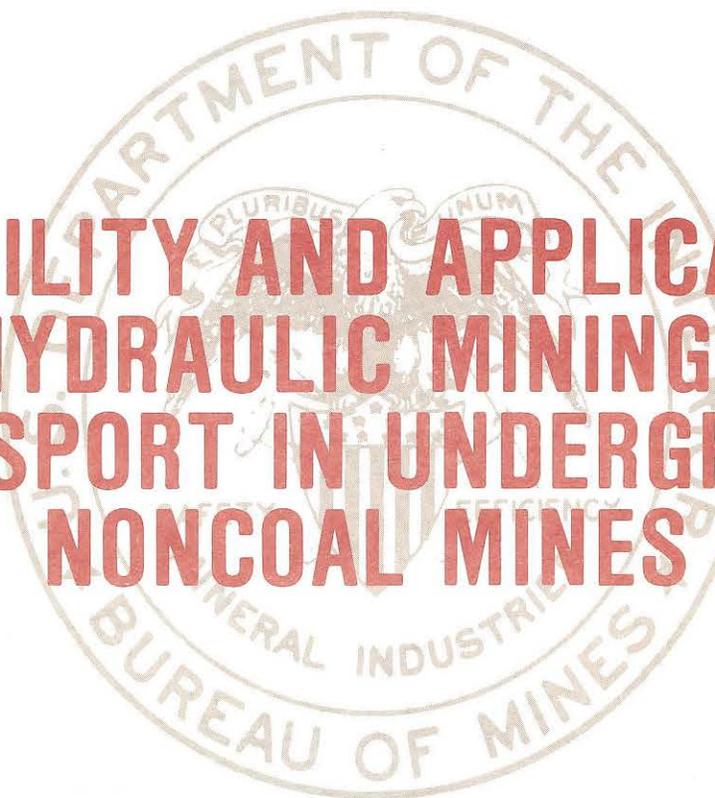


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A minerals research contract report  
August 1981



**FEASIBILITY AND APPLICABILITY  
OF HYDRAULIC MINING AND  
TRANSPORT IN UNDERGROUND  
NONCOAL MINES**

Contract J0205027  
Terraspace Inc.

BUREAU OF MINES ★ UNITED STATES DEPARTMENT OF THE INTERIOR  
Mineral Resources Technology

The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies or recommendations of the Interior Department's Bureau of Mines or of the U.S. Government.



# United States Department of the Interior

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**Report Date:** August 1981 **Type of Report (Final/Interim):** Final

**Value/Impact of Results:** This report outlines a method to screen and compare mineral deposits with reference to the economic viability of underground hydraulic mining. It also identifies and evaluates mineral deposits in the U.S. which are most amenable to underground hydraulic mining and/or hydraulic transport.

**Users/Audience:** This report will be useful to mining companies contemplating hydraulic mining.

**Contractor Name:** Terraspace, Inc.

**Contract Number:** J0205027 **Total Contract Funding:** \$99,445

**TPO:** George A. Savanick **Element Manager:** D. Barna/L. L. Davis

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## FOREWORD

This report was prepared by Terraspace Inc., Rockville, Maryland under USBM Contract number J0205027. The contract was initiated under the Mineral Resources Technology Program. It was administered under the technical direction of the Twin Cities Mining Research Center with George A Savanick as Technical Project Officer. Mr. R.J. Simonich was the contract administrator for the Bureau of Mines. This report is a summary of the work recently completed as a part of this contract during the period August 21, 1980 to August 20, 1981. This report was submitted by the author on September 11, 1981.

This Final Report covers work performed by Terraspace Inc. with the assistance of subcontractors, Science Applications, Inc., Golden, Colorado, and Mineral Systems, Inc., Stamford, Connecticut. Consulting services on hydrotransport were provided by Dr. Robert R. Faddick of the Colorado School of Mines.

Dr. Dipak Sengupta, David Conover and others of Science Applications, Inc. provided assistance in identifying noncoal mineral deposits, developing selection criteria, ranking of various deposits, evaluating mining methods, and comparing hydraulic and conventional technologies. Ms. Nellie Guernsey and Alfred Weiss of Mineral Systems, Inc. assisted in obtaining data on mineral deposits, developing cost estimation models, and comparing costs of hydraulic and conventional mines. Dr. Faddick provided data on hydraulic transport and hoisting technology for application to various minerals.

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## 2. INTRODUCTION

Hydraulic mining and hydraulic transport of minerals are gaining wider acceptance. Underground hydromining of coal and hydrohoisting and hydrotransport of coarse coal have been practiced in the USSR for many years. Hydromining of coal has also been applied in Germany, China, Canada, Poland and Czechoslovakia. Programs for hydromining and hydrotransport of coal are underway in the U.S. with support of the Department of Energy. Gilsonite has been mined hydraulically and hydraulically hoisted to a preparation plant in Utah and for many years it was transported 72 miles by pipeline to a refinery. Coarse coal is being hydraulically transported in hoses and pipes from underground faces to a preparation plant at Loveridge mine in West Virginia.

Borehole hydraulic mining is under development by the U.S. Bureau of Mines and tests have been conducted in near-surface deposits of coal, uranium, oil sand, and phosphates. Hydraulic transport of slurries by pipeline on the surface is becoming more widely used for coal, iron ore, phosphate matrix, kaolin, and other minerals.

This study was undertaken to accelerate technology transfer to the underground noncoal mining industries and to identify and evaluate the most feasible and applicable technologies for early development.

The specific objective was to evaluate underground noncoal mines in the U.S. for hydraulic mining, hoisting and transport applications.

