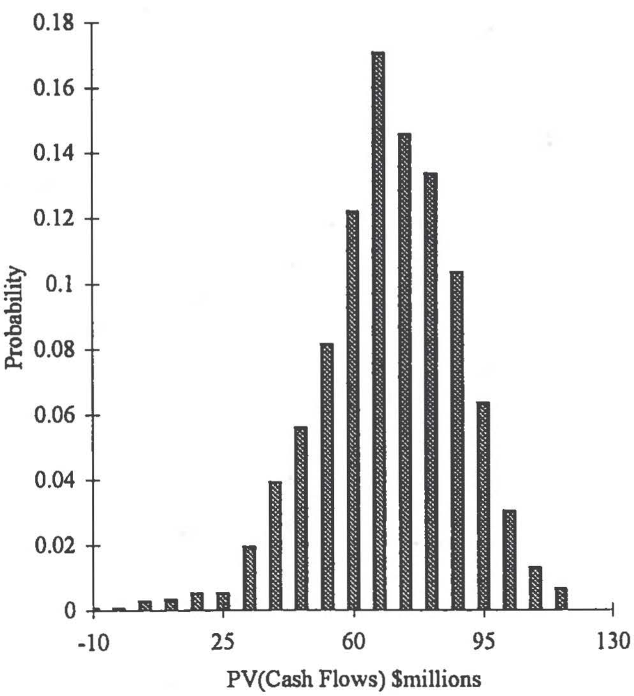


Figure 16
Sylvite 1000K Annual Production

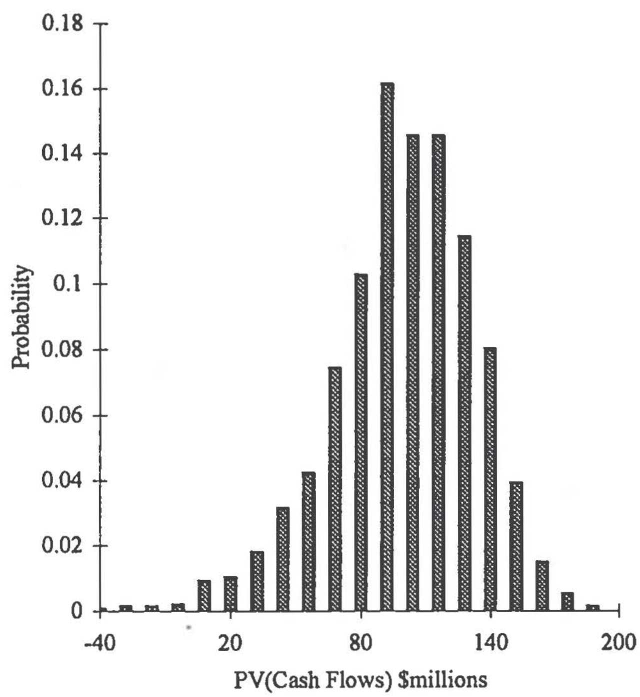


Figure 17
Sample Potash Price Paths

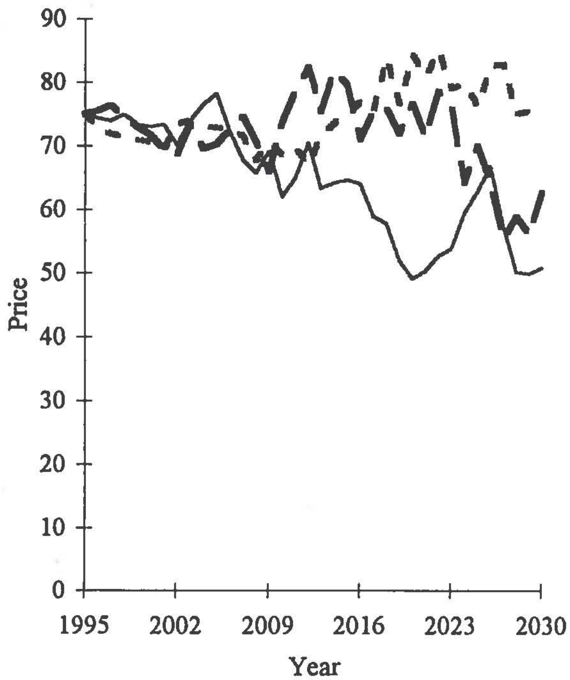


Figure 18
E(PV) of Langbeinite Revenues

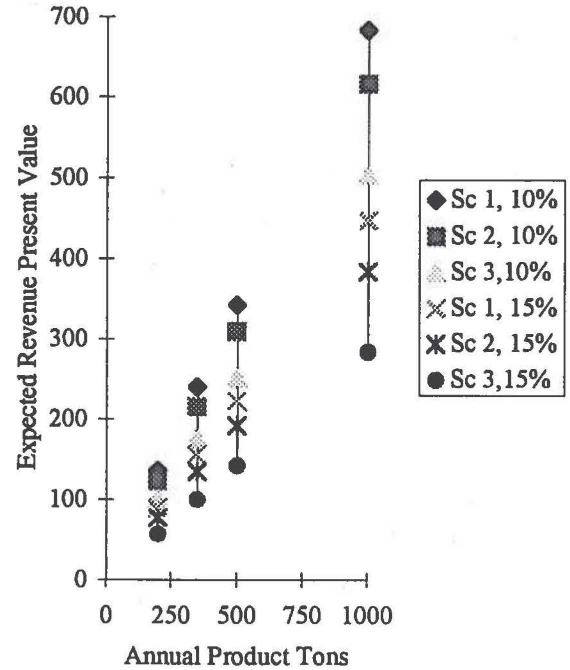


Figure 19
E(PV) of Sylvite Revenues

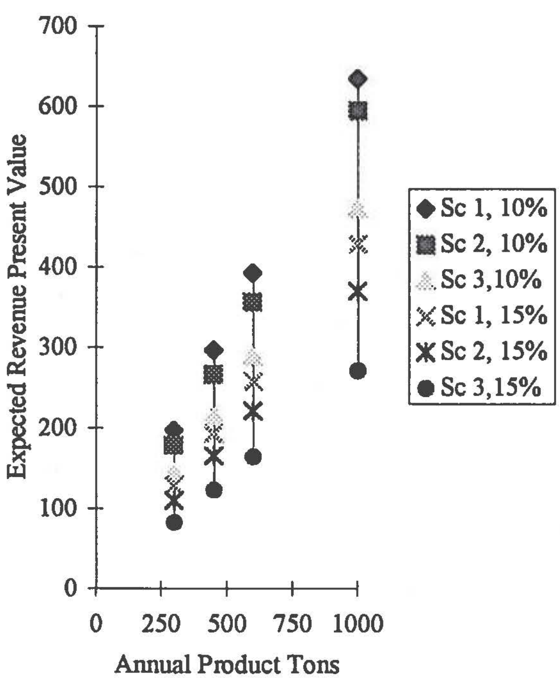


Figure 20
E(NPV) of Langbeinite Revenues

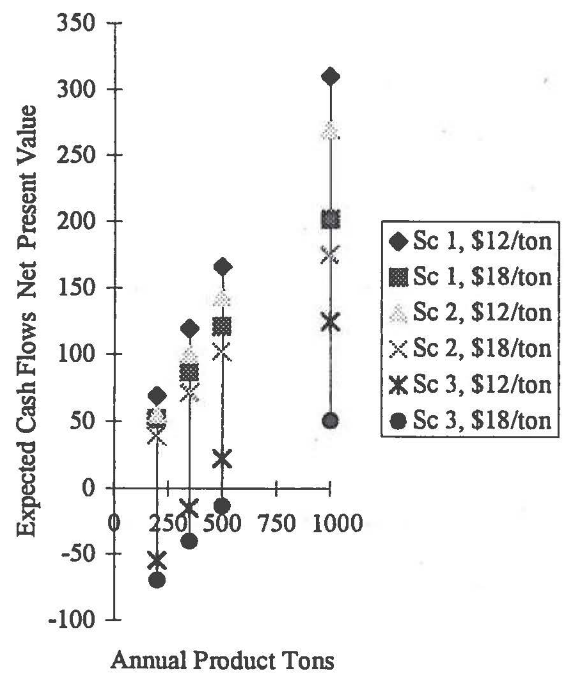
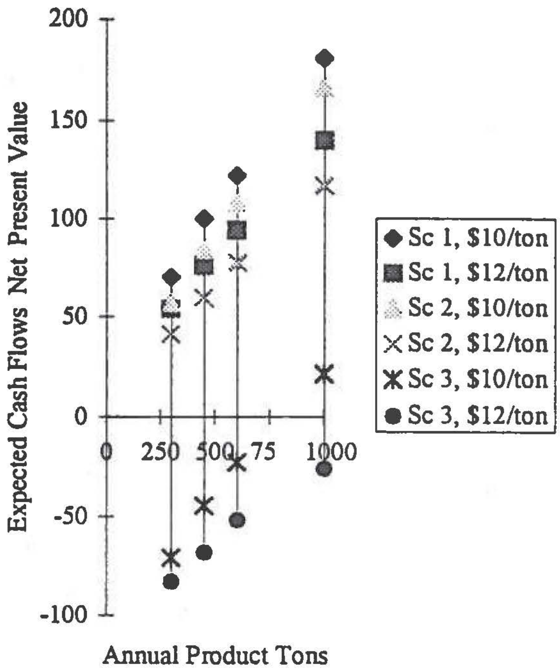