### 3. BASIC DEFINITIONS AND ASSUMPTIONS

Hydraulic mining ( hydromining) involves the use of high pressure jets of water to disintegrate a mineral and form a solid-liquid suspension (slurry) which can be hydraulically transported by gravity in flumes or by pump through a pipeline. Hydromining is distinguished from jet cutting, in which small diameter (less than 1/4 inch) high pressure water jets cut or disintegrate a material, but do not provide enough water to permit hydraulic transport (hydrotransport). Typical underground hydraulic mining of coal uses monitor jets with nozzle diameters of 1 to 4 cm and pressures of 5 and 20 MPa (700 to 3000 psi) to break coal. Monitor jets typically provide mixture ratios of water to solid over 2 to 1, which permits hydrotransport by gravity fluming, jet pump, centrifugal pump, pipe-feeder or airlift methods.

Monitor jets are typically produced by portable nozzle systems with provisions for moving the nozzle in a pattern to undercut and wash away a soft mineral at ranges of 1 to 10 meters or more. Similar jets can be produced by an underground borehole mining tool to disintegrate soft minerals and permit hoisting to the surface by a jet pump. In this program we have also considered the possibility of using such borehole hydraulic mining tools from underground entries in mines. In this case, if the borehole were driven vertically or at an inclined angle, upward from the entry, the slurry could flow by gravity to the entry and then be transported within the mine by flume or pipe. This would avoid the need for a jet pump within the mining tool.

The minerals considered in this study were metallic ores, industrial minerals and rocks, and certain fuel minerals including uranium and oil-bearing sandstones. Industrial minerals are defined as "any rock, mineral, or other naturally occurring substance of economic value, exclusive of metallic ores, mineral fuels, and gemstones; one of the nonmetallics." (Ref. 86).

#### 4. HISTORICAL REVIEW

Previous studies have summarized the technologies of underground hydraulic mining of coal (Ref. 1), surface hydraulic mining (Ref. 2), and hydrotransport of coal (Ref. 3, 4, 5 and 6). These studies show the advantages of hydraulic mining to be:

1. Permits disintegrating a soft mineral at appreciable range, permitting mining with roof caving and avoiding roof support except where miners are located.
2. Avoids spark hazards and dust, improving safety and health of miners.
3. Provides a slurry which can be safely transported in pitching seams by gravity in flumes or by pipe (hydrotransport) in small entries or boreholes.
4. Is adaptable for applications involving remote control and automation, which are particularly important with minerals that are hazardous from the standpoint of rock bursts, gas outbursts, fire and radioactivity.

Many of these advantages have been demonstrated in hydraulic mining of pitching seams of coal in the Donetz and Kusnetz coal basins of the USSR (Ref. 7) as well as in mines in China (Ref. 8), Japan (Ref. 9), West Germany (Ref. 10) and Canada (Ref. 11,12 and 13). The Kaiser Resources hydromine in British Columbia is one of the most successful underground coal mines in the world, as well as one of the safest (Ref. 11 and 50).

In West Germany, the Hansa Hydromine operated from 1977 to 1980 but was closed because of poor geological conditions of coal seams which were encountered, particularly undulating and faulted thin seams.

Coarse coal has been transported by pipelines of 10 to 11 km distance in the USSR since 1966 and plans for longer distance pipelines are underway. (Ref. 4). Development of hydraulic transport of coarse coal for use in underground coal mines has been underway for over ten years by the Consolidation Coal Co. (Ref. 14). A slurry transport system is operating in the Loveridge mine near Fairmont, West Virginia. The system includes face haulage for both longwall and continuous miner sections, hydraulic hoisting, and 4.0 km (2.4 miles) of overland slurry transport. The system uses flexible hoses underground to follow the mining machine.

Recently a review was prepared of water jet research and development related to drilling (Ref. 15). It covers a broad scope, much of which relates to mining.

Gilsonite is a shiny black asphaltite mineral of specific gravity only 1.04 which occurs in vertical seams near Bonanza, Utah. It was mined hydraulically with a nozzle diameter of 1/4 inch and water pressure of 2000 psi with a flow of 70 gpm beginning about 1956. The nozzles were mounted on an air-driven tractor. Underground transport was by flumes requiring 7% slope and 1000 gpm of water. A shaft depth of 850 ft. was used with the lower 100 ft. as a mine sump for hydromined ore. Fig. 4-1 shows a schematic diagram of this early hydraulic mine. (Ref. 16).

The oversize gilsonite was crushed to minus 3/4 inch and pumped to the surface by five centrifugal pumps in series. After preparation, the slurry was pumped by a 6 inch diameter pipeline 72 miles to a refinery near Grand Junction, Colorado.

Over the years, many changes have evolved in the gilsonite mining and transport processes and now neither hydraulic mining nor hydraulic transport are used.