Figure 21
E(NPV) of Sylvite Revenues



200K ANNUAL LANGBEINITE PRODUCTION (All figures in millions of dollars)

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	89.2	103	74.2	89.1	4.38	0.037
PV Cash Flow	34.4	51.3	15.6	34.5	5.06	-0.118
PV Severance Tax	1.11	1.29	0.928	1.11	0.055	0.037
PV State Tax	1.53	2.34	0.668	1.53	0.247	-0.164
PV Corporate Tax	7.35	11.0	3.39	7.37	1.12	-0.196
PV Royalties	2.23	2.57	1.86	2.23	0.109	0.037

Table A1
15% Discount Rate: $18/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	88.9	104	73.1	88.8	4.38	-0.084
PV Cash Flow	38.1	53.4	18.1	38.1	4.78	-0.220
PV Severance Tax	1.11	1.30	0.914	1.11	0.055	-0.084
PV State Tax	1.71	2.44	0.852	1.71	0.231	-0.222
PV Corporate Tax	8.15	11.4	4.25	8.15	1.04	-0.248
PV Royalties	2.34	4.02	1.83	2.23	0.379	2.47

Table A2
15% Discount Rate: $16/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	88.9	107	75.5	88.8	4.33	0.174
PV Cash Flow	45.4	60.1	29.4	45.4	4.18	-0.010
PV Severance Tax	1.11	1.34	0.943	11.1	0.054	0.174
PV State Tax	2.06	2.76	1.27	2.06	0.201	-0.011
PV Corporate Tax	9.72	12.9	6.14	9.72	0.899	-0.018
PV Royalties	2.22	2.67	1.89	2.22	0.108	0.174

Table A3
15% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	76.8	91.6	62.9	76.6	4.27	0.113
PV Cash Flow	22.1	37.6	5.72	22.2	4.98	-0.055
PV Severance Tax	0.960	1.14	0.787	0.958	0.053	0.113
PV State Tax	1.24	1.98	0.466	1.24	0.243	-0.095
PV Corporate Tax	5.97	9.30	2.37	5.98	1.10	-0.130
PV Royalties	1.92	2.29	1.57	1.92	0.106	0.113

Table A4
15% Discount Rate: $18/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	76.7	90.4	63.0	76.7	4.25	0.002
PV Cash Flow	25.4	37.7	7.10	25.4	4.69	-0.187
PV Severance Tax	0.959	1.13	0.788	0.959	0.053	0.002
PV State Tax	1.39	1.98	0.490	1.40	0.227	-0.222
PV Corporate Tax	6.67	9.32	2.54	6.68	1.02	-0.247
PV Royalties	1.92	2.26	1.58	1.92	0.106	0.002

Table A5
15% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	76.7	92.6	60.7	76.6	4.54	0.008
PV Cash Flow	31.7	43.6	16.6	31.9	4.27	-0.190
PV Severance Tax	0.958	1.16	0.759	0.958	0.057	0.008
PV State Tax	1.70	2.27	0.959	1.71	0.205	-0.192
PV Corporate Tax	80.5	10.6	4.71	8.09	0.918	-0.199
PV Royalties	1.92	2.31	1.52	1.92	0.113	0.008

Table A6
15% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	56.9	69.5	42.8	56.7	4.18	0.098
PV Cash Flow	-77.4	-60.5	-94.3	-77.3	5.15	-0.040
PV Severance Tax	0.711	0.869	0.535	0.709	0.052	0.098
PV State Tax	0.220	0.605	0	0.219	0.106	0.082
PV Corporate Tax	1.06	2.84	0	1.06	0.486	0.028
PV Royalties	1.42	1.74	1.07	1.42	0.104	0.098

Table A7
15% Discount Rate: $18/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	56.7	70.0	37.8	56.9	4.18	-0.050
PV Cash Flow	-74.5	-59.6	-90.4	-74.4	4.89	-0.107
PV Severance Tax	0.709	0.875	0.472	0.711	0.052	-0.050
PV State Tax	0.253	0.581	0	0.255	0.103	0.008
PV Corporate Tax	1.21	2.70	0	1.22	0.471	-0.028
PV Royalties	1.42	1.75	0.944	1.42	0.105	-0.050

Table A8
15% Discount Rate: $16/ton

200K ANNUAL LANGBEINITE PRODUCTION (All figures in millions of dollars)

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	56.9	72.3	42.3	56.9	4.13	0.008
PV Cash Flow	-68.7	-53.7	-82.9	-68.7	4.34	-0.116
PV Severance Tax	0.711	0.904	0.529	0.711	0.052	0.008
PV State Tax	0.326	0.837	0.011	0.319	0.103	0.336
PV Corporate Tax	1.55	3.92	0.061	1.52	0.474	0.361
PV Royalties	1.42	1.81	1.06	1.42	0.103	0.008

Table A9
15% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	136	179	108	136	9.04	0.118
PV Cash Flow	51.8	82.1	18.3	51.7	9.75	-0.039
PV Severance Tax	1.71	2.23	1.35	1.71	0.113	0.118
PV State Tax	2.30	3.75	0.926	2.29	0.470	-0.005
PV Corporate Tax	11.0	17.6	4.61	11.0	2.13	-0.050
PV Royalties	3.41	4.47	2.69	3.41	0.226	0.118

Table A10
10% Discount Rate: $18/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	137	170	109	137	9.19	0.050
PV Cash Flow	57.7	87.0	20.1	58.3	9.70	-0.128
PV Severance Tax	1.71	2.13	1.36	1.71	0.115	0.050
PV State Tax	2.58	3.99	1.14	2.61	0.465	-0.091
PV Corporate Tax	12.3	18.6	5.55	12.5	2.10	-0.125
PV Royalties	3.42	4.25	2.71	3.42	0.230	0.050

Table A11
10% Discount Rate: $16/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	137	164	105	137	9.07	0.068
PV Cash Flow	69.5	94.3	40.8	69.3	8.37	-0.104
PV Severance Tax	1.71	2.05	1.32	1.71	0.113	0.068
PV State Tax	3.15	4.34	1.83	3.14	0.402	-0.106
PV Corporate Tax	14.9	20.2	8.79	14.8	1.80	-0.118
PV Royalties	3.42	4.09	2.64	3.42	0.227	0.068

Table A12
10% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	101	127	69.6	101	8.89	0.026
PV Cash Flow	-64.7	-36.7	-101	-64.9	9.85	-0.041
PV Severance Tax	1.26	1.59	0.870	1.26	0.111	0.026
PV State Tax	0.680	1.59	0	0.670	0.280	0.105
PV Corporate Tax	3.26	7.36	0	3.22	1.28	0.061
PV Royalties	2.52	3.17	1.74	2.51	0.222	0.026

Table A17
10% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	124	157	86.6	124	9.40	-0.027
PV Cash Flow	39.1	73.1	-2.15	38.9	9.82	-0.110
PV Severance Tax	1.54	1.96	1.08	1.55	0.117	-0.027
PV State Tax	1.98	3.62	0.632	1.98	0.474	-0.059
PV Corporate Tax	9.56	16.9	3.17	9.56	2.15	-0.109
PV Royalties	3.09	3.92	2.17	3.10	0.235	-0.027

Table A13
10% Discount Rate: $18/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	124	153	95.9	123	8.98	0.001
PV Cash Flow	44.4	72.0	15.1	44.2	9.16	-0.028
PV Severance Tax	1.54	1.91	1.20	15.4	0.112	0.001
PV State Tax	2.24	3.57	0.835	2.23	0.442	-0.028
PV Corporate Tax	10.7	16.7	4.18	10.7	1.99	-0.059
PV Royalties	3.09	3.82	2.40	3.09	0.225	0.001

Table A14
10% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	124	150	93.6	124	9.28	0.005
PV Cash Flow	54.9	80.2	26.8	54.8	8.49	0.044
PV Severance Tax	1.55	1.87	1.17	1.55	0.116	0.005
PV State Tax	2.75	3.96	1.47	2.74	0.407	-0.030
PV Corporate Tax	13.0	18.4	7.23	13.0	1.82	-0.411
PV Royalties	3.09	3.75	2.34	3.09	0.232	0.005

Table A15
10% Discount Rate: $12ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	100	128	71.5	101	9.11	-0.171
PV Cash Flow	-70.0	-33.1	-117	-69.3	10.8	-0.387
PV Severance Tax	1.26	1.60	0.894	1.26	0.114	-0.171
PV State Tax	0.584	1.71	0	0.601	0.288	-0.004
PV Corporate Tax	2.81	7.93	0	2.91	1.33	-0.072
PV Royalties	2.51	3.19	1.79	2.52	0.228	-0.171