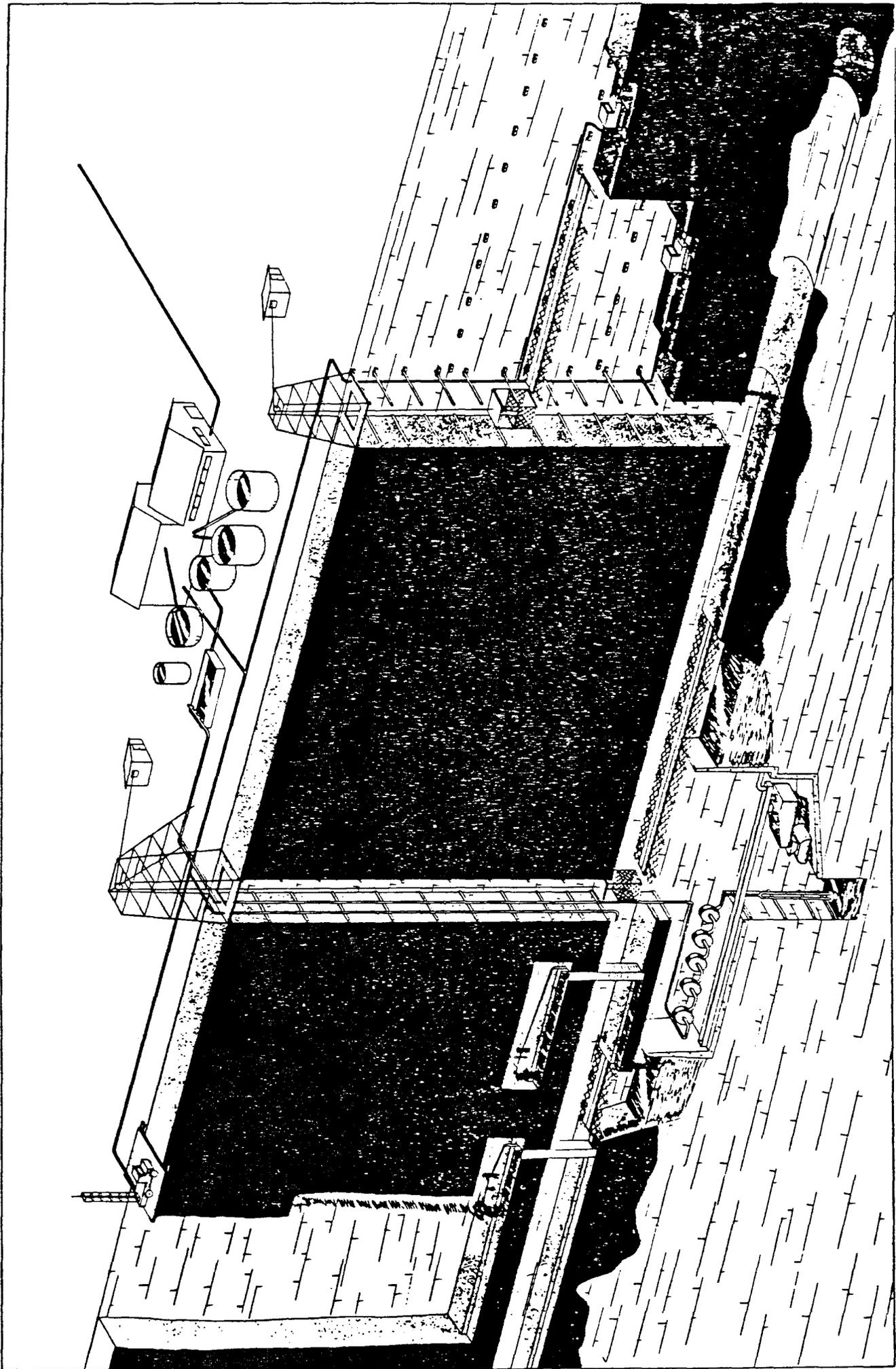


Fig. 2-1 Schematic View of Early American Gilsonite Company Hydraulic Mine (Ref. 16)

## 5. TECHNICAL APPROACH

The scope of work was carried out under the following four tasks:

1. Evaluate noncoal deposits in the U.S. for hydraulic monitor mining potential and hydraulic transport applications.
2. Rank types of deposits evaluated in order of amenability to hydraulic mining and transport.
3. Within the top ranking types of deposits, identify and evaluate selected existing mining operations for hydraulic mining and transport applications.
4. Rank mines evaluated in order of amenability to hydraulic mining and transport.

One of the most difficult problems in Tasks 1 and 2 was to predict whether a particular mineral deposit would be sufficiently easy to break to permit hydraulic mining. In most cases, no experimental data were available to permit prediction of mineral breakage rates other than for coal. Therefore, estimates had to be based on limited data on strength properties of the ore and variability of strength, combined with engineering judgment by comparison with coal and limited data on uranium sandstone.

For ores which were judged not to be sufficiently easily broken to permit hydraulic mining, consideration was given to disintegration by mechanical or drill and blast methods, followed by hydraulic transport and hoisting.

The minerals were screened on the basis of physical properties, size of deposit, water availability, and compatibility with water. Then ranking of deposits was conducted based on evaluation criteria involving economics, health, safety, environmental impact, recovery and other factors.

## 6. EVALUATION OF NONCOAL MINERAL DEPOSITS

### A. Effect of Mineral Properties and Other Factors on Hydraulic Mining

Research on breaking coal by monitor jets (Ref. 8) shows that the three mechanisms involved in hydraulic breaking are:

1. Slot cutting (by erosion)
2. Fracturing of lumps to the slot
3. Water injection and wedging into pores and fissures in the mineral (hydraulic fracture)

The properties of coal which affect its monitor jet breakage rate are:

1. Hardness of ore
2. Water permeability
3. Friability, which is related to fissures (stratifications and joints) and structure (presence of soft and hard layers)

The jet characteristics are dependent on the nozzle diameter, water pressure and quality of the hydrodynamic flow supplying the nozzle. In addition, the production rate is affected by the strata stresses in the ore, which are a function of depth, seam thickness, dip angle of seam, properties of roof rock and the nearby mining activities. These effects can increase the production rate by a factor of 2 to 3 over the rate for a monitor operating at short range during entry development.

It is very difficult to predict production rates based on laboratory samples. The theory of fracture mechanics of brittle solids by water jets is not well-developed. The best method for prediction is by in situ experiments. However, there have been only very limited tests reported on breakage rates by monitor jets of minerals other than coal.

Some applicable data on production rates were obtained in borehole hydraulic mining experiments by the Bureau of Mines (Ref. 17, 18, 19). These tests indicate that production rates in the range of 20 to 45 tons per hour can be attained in relatively weakly-consolidated deposits of uranium, oil sands and phosphates using a water flow rate of at least 300 gpm and pressures of 400 to 2500 psi. The weight ratio of water from the jet to solid is of the order of 2 to 4 or higher, which increases with an increase in jet range. The effective range of the jet is 5 to 10 meters. The effect of mineral properties on performance has not been investigated. Commercial equipment for borehole mining is produced by Flow Industries, Inc. (Ref. 20).