Table A16
10% Discount Rate: $18/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	100	129	70.6	101	9.15	-0.004
PV Cash Flow	-55.0	-29.0	-92.9	-54.7	8.87	-0.139
PV Severance Tax	1.26	1.61	0.882	1.26	0.114	-0.004
PV State Tax	0.859	1.80	5.29	0.852	0.278	0.121
PV Corporate Tax	4.08	8.45	0.037	4.05	1.26	0.121
PV Royalties	2.51	3.21	1.76	2.52	0.229	-0.004

Table A18
10% Discount Rate: $12/ton

350K ANNUAL LANGBEINITE PRODUCTION (All figures in millions of dollars)

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	156	182	133	156	7.67	0.131
PV Cash Flow	58.1	88.3	27.0	58.3	9.00	-0.018
PV Severance Tax	1.95	2.27	1.67	1.95	0.096	0.131
PV State Tax	2.66	4.12	1.05	2.68	0.444	-0.084
PV Corporate Tax	12.4	18.9	4.98	12.5	2.00	-0.106
PV Royalties	3.89	4.54	3.23	3.89	192	0.131

Table A19
15% Discount Rate: $18/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	155	183	125	155	7.67	0.021
PV Cash Flow	63.8	93.0	32.2	64.0	9.01	-0.223
PV Severance Tax	1.94	2.29	1.56	1.94	0.096	0.021
PV State Tax	2.94	4.34	1.46	2.95	0.438	-0.247
PV Corporate Tax	13.7	19.9	6.89	13.7	1.97	-0.264
PV Royalties	3.88	4.57	3.13	3.88	0.192	0.021

Table A20
15% Discount Rate: $16/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	156	180	133	156	7.72	0.006
PV Cash Flow	77.1	100	43.4	77.9	8.69	-0.426
PV Severance Tax	1.95	2.24	1.66	1.95	0.096	0.006
PV State Tax	3.58	4.68	1.97	3.62	0.418	-0.444
PV Corporate Tax	16.5	21.5	9.26	16.7	1.87	-0.449
PV Royalties	3.90	4.49	3.32	3.90	0.193	0.006

Table A21
15% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	134	158	106	135	7.81	-0.044
PV Cash Flow	43.0	69.4	5.29	43.4	8.93	-0.173
PV Severance Tax	1.68	1.98	1.33	1.68	0.098	-0.436
PV State Tax	2.23	3.51	0.736	2.26	0.441	-0.218
PV Corporate Tax	10.4	16.1	3.55	10.5	1.98	-0.238
PV Royalties	3.36	3.95	2.65	3.36	0.195	-0.044

Table A22
15% Discount Rate: $18/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	135	161	106	134	7.59	-0.043
PV Cash Flow	48.8	74.5	12.5	49.2	8.41	-0.267
PV Severance Tax	1.68	2.02	1.33	1.68	0.095	-0.043
PV State Tax	2.51	3.75	1.05	2.54	0.408	-0.285
PV Corporate Tax	11.7	17.2	4.95	11.8	1.83	-0.302
PV Royalties	3.36	4.03	2.66	3.36	0.190	-0.043

Table A23
15% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	134	161	109	134	7.71	0.014
PV Cash Flow	60.1	81.9	34.4	60.2	7.60	-0.099
PV Severance Tax	1.68	2.02	1.36	1.68	0.096	0.137
PV State Tax	3.06	4.10	1.79	3.07	0.365	-0.100
PV Corporate Tax	14.1	18.8	8.41	14.2	1.63	-0.105
PV Royalties	3.36	4.04	2.72	3.36	0.193	0.014

Table A24
15% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	99.5	122	72.9	99.5	7.23	-0.080
PV Cash Flow	-59.2	-34.8	-91.9	-58.6	8.82	-0.282
PV Severance Tax	1.24	1.53	0.911	1.24	0.090	-0.080
PV State Tax	0.456	1.39	0	0.430	0.261	0.517
PV Corporate Tax	2.15	6.45	0	2.04	1.21	0.495
PV Royalties	2.49	3.06	1.82	2.49	0.181	-0.080

Table A25
15% Discount Rate: $18/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	99.7	128	77.5	99.5	7.16	0.091
PV Cash Flow	-54.3	-31.7	-88.5	-53.8	8.08	-0.331
PV Severance Tax	1.25	1.60	0.968	1.24	0.090	0.091
PV State Tax	0.565	1.50	0	0.531	0.283	0.355
PV Corporate Tax	2.66	6.90	0	2.50	1.31	0.325
PV Royalties	2.49	3.19	1.94	2.49	0.179	0.091

Table A26
15% Discount Rate: $16/ton

350K ANNUAL LANGBEINITE PRODUCTION (All figures in millions of dollars)

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	99.5	123	74.8	99.6	7.24	-0.035
PV Cash Flow	-45.2	-25.1	-75.2	-45.2	6.85	-0.215
PV Severance Tax	1.24	1.53	0.935	1.25	90.5	-0.035
PV State Tax	0.854	1.73	0	0.857	0.301	-0.017
PV Corporate Tax	4.01	7.97	0	4.03	1.38	-0.051
PV Royalties	2.49	3.07	1.87	2.49	0.181	0.035

Table A27
15% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	240	286	182	241	15.9	-0.091
PV Cash Flow	87.5	137	20.1	88.3	17.6	-0.200
PV Severance Tax	3.00	3.57	2.27	3.01	0.199	-0.091
PV State Tax	4.00	6.41	1.25	4.04	0.893	-0.159
PV Corporate Tax	18.7	29.4	5.94	18.9	3.85	-0.186
PV Royalties	5.99	7.14	4.54	6.01	0.398	-0.091

Table A28
10% Discount Rate: $18/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	240	284	191	239	16.2	-0.014
PV Cash Flow	98.7	144	37.2	99.0	17.2	-0.112
PV Severance Tax	3.00	3.55	2.38	2.99	0.203	-0.014
PV State Tax	4.55	6.72	1.94	4.56	0.827	-0.100
PV Corporate Tax	21.1	30.8	9.18	21.2	3.72	-0.117
PV Royalties	6.00	7.11	4.77	5.98	0.405	-0.014

Table A29
10% Discount Rate: $16/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	240	296	187	239	16.4	-0.056
PV Cash Flow	119	167	69.4	120	15.1	-0.092
PV Severance Tax	3.00	3.70	2.33	2.99	0.205	-0.056
PV State Tax	5.55	7.85	3.13	5.58	0.724	-0.083
PV Corporate Tax	25.6	35.9	14.7	25.7	3.24	-0.089
PV Royalties	6.00	7.40	4.67	5.99	0.410	-0.056

Table A30
10% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	216	281	168	216	15.9	0.021
PV Cash Flow	71.9	123	-11.0	72.7	17.4	-0.249
PV Severance Tax	2.70	3.51	2.10	2.70	198	0.021
PV State Tax	3.55	6.01	0.878	3.59	0.842	-0.158
PV Corporate Tax	16.6	27.6	4.34	16.8	3.80	-0.187
PV Royalties	5.41	7.02	4.19	5.40	0.397	0.021

Table A31
10% Discount Rate: $18/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	216	270	166	217	15.8	-0.033
PV Cash Flow	80.8	132	18.0	81.0	17.0	-0.142
PV Severance Tax	2.70	3.38	2.08	2.71	0.197	-0.033
PV State Tax	3.98	6.42	1.56	4.00	0.819	-0.118
PV Corporate Tax	18.1	29.4	7.35	18.6	3.68	-0.136
PV Royalties	5.41	6.75	4.16	5.42	0.394	-0.033

Table A32
10% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	217	276	166	217	16.0	-0.018
PV Cash Flow	100	151	44.5	100	14.8	-0.085
PV Severance Tax	2.71	3.45	2.08	2.71	0.200	-0.018
PV State Tax	4.91	7.36	2.30	4.91	0.711	-0.089
PV Corporate Tax	22.7	33.6	10.9	22.7	3.18	-0.096
PV Royalties	5.41	6.91	4.15	5.41	0.401	-0.018

Table A33
10% Discount Rate: $12ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	176	227	127	176	15.2	0.023
PV Cash Flow	-40.3	15.0	-125	-39.5	17.6	-0.240
PV Severance Tax	2.20	2.83	1.58	2.20	0.190	0.023
PV State Tax	1.11	3.56	0	1.07	0.623	0.389
PV Corporate Tax	5.23	16.3	0	5.03	2.87	0.361
PV Royalties	4.40	5.67	3.17	4.39	0.380	0.023

Table A34
10% Discount Rate: $18/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	176	218	121	177	16.0	-0.115
PV Cash Flow	-30.9	17.9	-87.1	-30.3	17.0	-0.279
PV Severance Tax	2.20	2.72	1.51	2.21	0.200	-0.115
PV State Tax	1.38	3.56	0	1.34	0.673	0.227
PV Corporate Tax	6.48	16.4	0	6.33	3.09	0.200
PV Royalties	4.40	5.45	3.02	4.42	0.399	-0.115

Table A35
10% Discount Rate: $16/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	176	221	123	176	15.8	-0.068
PV Cash Flow	-15.1	29.9	-75.2	-15.0	14.3	-0.119
PV Severance Tax	2.20	2.77	1.54	2.20	0.197	-0.068
PV State Tax	1.96	4.01	0.112	1.94	0.666	0.031
PV Corporate Tax	9.15	18.4	0.582	9.09	3.02	0.005
PV Royalties	4.40	5.53	3.08	4.40	0.394	-0.068

Table A36
10% Discount Rate: $12/ton

500K ANNUAL LANGBEINITE PRODUCTION (All figures in millions of dollars)

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	222	263	187	222	10.8	0.108
PV Cash Flow	81.2	120	31.8	81.8	13.2	-0.151
PV Severance Tax	10.7	112	2.34	2.80	23.9	2.83
PV State Tax	3.67	5.64	1.62	3.70	0.682	-0.035
PV Corporate Tax	16.0	25.8	1.87	17.1	4.93	-1.30
PV Royalties	6.73	24.0	4.68	5.59	3.66	2.96

Table A37
15% Discount Rate: $18/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	223	260	186	223	11.0	0.123
PV Cash Flow	91.0	133	49.6	91.3	12.4	-0.080
PV Severance Tax	11.7	120	2.32	2.80	27.1	2.76
PV State Tax	4.09	6.27	2.08	4.18	0.725	-0.287
PV Corporate Tax	17.9	28.6	2.88	19.2	5.24	-1.56
PV Royalties	6.99	25.7	4.64	5.61	4.34	2.82

Table A38
15% Discount Rate: $16/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	222	262	187	222	11.1	-0.061
PV Cash Flow	110	142	70.9	110	11.2	-0.087
PV Severance Tax	13.5	134	2.33	2.80	32.3	2.73
PV State Tax	4.93	6.69	2.43	5.11	0.884	-1.21
PV Corporate Tax	21.8	30.5	3.81	23.4	6.01	-2.00
PV Royalties	7.35	28.7	4.66	5.61	5.45	2.76

Table A39
15% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	192	226	158	192	10.7	0.041
PV Cash Flow	62.4	102	11.9	62.7	12.9	-0.119
PV Severance Tax	8.34	95.4	2.01	2.42	18.3	2.92
PV State Tax	3.08	5.06	0.946	3.09	0.650	0.009
PV Corporate Tax	13.4	23.1	1.35	14.3	4.39	-1.05
PV Royalties	5.76	21.7	4.01	4.84	3.04	3.07

Table A40
15% Discount Rate: $18/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	192	228	155	192	10.9	-0.015
PV Cash Flow	71.4	109	35.7	71.6	11.7	-0.136
PV Severance Tax	9.34	92.7	1.94	2.42	21.1	2.79
PV State Tax	3.48	5.40	1.78	3.53	0.654	-0.168
PV Corporate Tax	15.2	24.6	2.09	16.2	4.59	-1.40
PV Royalties	5.98	21.1	3.88	4.85	3.63	2.83

Table A41
15% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	192	223	159	193	10.9	-0.107
PV Cash Flow	88.1	122	52.2	88.4	10.6	-0.213
PV Severance Tax	2.41	2.79	2.00	2.41	0.136	-0.107
PV State Tax	4.40	6.03	2.63	4.42	0.510	-0.220
PV Corporate Tax	20.1	27.4	12.1	20.2	2.28	-0.223
PV Royalties	4.81	5.58	3.98	4.81	0.272	-0.107

Table A42
15% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	142	171	104	143	10.3	-0.108
PV Cash Flow	-42.8	-8.29	-87.7	41.8	12.2	-0.429
PV Severance Tax	1.78	2.14	130	1.78	0.129	-0.108
PV State Tax	0.823	2.34	0	0.797	0.492	0.268
PV Corporate Tax	3.85	10.7	0	3.74	2.26	0.237
PV Royalties	3.56	4.28	2.60	3.56	0.257	-0.108

Table A43
15% Discount Rate: $18/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	142	173	105	142	10.3	-0.038
PV Cash Flow	-36.4	5.24	-75.3	-36.0	11.3	-0.158
PV Severance Tax	1.78	2.16	1.31	1.78	0.129	-0.038
PV State Tax	1.06	3.06	0	1.06	0.523	0.146
PV Corporate Tax	4.93	14.0	0	4.95	2.39	0.116
PV Royalties	3.56	4.31	2.63	3.56	0.257	-0.038

Table A44
15% Discount Rate: $16/ton

500K ANNUAL LANGBEINITE PRODUCTION (All figures in millions of dollars)

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	142	175	104	142	10.2	0.029
PV Cash Flow	-23.4	5.69	-58.3	-23.3	9.51	-0.105
PV Severance Tax	1.78	2.19	1.30	1.78	0.127	0.029
PV State Tax	1.65	3.07	0.124	1.66	0.472	-0.198
PV Corporate Tax	7.62	14.1	0.650	7.68	2.13	-0.218
PV Royalties	3.56	4.38	2.60	3.56	0.255	0.029

Table A45
15% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	342	410	275	341	22.5	0.130
PV Cash Flow	121	194	40.2	121	25.3	-0.075
PV Severance Tax	16.1	178	3.43	4.31	36.4	2.90
PV State Tax	5.46	9.12	2.14	5.44	1.23	0.150
PV Corporate Tax	23.8	41.6	2.12	25.1	8.01	-0.854
PV Royalties	10.3	38.2	6.87	8.61	5.59	3.08

Table A46
10% Discount Rate: $18/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	342	435	271	343	22.9	0.054
PV Cash Flow	137	214	54.5	137	24.3	-0.168
PV Severance Tax	17.7	196	3.39	4.32	40.9	2.82
PV State Tax	6.18	10.1	2.71	6.25	1.27	-0.039
PV Corporate Tax	27.0	45.9	3.65	28.7	8.49	-1.17
PV Royalties	10.7	42.0	6.78	8.64	6.52	2.90

Table A47
10% Discount Rate: $16/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	341	420	266	340	22.5	0.071
PV Cash Flow	166	230	80.2	167	21.1	-0.066
PV Severance Tax	20.6	208	3.32	4.29	49.3	2.74
PV State Tax	7.44	10.9	3.58	7.67	1.43	-0.754
PV Corporate Tax	32.9	49.4	5.61	35.1	9.41	-1.68
PV Royalties	11.3	44.5	6.64	8.58	8.32	2.77

Table A48
10% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	309	388	223	309	22.6	0.122
PV Cash Flow	102	175	-18.2	103	26.2	-0.296
PV Severance Tax	13.7	175	2.79	3.90	30.9	3.03
PV State Tax	4.87	8.46	1.42	4.86	1.24	-0.009
PV Corporate Tax	21.1	38.6	1.39	22.4	7.61	-0.695
PV Royalties	9.26	38.8	5.58	7.80	5.01	3.23

Table A49
10% Discount Rate: $18/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	308	393	238	308	23.4	0.065
PV Cash Flow	114	206	26.9	114	24.8	-0.039
PV Severance Tax	3.85	4.92	2.98	3.85	0.292	0.065
PV State Tax	5.57	10.0	1.71	5.59	1.20	-0.054
PV Corporate Tax	25.6	45.5	8.02	25.7	5.40	-0.069
PV Royalties	7.70	9.84	5.96	7.71	0.584	0.065

Table A50
10% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	309	395	231	309	22.9	0.023
PV Cash Flow	143	209	73.4	144	21.5	-0.148
PV Severance Tax	3.87	4.93	2.89	3.87	0.286	0.023
PV State Tax	6.98	10.1	3.43	7.02	1.03	-0.143
PV Corporate Tax	31.9	46.1	15.9	32.1	4.63	-0.149
PV Royalties	7.73	9.87	5.79	7.74	0.572	0.023

Table A51
10% Discount Rate: $12ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	252	333	179	252	22.6	-0.004
PV Cash Flow	-13.0	82.7	-128	-11.5	25.6	-0.474
PV Severance Tax	3.15	4.16	2.24	3.15	0.283	-0.004
PV State Tax	1.87	6.37	0	1.83	1.06	0.278
PV Corporate Tax	8.68	29.0	0	8.50	4.86	0.244
PV Royalties	6.29	8.32	4.48	6.29	0.566	-0.004

Table A52
10% Discount Rate: $18/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	251	322	184	251	22.2	-0.013
PV Cash Flow	-0.836	61.5	-87.5	-0.382	23.0	-0.178
PV Severance Tax	3.14	4.03	2.30	3.14	0.277	-0.013
PV State Tax	2.35	5.48	0	2.34	1.09	0.063
PV Corporate Tax	10.9	25.0	0	10.9	4.96	0.034
PV Royalties	6.28	8.06	4.61	6.29	0.555	-0.013

Table A53
10% Discount Rate: $16/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	252	325	184	252	22.4	-0.052
PV Cash Flow	21.9	90.2	-56.1	22.5	20.4	-0.100
PV Severance Tax	3.14	4.06	2.31	3.15	0.280	-0.052
PV State Tax	3.42	6.75	0.055	3.45	1.01	-0.145
PV Corporate Tax	15.8	30.8	0.289	15.9	4.55	-0.161
PV Royalties	6.29	8.12	4.61	6.30	0.560	-0.052

Table A54
10% Discount Rate: $12/ton

1000K ANNUAL LANGBEINITE PRODUCTION (All figures in millions of dollars)