When using skid-mounted monitor jet systems for coal, the production rates are typically 50 to 300 T/h with jet pressures up to 19 MPa (2700 psi) and flowrates up to 200 to 340 m<sup>3</sup>/h (880 to 1500 gpm). Typical monitor nozzle diameters are 15 to 30 mm. The effective range (standoff distance) with a soft coking coal is out to 15 meters. Water to coal ratios as low as 1.25 are obtained (Ref. 8). This applies to coal of Protodyakanov hardness near 1 and unconfined compressive strength near 1500 psi. With harder minerals, the range for effective cutting decreases and the water to coal ratio generally increases. This requires an increase in water consumption and more pump power for hydraulic hoisting.

The size of lumps produced by hydraulic breaking is important with respect to hydrotransport. Generally lump sizes below 50 mm are required for hydraulic transport by centrifugal pumps. In some cases, (for example, the Kaiser Crows Nest mine), a feeder-breaker is used at the mining face to crush large lumps prior to hydrotransport (Ref. 13). A certain degree of lump attrition will occur during gravity fluming or centrifugal pumping and transport through pipes. Lumps should be smaller than one-third the pipe diameter.

## B. Physical Properties of Minerals

In order to identify minerals which might be amenable to hydraulic mining, the first level of screening information concerns the strength or hardness of the mineral ore as it occurs underground. A list of industrial minerals, showing, where available, their Moh's hardness is in Table 6-1 and 6-2. The Moh's scale is based on relative scratch hardness. The basic scale is based on talc (1), gypsum (2), calcite (3), fluorite (4), apatite (5), orthoclase (6), quartz (7), topaz (8), corundum (9) and diamond (10). In order to correlate hardness and strength properties of various soft minerals, Fig. 6-1 was prepared. It shows Mohs' hardness plotted against unconfined compressive strength  $\sigma_c$ . The Protodyakonov hardness number  $f$  is also plotted on the abscissa under the assumption that  $100f = \sigma_c$  in kg/cm<sup>2</sup> (Ref. 22, p. 25). It may be noted that this assumption is approximately valid for correlating the compressive strength of coal samples loaded perpendicular to the bedding planes with the Impact Strength Index (I.S.I.) which was derived by Evans and Pomeroy (Ref. 23 p. 135) from the Protodyakonov test. These tests use sieve analysis following weight drops onto samples.

It appears that with weak minerals of the type which can be hydraulically mined, it is difficult to obtain core samples from which compressive strength can be directly measured. Therefore the Russian Protodyakanov test, or its modifications by Evans and Pomeroy (Ref. 23), or by Brook and Misra (Ref. 24) offer the best possibility of obtaining useful data on hardness from core sample material. Most of the Russian and Chinese correlations of hydraulic mining performance are referred to this number for coal as well as other rocks.

It is seen in Fig. 6-1 that Chinese coals which are hydraulically mined in four mines (Ref. 8) have Protodyakonov number of 0.6 to 1.2, which would put them in the range of Moh's hardness near 1, like talc.

Russian experience shows that monitor jet mining with pressures of 10 to 11

TABLE 6-1

LIST OF INDUSTRIAL MINERALS CONSIDERED FOR HYDRAULIC MINING,WITH MOH'S HARDNESS WHERE AVAILABLE

(from Ref. 21)

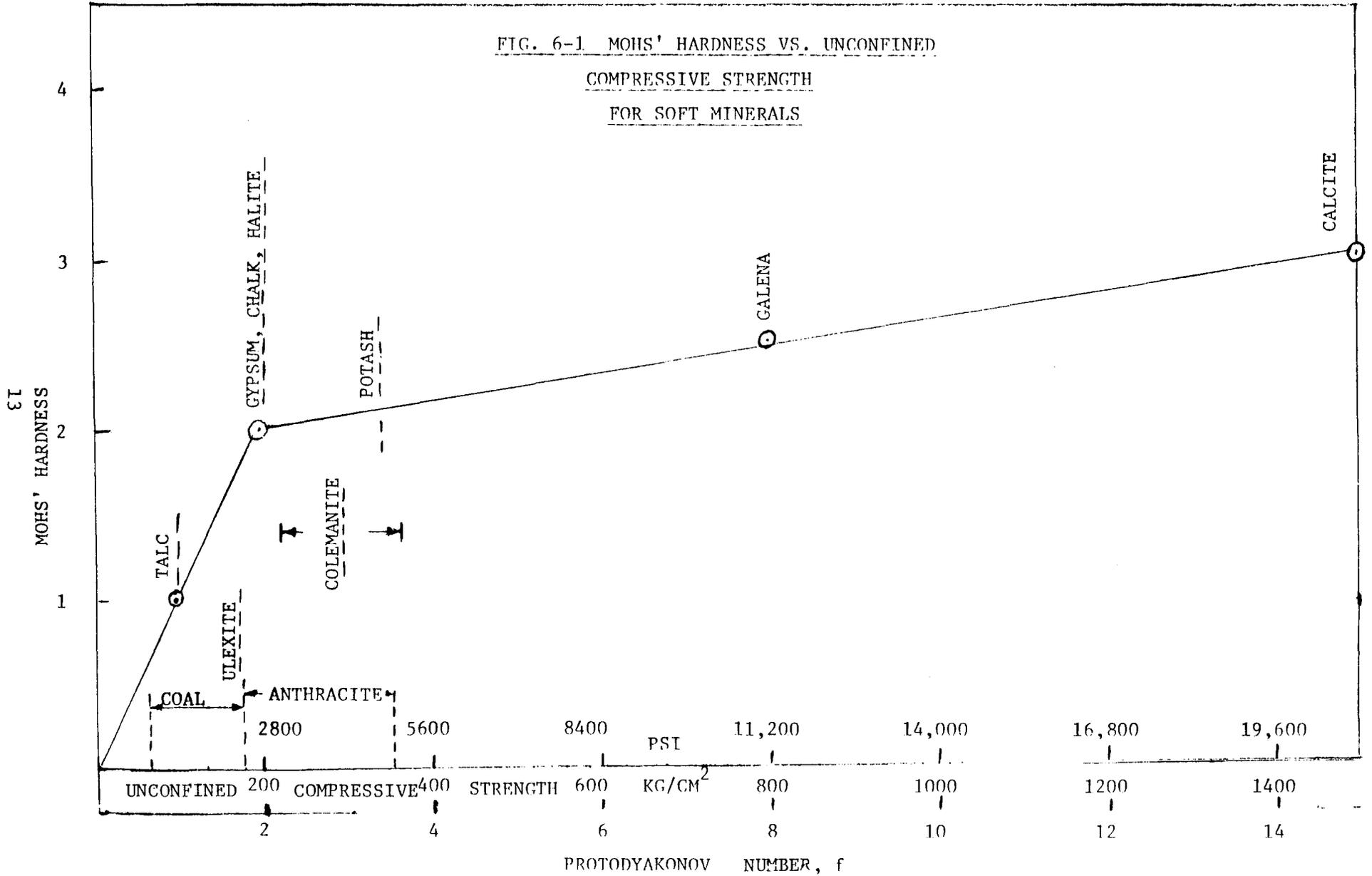
		Mohs' Hardness			Mohs' Hardness
Andalusite	$Al_2SiO_5$		Potash	KCl	
Antimony			Pumice		
Asbestos			Pyrites		
Attapulgite			Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	1 to 2
Ball clay			Quartz		
Barite	$BaSO_4$	3.0 to 3.5	Rare earths		
Bauxite	$Al_2O_3 \cdot 2H_2O$		Rutile	$TiO_2$	
Bentonite			Salt	NaCl	
Borates			Sepiolite	(Meerschaum)	
Bromine			Silica		
Chalk			Silicon carbide		
Chromite	$FeCr_2O_4$	5.5	Sillimanite	$Al_2OSiO_5-$	6 to 7
Colemanite		4 to 4.5	Soda ash	$Na_2CO_3$ (Trona)	2.5 to 3
Corundum	$Al_2O_3-9$		Salt cake	$Na_2SO_4$	
Cryolite	$Na_3AlF_6$	2.5	Strontium		
Diamond			Sulfur	1.5 to 2.5	
Dolomite	$CaMg(CO_3)_2$	3.5 to 4	Talc	$Mg_3(Si_4O_{10})(OH)_2$	1 to 1.5
Emery			Tripoli		
Feldspar		6	Vermiculite		
Fluorspar	$CaF_2$	4	Wollastonite		
Fused alumina	$Al_2O_3$		Zeolites		
Garnet			Zircon	$ZrSiO_4$	
Gilsonite		2			
Graphite		1-2			
Gypsum	$CaSO_4 \cdot 2H_2O$	1.5 to 2			
Ilmenite	$FeO \cdot TiO_2$	5 to 6			
Iodine					
Iron oxide					
Kaolin	$Al_4(Si_4O_{10})(OH)_8$				
Ryanite	$Al_2SiO_5$	5 to 7			
Limestone	$CaCO_3$				
Lithium					
Magnesite	$MgCO_3$				
Manganese					
Mica					
Nepheline syenite					
Nitrates					
Olivine					
Perlite					
Phosphates					