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	446	519	376	446	22.3	4.37×10^{-5}
PV Cash Flow	146	231	15.0	146	29.7	-0.306
PV Severance Tax	5.58	6.48	4.70	5.58	0.279	4.37×10^{-5}
PV State Tax	6.89	11.0	2.74	6.86	1.36	-0.058
PV Corporate Tax	31.3	49.6	12.5	31.2	6.10	-0.067
PV Royalties	11.2	13.0	9.40	11.2	0.558	4.37×10^{-5}

Table A55
15% Discount Rate: $18/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	447	509	378	447	21.7	-0.026
PV Cash Flow	168	246	36.2	170	27.1	-0.335
PV Severance Tax	5.58	6.37	4.73	5.59	0.271	-0.026
PV State Tax	7.97	11.7	3.17	8.04	1.26	-0.172
PV Corporate Tax	36.1	52.9	14.5	36.4	5.63	-0.179
PV Royalties	11.2	12.7	9.46	11.2	0.542	-0.026

Table A56
15% Discount Rate: $16/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	446	520	371	446	22.4	-0.018
PV Cash Flow	211	278	132	212	24.0	-0.254
PV Severance Tax	5.57	6.50	4.64	5.58	0.280	-0.018
PV State Tax	10.0	13.2	6.64	10.1	1.13	-0.171
PV Corporate Tax	45.4	59.6	30.2	45.5	5.08	-0.175
PV Royalties	11.2	13.0	9.29	11.2	0.559	-0.018

Table A57
15% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	384	453	302	385	21.5	-0.027
PV Cash Flow	119	218	0.765	120	28.4	-0.210
PV Severance Tax	4.80	5.67	3.78	4.81	0.268	-0.027
PV State Tax	5.89	10.6	2.04	5.91	1.32	-0.027
PV Corporate Tax	26.8	48.0	9.38	26.8	5.91	-0.035
PV Royalties	9.61	11.3	7.56	9.62	0.537	-0.027

Table A58
15% Discount Rate: $18/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	383	466	310	384	21.9	0.030
PV Cash Flow	137	219	43.6	138	26.1	-0.123
PV Severance Tax	4.79	5.82	3.88	4.80	0.274	0.030
PV State Tax	6.75	10.7	2.73	6.78	1.23	-0.057
PV Corporate Tax	30.6	48.2	12.5	30.8	5.53	-0.064
PV Royalties	9.59	11.6	7.75	9.59	0.548	0.030

Table A59
15% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	383	457	308	382	21.3	0.085
PV Cash Flow	173	250	88.5	174	21.6	-0.169
PV Severance Tax	4.78	5.71	3.85	4.77	0.266	0.085
PV State Tax	8.49	12.2	4.64	8.51	1.03	-0.118
PV Corporate Tax	38.4	55.0	21.2	38.5	4.61	-0.121
PV Royalties	9.57	11.4	7.71	9.54	0.533	0.085

Table A60
15% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	283	363	229	283	20.4	0.097
PV Cash Flow	-1.33	75.4	-100	0.350	24.5	-0.392
PV Severance Tax	3.54	4.54	2.86	3.54	0.255	0.097
PV State Tax	2.48	6.47	0	2.56	1.32	-0.021
PV Corporate Tax	11.4	29.3	0	11.7	5.96	-0.042
PV Royalties	7.08	9.07	5.72	7.08	0.510	0.097

Table A61
15% Discount Rate: $18/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	284	351	219	283	20.8	0.022
PV Cash Flow	12.9	84.7	-62.3	13.8	22.7	-0.221
PV Severance Tax	3.55	4.39	2.73	3.54	0.260	0.022
PV State Tax	3.34	6.98	0	3.46	1.26	-0.371
PV Corporate Tax	15.2	31.5	0	15.8	5.67	-0.387
PV Royalties	7.10	8.79	5.47	7.08	0.520	0.022

Table A62
15% Discount Rate: $16/ton

1000K ANNUAL LANGBEINITE PRODUCTION (All figures in millions of dollars)

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	284	357	218	284	20.4	0.026
PV Cash Flow	39.5	112	-36.7	39.4	19.9	-0.069
PV Severance Tax	3.55	4.46	2.73	3.55	0.254	0.026
PV State Tax	4.80	8.29	1.43	4.80	0.965	-0.112
PV Corporate Tax	21.8	37.4	6.63	21.8	4.32	-0.115
PV Royalties	7.11	8.92	5.46	7.10	0.509	0.026

Table A63
15% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	683	875	517	683	45.3	0.031
PV Cash Flow	202	362	-18.3	205	58.7	-0.315
PV Severance Tax	8.54	10.9	6.46	8.54	0.566	0.031
PV State Tax	9.74	17.2	3.23	9.67	2.40	0.214
PV Corporate Tax	44.3	77.6	14.8	44.0	10.8	0.204
PV Royalties	17.1	21.9	12.9	17.1	1.13	0.031

Table A64
10% Discount Rate: $18/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	683	863	553	682	45.3	0.078
PV Cash Flow	237	442	10.1	239	54.8	-0.287
PV Severance Tax	8.54	10.8	6.91	8.53	0.566	0.078
PV State Tax	11.3	21.0	4.77	11.3	2.39	0.079
PV Corporate Tax	51.3	94.8	21.8	51.1	10.7	0.071
$4.9x10^{-4}$						
PV Royalties	17.1	21.6	13.8	17.1	1.13	0.078

Table A65
10% Discount Rate: $16/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	683	823	526	684	44.8	-0.011
PV Cash Flow	310	443	131	311	46.2	-0.214
PV Severance Tax	8.54	10.3	6.58	8.55	0.560	-0.011
PV State Tax	14.7	21.1	7.82	14.7	2.15	-0.059
PV Corporate Tax	66.5	95.0	35.6	66.5	9.65	-0.065
PV Royalties	17.1	20.6	13.2	17.1	1.12	-0.011

Table A66
10% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	617	781	474	617	44.3	0.094
PV Cash Flow	175	335	-62.1	179	59.9	-0.430
PV Severance Tax	7.72	9.76	5.93	7.71	0.554	0.094
PV State Tax	8.73	16.2	2.36	8.71	2.48	0.091
PV Corporate Tax	39.7	73.2	10.9	39.6	11.2	0.082
PV Royalties	15.4	19.5	11.9	15.4	1.11	0.094

Table A67
10% Discount Rate: $18/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	618	794	481	617	45.0	0.146
PV Cash Flow	208	364	-45.3	212	55.8	-0.355
PV Severance Tax	7.72	9.93	6.01	7.71	0.563	0.146
PV State Tax	10.2	17.6	3.12	10.3	2.42	0.034
PV Corporate Tax	46.5	79.3	14.4	46.7	10.9	0.026
PV Royalties	15.4	19.9	12.0	15.4	1.13	0.146

Table A68
10% Discount Rate: $16/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	617	811	481	619	45.7	0.049
PV Cash Flow	270	445	124	270	45.5	-0.087
PV Severance Tax	7.71	10.1	6.01	7.73	0.572	0.049
PV State Tax	13.1	21.5	5.76	13.1	2.14	0.005
PV Corporate Tax	59.3	96.7	26.3	59.1	9.59	-
PV Royalties	15.4	20.3	12.0	15.5	1.14	0.049

Table A69
10% Discount Rate: $12ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	502	647	340	502	45.6	-0.025
PV Cash Flow	50.8	208	-140	53.5	53.2	-0.351
PV Severance Tax	6.28	8.09	4.25	6.28	0.570	-0.025
PV State Tax	4.64	12.6	0	4.68	2.51	0.170
PV Corporate Tax	21.2	56.8	0	21.5	11.3	0.151
PV Royalties	12.6	16.2	8.49	12. 6	1.14	-0.025

Table A70
10% Discount Rate: $18/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	502	652	347	503	44.2	-0.028
PV Cash Flow	75.1	226	-121	77.1	49.4	-0.342
PV Severance Tax	6.28	8.14	4.33	6.29	0.553	-0.028
PV State Tax	5.99	13.4	0	6.03	2.40	-0.105
PV Corporate Tax	27.3	60.5	0	27.5	10.8	-0.120
PV Royalties	12.6	16.3	8.67	12.6	1.11	-0.028

Table A71
10% Discount Rate: $16/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	501	650	356	500	44.0	0.091
PV Cash Flow	125	260	-63.8	125	42.1	-0.060
PV Severance Tax	6.26	8.12	4.45	6.25	0.550	0.091
PV State Tax	8.56	15.0	0.270	8.52	2.00	0.023
PV Corporate Tax	38.8	67.8	1.36	38.7	8.96	0.017
PV Royalties	12.5	16.2	8.91	12.5	1.10	0.091

Table A72
10% Discount Rate: $12/ton

300K ANNUAL SYLVITE PRODUCTION (All figures in millions of dollars)

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	129	151	99.7	128	6.80	0.017
PV Cash Flow	36.7	62.6	2.69	37.1	8.97	-0.320
PV Severance Tax	1.61	1.89	1.25	1.60	0.085	0.017
PV State Tax	1.61	2.89	0.446	1.63	0.449	-0.157
PV Corporate Tax	7.67	13.4	2.23	7.80	2.05	-0.205
PV Royalties	3.21	3.78	2.49	3.21	0.170	0.017