TABLE 6-2

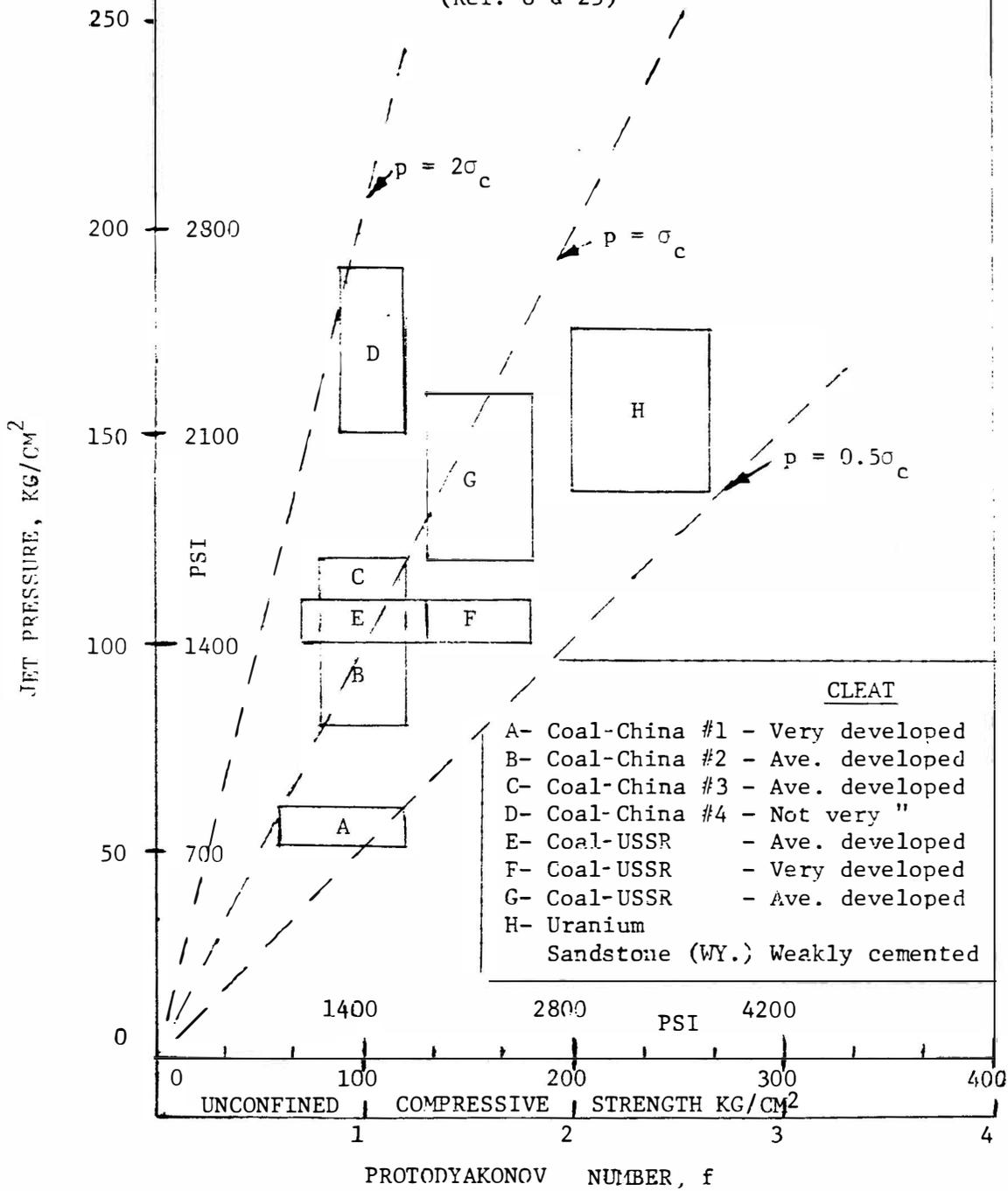
CLASSIFICATION OF MINERALS  
WITH RESPECT TO MOHS' HARDNESS

<u>MOHS' HARDNESS</u>	<u>MATERIAL</u>
1-1.5	Graphite, talc, pyrophyllite, bentonite, kaolin
1.5-2	Graphite, gypsum, pyrophyllite, sulfur, sylvanite, sylvite, gilsonite
2-2.5	Salt (NaCl), sodium sulfate (thenardite), sulfur, gilsonite
2.5-3	Cryolite, calcite, galena, trona
3.0-3.5	Barite
3.5-4	Dolomite, langbeinite [ $K_2Mg_2(SO_4)_3$ ], alunite, zinc sulfide
4-5	Fluorspar, colemanite, apatite
5-6	Chromite, ilmenite, kyanite
6-7	Feldspar, sillimanite, kyanite, spodumene, orthoclase
7-8	Quartz
8-9	Corundum, topaz

FIG. 6-1. MOHS' HARDNESS VS. UNCONFINED  
 COMPRESSIVE STRENGTH  
 FOR SOFT MINERALS



**FIG6-2 MONITOR JET**  
**PRESSURE REQUIRED VS.**  
**COMPRESSIVE STRENGTH OF COALS AND SANDSTONE**  
**FOR STANDOFF DISTANCE ABOVE 4 METERS**  
 (Ref. 8 & 25)



MPa (1500 to 1600 psi) is effective with monolithic coal having a Protodyakonov number up to 1.3 (Mohs hardness of 1.3 according to Fig. 6-1 and with severely jointed coal with Protodyakonov number of 1.3 to 1.8. Harder coal requires higher pressures of 12 to 16 MPa (1750 to 2350 psi) which involves many mechanical difficulties for practical implementation in a mine. Water-driven pressure intensifiers have been tested in Soviet coal mines, but were found to be large and to require special equipment to transport them through the mine. Experiments have shown that pulsating monitor jets can extend the region of application for hydraulic breaking of coal. (Ref. 25). However equipment is not yet available in the U.S.

Anthracite is known to be generally too hard for effective monitor jet mining without pre-breaking by explosives or water infusion. Anthracite has a typical Protodyakonov number of 2 (Ref. 9) which corresponds to a Mohs' hardness of near 2. One may then make a preliminary estimate that rock minerals will not be suitable for hydraulic mining unless their Mohs' hardness is about 2 or less. According to Fig. 6-1 the limiting value of unconfined compressive strength would nominally be  $200 \text{ kg/cm}^2$  or about 3000 psi. However, an exception may be when mineral grains are very weakly cemented and easily washed away by water. It appears that some sandstones, including uranium-bearing sandstones in Wyoming, meet this criterion.

The feasibility of breakage is related to the failure mechanisms which predominate. For example a weakly cemented sandstone can be washed away by erosion with quite low jet pressure. Similarly a highly cleated coal will break into fragments at reasonable jet pressure. However, a low porosity mineral with very few cracks or cleavage planes may be very difficult to break except at high jet pressures and with the jet at short range.

In order to estimate the water jet pressure required to break minerals at an economic rate, Fig. 6-2 was prepared. It shows the range of monitor pressures and mineral hardnesses which have been used successfully in hydraulic mining of coal in China (Ref. 8) and in the USSR (Ref. 25). It may be seen that coal in the range of Protodyakonov number ( $f$ ) from 0.6 to 1.8 can be mined with pressures in the range 0.5 to 2 times the unconfined compressive strength ( $100f$ ). The lower range,  $0.5\sigma_c < p < \sigma_c$ , corresponds to highly fractured and cleated coal. The upper range,  $\sigma_c < p < 2\sigma_c$ , is for coal without highly developed cleat.

The Figure 6-2 also shows the potential range for mining soft uranium sandstones of the type found in Wyoming (Ref. 26) which have a compressive strength below 4000 psi. The upper limit of monitor pressure for practical underground mine design is assumed to be about 2800 psi, although future technology improvements may increase this value.

In general, it appears that igneous rocks are too hard for hydraulic mining. The most likely candidates for hydraulic mining are sedimentary rocks, preferable with porosity and/or fractures and with weak grain cementing. These rocks may include the products of weathering by water or air (limestones, sandstones, tripoli or diatomite, coal, sedimentary iron ores, etc). The minerals derived from sedimentary rocks include calcite, dolomite, gypsum, halides, kaolin, etc. (Ref. 22, p.21).

With sedimentary rocks, the stratification, grain size, porosity and cementing characteristics are extremely variable. Reasonably weak minerals like calcite, gypsum, etc. may have a low porosity and therefore not be easily broken by a water jet, except where tectonic stresses have fractured the material. The asphaltite, gilsonite, occurring in near-vertical veins can only be hydraulically mined economically if the local deposit has fractures and weakness planes. (Ref. 16).

It is known that evaporitic rocks, such as gypsum, anhydrite, potash and rock salt, are notoriously more difficult to cut with mechanical drag tools than their compressive strength would indicate because they have a high fracture toughness. Potash has a compressive strength of only 4400 psi (Ref. 27). However it is not likely to be cut easily by a water jet because it is tough and generally not porous or fractured.

### C. Methods of Evaluation of Minerals

In order to identify deposits for potential hydraulic mining, use was made of selected portions of the Bureau of Mines Mineral Availability System (MAS) (Ref. 28). This was found to be of limited applicability because of lack of completeness for many minerals and because data on the ore physical properties were very limited. The minerals to be covered by MAS include Cu, Al, Cr, Co, Mn, P, Zn, Ni, Pt, Fe and Sn, in that order. The available open data relate to Cu and Al, which are of little interest here. The most valuable information was found by a detailed search of relevant literature on metallic and non-metallic ores. The Mineral Commodity Profiles published by the Bureau of Mines were useful in starting some of the searches. Further information on uranium deposits and potash deposits was gained in a visit to New Mexico. Telephone calls were made to selected mine operations.

A list of 23 candidate ores was developed and then a preliminary screening process was used to reduce the list to 8, to which a detailed screening process was then applied.

Table 6-3 shows the 23 minerals which were considered in the preliminary screening. These minerals were considered for screening because one or more of the following factors:

1. Potentially economic underground deposits in the U.S.
2. Possibility of ore being broken by monitor jet
3. Possibility of water availability

In order to screen the deposits for their hydraulic mining potential, the selection criteria shown in Table 6-4 were applied. Fig. 6-3 shows schematically the steps in this screening process. In order to apply the screening criteria it was necessary to collect data regarding mineral deposits and specific mines. (See Section 7 below). Data sheets on the mineral deposits and mines are included in Appendix A.

TABLE 6-3

LIST OF MINERALS SELECTED FOR PRELIMINARY SCREENING

1. Potash
2. Trona
3. Phosphates
4. Bauxite
5. Uranium
6. Oil Bearing Rocks
7. Hematite (iron ore)
8. Gypsum
9. Manganese
10. Chromite
11. Nickel/Cobalt
12. Copper
13. Borates
14. Talc
15. Platinum sands
16. Gold sands
17. Kaolin
18. Pyrophyllite
19. Fluorspar
20. Bentonite
21. Sandstone (St. Peter)
22. Tar sands
23. Zeolites

TABLE 6-4

CRITERIA FOR SELECTING DEPOSITS AMENABLE TO UNDERGROUND  
HYDRAULIC MINING AND/OR TRANSPORT

Q1: Is the depth compatible to hydraulic mining:

The economic range of depth for amenability to underground hydraulic mining has been arbitrarily considered to be between 300 ft. to 3,500 ft. Above 300 ft. the deposit may best be mined by surface mining techniques. Below 3,500 ft. technical problems may make the system uneconomic.

Q2: Is the size of deposit economic?

The economic size of the deposit is defined by the annual production rate of an average mine of similar mineral multiplied by 20 years of life of the mine.

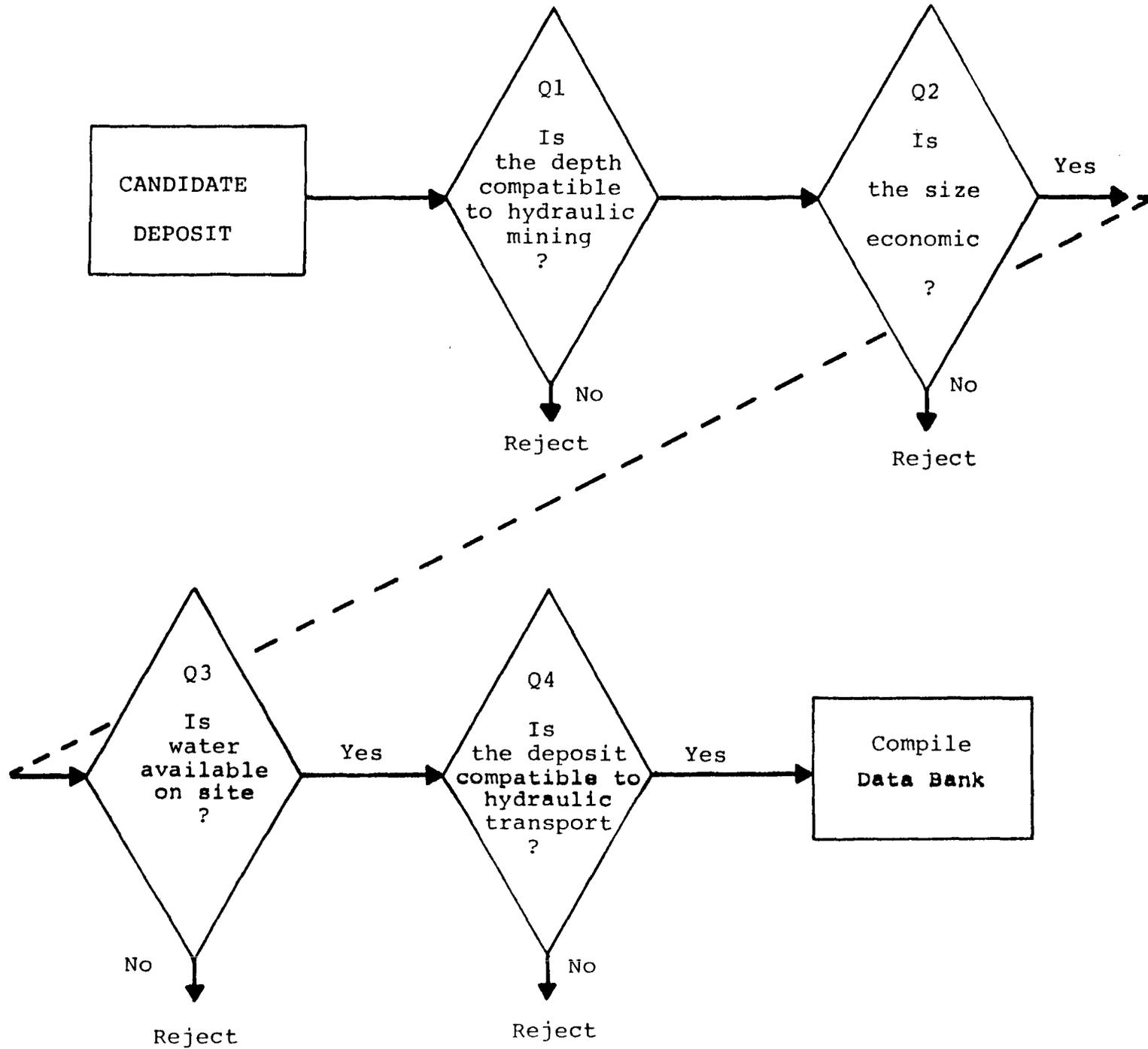
Q3: Is water available on site?