Table A73
15% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	128	752	101	129	6.82	-0.125
PV Cash Flow	47.0	71.7	18.9	47.2	7.91	-0.190
PV Severance Tax	1.61	1.91	1.27	1.61	0.085	-0.125
PV State Tax	2.13	3.32	0.905	2.14	0.388	-0.204
PV Corporate Tax	10.0	15.4	4.35	10.1	1.75	-0.237
PV Royalties	3.21	3.81	2.53	3.22	0.170	-0.125

Table A74
15% Discount Rate: $10/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	111	136	92.1	111	6.58	0.134
PV Cash Flow	24.6	49.6	-4.15	24.8	8.66	-0.165
PV Severance Tax	1.38	1.70	1.15	1.38	0.082	0.134
PV State Tax	1.32	2.56	0.202	1.34	0.440	-0.068
PV Corporate Tax	6.31	11.9	1.07	6.41	2.02	-0.121
PV Royalties	2.77	3.40	2.30	2.76	0.164	0.134

Table A75
15% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	110	133	91.2	110	6.50	0.075
PV Cash Flow	33.2	59.7	4.36	33.4	7.53	-0.161
PV Severance Tax	1.38	1.66	1.14	1.38	0.081	0.075
PV State Tax	1.76	3.04	0.579	1.78	0.371	-0.185
PV Corporate Tax	8.31	14.1	2.82	8.40	1.68	-0.218
PV Royalties	2.76	3.32	2.28	2.76	0.162	0.075

Table A76
15% Discount Rate: $10/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	178	241	131	178	13.6	0.113
PV Cash Flow	41.1	103	-32.7	42.3	16.6	-0.338
PV Severance Tax	2.23	3.01	1.64	2.23	0.170	0.113
PV State Tax	2.05	5.08	0.309	2.06	0.782	0.070
PV Corporate Tax	9.79	23.4	1.57	9.88	3.59	0.016
PV Royalties	4.46	6.02	3.28	4.45	0.341	0.113

Table A81
10% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	179	232	133	179	15.2	0.221
PV Cash Flow	56.6	110	1.84	56.4	16.0	-0.122
PV Severance Tax	2.24	2.90	1.67	2.24	0.190	0.221
PV State Tax	2.79	5.07	0.596	2.79	0.746	-0.099
PV Corporate Tax	13.2	23.5	2.88	13.2	3.39	-0.134
PV Royalties	4.49	5.80	3.33	4.47	0.379	0.221

Table A82
10% Discount Rate: $10/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	81.7	106	59.3	81.8	6.22	-0.077
PV Cash Flow	-90.2	-64.2	-120	-89.5	8.80	-0.302
PV Severance Tax	1.02	1.32	0.742	1.02	0.078	-0.077
PV State Tax	0.211	0.949	0	0.202	0.161	0.529
PV Corporate Tax	1.01	4.40	0	0.980	0.749	0.486
PV Royalties	2.04	2.64	1.48	2.05	0.155	-0.077

Table A77
15% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	82.0	102	59.7	82.0	6.25	-0.078
PV Cash Flow	-82.3	-60.6	-123	-81.8	7.99	-0.398
PV Severance Tax	1.02	1.27	0.746	1.03	0.078	-0.078
PV State Tax	0.318	1.01	0	0.311	0.183	0.404
PV Corporate Tax	1.51	4.73	0	1.48	0.847	0.391
PV Royalties	2.05	2.55	1.49	2.05	0.156	-0.078

Table A78
15% Discount Rate: $10/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	198	243	146	198	13.6	-0.096
PV Cash Flow	54.5	104	-28.0	55.4	16.6	-0.427
PV Severance Tax	2.47	3.04	1.83	2.47	0.170	-0.096
PV State Tax	2.40	4.83	0.549	2.43	0.777	-0.006
PV Corporate Tax	11.4	22.4	2.71	11.6	3.57	-0.053
PV Royalties	4.94	6.08	3.65	4.94	0.341	-0.096

Table A79
10% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	197	252	143	198	13.5	-0.101
PV Cash Flow	70.4	137	8.15	71.2	15.1	-0.284
PV Severance Tax	2.47	3.15	1.79	2.47	0.169	-0.101
PV State Tax	3.18	6.41	1.12	3.22	0.729	-0.177
PV Corporate Tax	15.0	29.5	5.41	15.2	3.31	-0.213
PV Royalties	4.93	6.30	3.58	4.94	0.338	-0.101

Table A80
10% Discount Rate: $10/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	145	186	108	145	13.3	0.101
PV Cash Flow	-83.2	-28.1	-158	-82.3	17.6	-0.392
PV Severance Tax	1.81	2.33	1.35	1.81	0.167	0.101
PV State Tax	0.585	2.48	0	0.548	0.439	0.535
PV Corporate Tax	2.79	11.5	0	2.65	2.04	0.489
PV Royalties	3.62	4.66	2.71	3.62	0.333	0.101

Table A83
10% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	145	184	94.2	145	13.4	-0.044
PV Cash Flow	-70.9	-32.3	-141	-70.2	16.3	-0.380
PV Severance Tax	1.81	2.30	1.18	1.81	0.168	-0.044
PV State Tax	0.807	2.34	0	0.791	0.477	0.344
PV Corporate Tax	3.82	10.8	0	3.75	2.20	0.311
PV Royalties	3.62	4.60	2.35	3.62	0.336	-0.044

Table A84
10% Discount Rate: $10/ton

450K ANNUAL SYLVITE PRODUCTION (All figures in millions of dollars)

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	193	228	164	192	9.79	-0.028
PV Cash Flow	52.1	98.6	1.53	52.9	13.9	-0.280
PV Severance Tax	2.41	2.85	2.05	2.41	0.122	-0.028
PV State Tax	2.33	4.61	0.697	2.36	0.681	-0.032
PV Corporate Tax	10.9	21.1	3.30	11.1	3.10	-0.067
PV Royalties	4.82	5.70	4.09	4.81	0.245	0.028

Table A85
15% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	193	225	162	193	9.83	0.050
PV Cash Flow	68.3	103	22.0	68.6	12.1	-0.176
PV Severance Tax	2.41	2.81	2.03	2.41	0.123	0.050
PV State Tax	3.14	4.80	1.23	3.17	0.595	-0.193
PV Corporate Tax	14.6	22.0	5.69	14.7	2.68	-0.214
PV Royalties	4.82	5.62	4.06	4.81	0.246	0.050

Table A86
15% Discount Rate: $10/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	166	195	137	166	9.64	0.096
PV Cash Flow	37.4	73.8	-13.7	38.1	12.8	-0.313
PV Severance Tax	2.07	2.44	1.71	2.07	0.120	0.096
PV State Tax	1.91	3.72	0.305	1.95	0.646	-0.078
PV Corporate Tax	8.93	17.1	1.48	9.15	2.94	-0.109
PV Royalties	4.15	4.88	3.42	4.14	0.241	0.096

Table A87
15% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	166	196	135	165	9.97	0.045
PV Cash Flow	50.8	90.0	4.15	50.9	12.0	-0.103
PV Severance Tax	2.07	2.45	1.69	2.07	0.125	0.045
PV State Tax	2.59	4.49	0.830	2.61	0.596	-0.120
PV Corporate Tax	12.0	20.5	3.98	12.1	2.69	-0.143
PV Royalties	4.14	4.90	3.37	4.13	0.249	0.045

Table A88
15% Discount Rate: $10/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	266	343	206	266	20.3	0.132
PV Cash Flow	58.8	134	-44.6	60.6	26.4	-0.415
PV Severance Tax	3.32	4.29	2.57	3.32	0.253	0.132
PV State Tax	2.88	6.54	0.314	2.88	1.20	0.145
PV Corporate Tax	13.5	30.0	1.53	13.6	5.46	0.109
PV Royalties	6.65	8.58	5.15	6.65	0.507	0.132

Table A93
10% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	268	342	208	267	20.3	0.091
PV Cash Flow	83.9	163	-5.06	84.5	22.9	-0.122
PV Severance Tax	3.35	4.27	2.60	3.34	0.253	0.091
PV State Tax	4.12	7.94	1.01	4.15	1.10	0.018
PV Corporate Tax	19.1	36.2	4.85	19.3	4.96	-0.007
PV Royalties	6.69	8.54	5.20	6.68	0.507	0.091

Table A94
10% Discount Rate: $10/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	123	152	92.0	123	9.19	0.015
PV Cash Flow	-78.4	-41.4	-128	-77.5	13.5	-0.371
PV Severance Tax	1.54	1.90	1.15	1.54	0.115	0.015
PV State Tax	0.334	1.64	0	0.280	0.304	1.07
PV Corporate Tax	1.58	7.60	0	1.34	1.41	1.04
PV Royalties	3.07	3.80	2.30	3.08	0.230	0.015

Table A89
15% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	123	152	96.0	122	9.23	0.123
PV Cash Flow	-67.3	-34.7	-111	-66.5	11.3	-0.426
PV Severance Tax	1.53	1.89	1.20	1.53	0.115	0.123
PV State Tax	0.552	1.94	0	0.510	0.368	0.609
PV Corporate Tax	2.60	8.92	0	2.41	1.70	0.515
PV Royalties	3.07	3.78	2.40	3.06	0.231	0.123

Table A90
15% Discount Rate: $10/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	296	366	226	296	20.4	0.050
PV Cash Flow	75.8	148	-21.3	77.2	26.3	-0.350
PV Severance Tax	3.70	4.58	2.83	3.70	0.255	0.050
PV State Tax	3.40	6.92	0.653	3.40	1.22	0.085
PV Corporate Tax	15.9	31.7	3.13	15.9	5.57	0.053
PV Royalties	7.40	9.15	5.66	7.40	0.509	0.050

Table A91
10% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	296	375	215	296	20.3	-0.035
PV Cash Flow	99.5	167	21.3	100	23.7	-0.302
PV Severance Tax	3.70	4.68	2.69	3.70	0.254	-0.035
PV State Tax	4.58	7.82	1.39	4.61	1.12	-0.105
PV Corporate Tax	21.2	35.8	6.62	21.4	5.06	-0.130
PV Royalties	7.40	9.37	5.37	7.41	0.507	-0.035

Table A92
10% Discount Rate: $10/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	216	284	149	215	20.1	0.099
PV Cash Flow	-67.8	13.8	-180	-66.2	26.8	-0.468
PV Severance Tax	2.70	3.55	1.86	2.69	0.251	0.099
PV State Tax	0.796	3.94	0	0.667	0.714	0.872
PV Corporate Tax	3.74	18.1	0	3.18	3.30	0.838
PV Royalties	5.39	7.09	3.71	5.38	0.502	0.099

Table A95
10% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	218	290	144	219	19.9	0.014
PV Cash Flow	-44.8	37.2	-130	-43.2	23.0	-0.351
PV Severance Tax	2.72	3.63	1.80	2.73	0.249	0.014
PV State Tax	1.36	5.32	0	1.29	0.864	0.458
PV Corporate Tax	6.37	24.2	0	6.07	3.97	0.424
PV Royalties	5.45	7.26	3.60	5.46	0.498	0.014

Table A96
10% Discount Rate: $10/ton

600K ANNUAL SYLVITE PRODUCTION (All figures in millions of dollars)

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	257	299	212	257	13.1	0.063
PV Cash Flow	66.0	119	-11.2	66.9	19.2	-0.431
PV Severance Tax	3.21	3.74	2.65	3.21	0.164	0.063
PV State Tax	2.98	5.57	0.856	2.99	0.916	0.019
PV Corporate Tax	13.8	25.4	4.05	13.9	4.15	-0.005
PV Royalties	6.43	7.48	5.29	6.42	0.328	0.063

Table A97
15% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	257	301	217	256	13.3	-0.012
PV Cash Flow	84.7	131	-3.81	86.0	17.9	-0.540
PV Severance Tax	3.21	3.76	2.71	3.20	0.166	-0.012
PV State Tax	3.91	6.15	0.918	3.99	0.872	-0.421
PV Corporate Tax	18.0	28.0	4.37	18.3	3.93	-0.442
PV Royalties	6.41	7.53	5.41	6.41	0.332	-0.012

Table A98
15% Discount Rate: $10/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	221	264	171	221	13.2	0.037
PV Cash Flow	49.3	110	-13.1	50.2	17.7	-0.360
PV Severance Tax	2.76	3.30	2.14	2.76	0.165	0.037
PV State Tax	2.46	5.44	0.347	2.50	0.877	-0.049
PV Corporate Tax	11.4	24.8	1.70	11.6	3.98	-0.076
PV Royalties	5.53	6.60	4.29	5.52	0.330	0.037

Table A99
15% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	221	261	181	221	13.2	0.011
PV Cash Flow	68.3	115	12.7	69.3	15.7	-0.250
PV Severance Tax	2.77	3.26	2.27	2.76	0.165	0.011
PV State Tax	3.43	5.69	1.02	3.49	0.779	-0.245
PV Corporate Tax	15.8	25.9	4.87	16.0	3.51	-0.262
PV Royalties	5.53	6.53	4.53	5.53	0.330	0.011

Table A100
15% Discount Rate: $10/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	164	206	120	164	12.6	-0.027
PV Cash Flow	-68.4	-17.2	-134	-67.0	18.1	-0.418
PV Severance Tax	2.05	2.57	1.50	2.05	0.158	-0.027
PV State Tax	0.500	2.62	0	0.374	0.491	1.06
PV Corporate Tax	2.34	12.0	0	1.76	2.27	1.03
PV Royalties	4.10	5.14	3.01	4.10	0.316	-0.027

Table A101
15% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	164	201	121	164	12.6	0.002
PV Cash Flow	-53.5	-12.8	-108	-52.5	14.6	-0.341
PV Severance Tax	2.05	2.52	1.51	2.05	0.157	0.002
PV State Tax	0.885	2.85	0	0.814	0.599	0.466
PV Corporate Tax	4.12	13.0	0	3.83	2.75	0.435
PV Royalties	4.09	5.04	3.02	4.09	0.315	0.002

Table A102
15% Discount Rate: $10/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	395	479	286	395	27.4	-0.051
PV Cash Flow	93.5	201	-52.2	93.5	35.9	-0.413
PV Severance Tax	4.93	5.99	3.58	4.94	0.342	-0.051
PV State Tax	4.24	9.48	0.946	4.14	1.59	0.285
PV Corporate Tax	19.7	43.2	4.44	19.2	7.21	0.262
PV Royalties	9.87	12.0	7.16	9.87	0.684	-0.051

Table 103
10% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	391	488	299	392	29.6	-0.089
PV Cash Flow	122	225	-53.8	126	36.5	-0.549
PV Severance Tax	4.88	6.10	3.74	4.89	0.370	-0.089
PV State Tax	5.70	10.6	0.827	5.82	1.65	-0.184
PV Corporate Tax	26.2	48.3	3.99	26.8	7.47	-0.204
PV Royalties	9.77	12.2	7.47	9.79	0.741	-0.089

Table A104
10% Discount Rate: $10/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	356	451	270	356	28.0	0.120
PV Cash Flow	76.7	185	-91.7	77.4	36.4	-0.427
PV Severance Tax	4.45	5.64	3.38	4.44	0.350	0.120
PV State Tax	3.75	8.71	0.472	3.62	1.60	0.268
PV Corporate Tax	17.4	39.7	2.25	16.8	7.25	0.242
PV Royalties	8.90	11.3	6.76	8.89	0.699	0.120

Table A105
10% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	356	438	272	355	27.4	0.048
PV Cash Flow	108	208	-22.4	108	32.2	-0.111
PV Severance Tax	4.45	5.48	3.40	4.44	0.343	0.048
PV State Tax	5.29	10.1	1.40	5.28	1.52	0.091
PV Corporate Tax	24.3	45.8	6.59	24.3	6.89	0.072
PV Royalties	8.90	11.0	6.79	8.89	0.685	0.048

Table A106
10% Discount Rate: $10/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	289	377	201	289	26.7	-0.020
PV Cash Flow	-51.8	49.7	-258	-48.4	36.3	-0.607
PV Severance Tax	3.61	4.71	2.51	3.61	0.334	-0.020
PV State Tax	1.12	5.42	0	0.929	1.06	0.881
PV Corporate Tax	5.22	24.7	0	4.35	4.88	0.852
PV Royalties	7.22	9.42	5.03	7.21	0.667	-0.020

Table A107
10% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	290	386	212	290	26.9	0.091
PV Cash Flow	-23.5	80.2	-142	-20.2	32.3	-0.450
PV Severance Tax	3.62	4.83	2.64	3.63	0.337	0.061
PV State Tax	1.99	6.96	0	1.93	1.34	0.340
PV Corporate Tax	9.24	31.6	0	8.99	6.11	0.310
PV Royalties	7.24	9.66	5.29	7.25	0.673	0.061

Table A108
10% Discount Rate: $10/ton

1000K ANNUAL SYLVITE PRODUCTION (All figures in millions of dollars)

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	428	512	349	428	22.3	0.021
PV Cash Flow	96.4	194	-45.0	98.1	33.0	-0.398
PV Severance Tax	5.35	6.40	4.36	5.34	0.279	0.021
PV State Tax	4.39	9.20	1.15	4.32	1.47	0.226
PV Corporate Tax	20.1	41.6	5.29	19.8	6.66	0.213
PV Royalties	10.7	12.8	8.73	10.7	0.558	0.021

Table A109
15% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	429	500	349	429	21.6	-0.044
PV Cash Flow	131	215	-42.2	133	32.0	-0.501
PV Severance Tax	5.36	6.26	4.36	5.36	0.270	-0.004
PV State Tax	6.12	10.2	1.56	6.21	1.52	-0.204
PV Corporate Tax	27.9	46.2	7.19	28.3	6.82	-0.215
PV Royalties	10.7	12.5	8.72	10.7	0.540	-0.004

Table A110
15% Discount Rate: $10/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	369	438	303	370	21.4	0.014
PV Cash Flow	77.2	164	-61.1	80.0	31.4	-0.475
PV Severance Tax	4.62	5.47	3.79	4.62	0.267	0.014
PV State Tax	3.77	8.05	0.628	3.75	1.43	0.103
PV Corporate Tax	17.2	36.4	2.87	17.2	6.45	0.088
PV Royalties	9.23	10.9	7.57	9.24	0.535	0.014

Table A111
15% Discount Rate: $12/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	369	431	297	370	22.0	-0.005
PV Cash Flow	109	193	-24.1	110	28.3	-0.215
PV Severance Tax	4.61	5.38	3.71	4.62	0.275	-0.005
PV State Tax	5.34	9.46	1.49	5.42	1.38	-0.064
PV Corporate Tax	24.3	42.7	6.82	24.7	6.19	-0.076
PV Royalties	9.23	10.8	7.42	9.24	0.550	-0.005

Table A112
15% Discount Rate: $10/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	271	331	201	271	19.7	0.072
PV Cash Flow	-48.0	52.8	-161	-45.2	29.3	-0.525
PV Severance Tax	3.39	4.13	2.52	3.39	0.246	0.072
PV State Tax	0.946	6.12	0	0.582	1.02	1.17
PV Corporate Tax	4.37	27.7	0	2.74	4.65	1.15
PV Royalties	6.78	8.26	5.03	6.78	0.492	0.072

Table A113
15% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	271	343	208	271	20.6	0.098
PV Cash Flow	-23.4	60.7	-124	-22.3	24.5	-0.247
PV Severance Tax	3.39	4.29	2.61	3.39	0.257	0.098
PV State Tax	2.04	6.53	0	2.03	1.32	0.246
PV Corporate Tax	9.39	29.6	0	9.36	5.99	0.223
PV Royalties	6.79	8.57	5.21	6.77	0.514	0.098

Table A114
15% Discount Rate: $10/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	636	834	370	654	81.9	-1.43
PV Cash Flow	140	311	-113	144	62.2	-0.436
PV Severance Tax	7.95	10.4	4.63	8.18	1.02	-1.43
PV State Tax	6.59	14.7	1.59	6.34	2.47	0.492
PV Corporate Tax	30.1	66.6	7.33	28.9	11.2	0.478
PV Royalties	15.9	20.9	9.26	16.4	2.05	-1.43

Table A115
10% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	635	775	475	636	41.9	-0.069
PV Cash Flow	181	325	-16.6	183	53.6	-0.283
PV Severance Tax	7.94	9.69	5.94	7.94	0.524	-0.069
PV State Tax	8.50	15.4	2.77	8.38	2.42	0.125
PV Corporate Tax	38.7	69.6	12.7	38.2	10.9	0.113
PV Royalties	15.9	19.4	11.9	15.9	1.05	-0.069

Table A116
10% Discount Rate: $10/ton

SCENARIO 2	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	595	789	436	597	45.6	-0.061
PV Cash Flow	117	301	-162	120	63.9	-0.508
PV Severance Tax	7.43	9.86	5.45	7.46	0.570	-0.061
PV State Tax	5.79	14.6	1.03	5.41	2.51	0.541
PV Corporate Tax	26.5	65.9	4.76	24.8	11.3	0.526
PV Royalties	14.9	19.7	10.9	14.9	1.14	-0.061

Table A117
10% Discount Rate: $12/ton

SCENARIO 1	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	595	770	453	594	45.6	0.061
PV Cash Flow	167	348	-102	170	59.9	-0.526
PV Severance Tax	7.44	9.62	5.66	7.43	0.569	0.061
PV State Tax	8.12	16.8	1.64	8.07	2.62	0.061
PV Corporate Tax	37.0	75.8	7.58	36.7	11.8	0.048
PV Royalties	14.9	19.2	11.3	14.9	1.14	0.061

Table A118
10% Discount Rate: $10/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	473	598	322	471	42.2	-0.023
PV Cash Flow	-26.3	150	-310	-19.5	62.7	-0.721
PV Severance Tax	5.92	7.47	4.03	5.89	0.527	-0.023
PV State Tax	1.86	10.4	0	1.15	1.99	1.18
PV Corporate Tax	8.59	47.1	0	5.39	9.05	1.16
PV Royalties	11.8	14.9	8.06	11.8	1.05	-0.023

Table A119
10% Discount Rate: $12/ton

SCENARIO 3	Ave.	Max.	Min.	Med.	St. Dev.	Skew
PV Revenues	473	603	320	473	42.5	-0.131
PV Cash Flow	20.7	195	-189	23.1	50.7	-0.473
PV Severance Tax	5.91	7.53	4.00	5.92	0.532-131	
PV State Tax	3.80	12.7	0	3.72	2.40	0.259
PV Corporate Tax	17.4	57.3	0	17.1	10.9	0.238
PV Royalties	11.8	15.1	8.01	11.8	1.06	-0.131

Table A120
10% Discount Rate: $10/ton

Selected conversion factors*

TO CONVERT	MULTIPLY BY	TO OBTAIN
Length		
inches, in	2.540	centimeters, cm
feet, ft	3.048×10^{-1}	meters, m
yards, yds	9.144×10^{-1}	m
statute miles, mi	1.609	kilometers, km
fathoms	1.829	m
angstroms, Å	1.0×10^{-8}	cm
Å	1.0×10^{-4}	micrometers, µm
Area		
in^2	6.452	cm^2
ft^2	9.29×10^{-2}	m^2
yds^2	8.361×10^{-1}	m^2
mi^2	2.590	km^2
acres	4.047×10^{3}	m^2
acres	4.047×10^{-1}	hectares, ha
Volume (wet and dry)		
in^3	1.639×10^{1}	cm^3
ft^3	2.832×10^{-2}	m^3
yds^3	7.646×10^{-1}	m^3
fluid ounces	2.957×10^{-2}	liters, l *or* L
quarts	9.463×10^{-1}	l
U.S. gallons, gal	3.785	l
U.S. gal	3.785×10^{-3}	m^3
acre-ft	1.234×10^{3}	m^3
barrels (oil), bbl	1.589×10^{-1}	m^3
Weight, mass		
ounces avoirdupois, avdp	2.8349×10^{1}	grams, gr
troy ounces, oz	3.1103×10^{1}	gr
pounds, lb	4.536×10^{-1}	kilograms, kg
long tons	1.016	metric tons, mt
short tons	9.078×10^{-1}	mt
oz mt^{-1}	3.43×10^{1}	parts per million, ppm
Velocity		
ft sec^{-1} (= ft/sec)	3.048×10^{-1}	m sec^{-1} (= m/sec)
mi hr^{-1}	1.6093	km hr^{-1}
mi hr^{-1}	4.470×10^{-1}	m sec^{-1}
Pressure, stress		
lb in^{-2} (=lb/in^2), psi	7.03×10^{-2}	kg cm^{-2} (kg/cm^2)
lb in^{-2}	6.804×10^{-2}	atmospheres, atm
lb in^{-2}	6.895×10^{3}	newtons (N)/m^2, N m^{-2}
atm	1.0333	kg cm^{-2}
atm	7.6×10^{2}	mm of Hg (at 0°C)
inches of Hg (at 0°C)	3.453×10^{-2}	kg cm^{-2}
bars, b	1.020	kg cm^{-2}
b	1.0×10^{6}	dynes cm^{-2}
b	9.869×10^{-1}	atm
b	1.0×10^{-1}	megapascals, MPa
Density		
lb in^{-3} (= lb/in^3)	2.768×10^{1}	gr cm^{-3} (= gr/cm^3)
Viscosity		
poises	1.0	gr cm^{-1} sec^{-1} *or* dynes cm^{-2}
Discharge		
U.S. gal min^{-1}, gpm	6.308×10^{-2}	1 sec^{-1}
gpm	6.308×10^{-5}	m^3 sec^{-1}
ft^3 sec^{-1}	2.832×10^{-2}	m^3 sec^{-1}
Hydraulic conductivity		
U.S. gal day^{-1} ft^{-2}	4.720×10^{-7}	m sec^{-1}
Permeability		
darcies	9.870×10^{-13}	m^2
Transmissivity		
U.S. gal day^{-1} ft^{-1}	1.438×10^{-7}	$m^2 sec^{-1}$
U.S. gal min^{-1} ft^{-1}	2.072×10^{-1}	1 sec^{-1} m^{-1}
Magnetic field intensity		
gausses	1.0×10^{5}	gammas
Energy, heat		
British thermal units BTU	2.52×10^{2}	calories, cal
BTU	1.0758×10^{2}	kilogram-meters, kgm
BTU lb^{-1}	5.56×10^{-1}	cal kg^{-1}
Temperature		
°C + 273	1.0	°K (Kelvin)
°C + 17.78	1.8	°F (Fahrenheit)
°F - 32	5/9	°C (Celsius)

*_Divide by_ the factor number to reverse conversions.
Exponents: for example 4.047×10^{3} (see acres) = 4,047; 9.29×10^{-2} (see ft^2) = 0.0929

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