Availability of water is one of the major criteria for hydraulic mining amenability. An average of one ton of water is considered to be required per ton of material produced.

Q4: Is the deposit compatible with hydraulic transport?

Some of the deposits may not be suitable for hydraulic mining, but may be crushed and hydraulically transported. Some of the deposits due to their physical characteristics may not be suitable for hydraulic transport.

Fig. 6-3 Schematic Diagram of Screening Process



## D. Application of Screening Criteria to Mineral Deposits

### D1. Elimination of Candidate Ores

A preliminary review was made of the location, size and character of the major metallic and nonmetallic mineral deposits in the U.S. in order to eliminate minerals from consideration for hydraulic mining. Certain minerals were eliminated from further consideration because of relatively small size underground deposits in the U.S. or relatively low production rates. These included:

tin	asbestos
chromium	mica
bauxite	perlite
pyrophyllite	pumice & volcanic cinder
talc	vermiculite
	feldspar

Others were eliminated because U.S. deposits are primarily surface minable deposits:

barite	oil well frac sands
bentonite	other clays
diatomite	platinum sands
gold sands	sand and gravel
heavy minerals (beach sands)	spodumene (lithium)
kaolin	tar sands
lateritic nickel/cobalt	tripoli
	zeolites

Sulfur was eliminated because it is found in Louisiana and Texas in a matrix of hard rock, not amenable to hydraulic mining. It is also available as a byproduct of H<sub>2</sub>S removal from sour natural gas. A further discussion of some of the minerals eliminated is given below:

#### Bauxite

There is no major underground deposit of bauxite in the U.S. The underground deposit in Arkansas is becoming depleted.

Exploratory tests regarding hydraulic borehole mining of bauxites have been conducted in Hungary (Ref. 29). One problem which was identified is the separation of water from the very fine bauxite clay particles and the possibility of pollution of waste water. In France and Hungary, 80% of bauxite production is underground and water problems are common (Ref. 30).

Surface hydraulic mining has been used to remove overburden (clay and sand) from a bauxite deposit in Surinam and pump it 6 miles (Ref. 31). However, the ore itself is not hydraulically mined but is blasted.

### Gypsum (hydrated calcium sulfate)

Gypsum was eliminated because of its widespread availability in the U.S. from surface mines and eleven underground mines and as a by-product. It is potentially available from regenerative flue gas desulphurization at coal-burning power plants. For example, several utilities in Florida are planning gypsum regenerative scrubbers (Ref. 32). Gypsum is also available as a by-product of phosphoric acid production.

### Halite (NaCl)

Halite (NaCl or rock salt) was eliminated because it is available in large quantities in the U.S. It is not a critical mineral and in fact is available from mining caverns for petroleum storage in salt domes and as a by-product of potash mining. It is occasionally mined underground by solution mining. The disposal of the brine in the Gulf of Mexico has introduced ecological problems.

### Sodium sulphate

The U.S. production in 1979 was 1,072,000 metric tons of which only 484,000 metric tons were natural production and the rest synthetic (Ref. 33). There is declining demand and the percent produced by mining is falling. The main mine production is from near surface deposits (Searles Lake brines in California, Great Salt Lake, Utah, and shallow underground brine deposits in Texas). There is no underground deposit of consequence.

### Talc

There are 18 talc producing companies in the U.S. The highest tonnages are in Vermont, Montana, New York and Texas (Ref. 34). In 1978 approximately 933,000 short tons were consumed, plus 330,000 tons exported. Vermont produced the highest tonnage of 310,000 tons. Vermont Talc Inc. is a subsidiary of OMYA Inc. and operates a mine at Windham, VT. The ore is mined underground and trucked 11 miles to the processing plant at Chester, VT. Production was doubled in 18 months of 1977-78. Hydraulic mining and/or transport of this ore is possibly feasible, but the small production rates make it unlikely that process development would be economic. Therefore no detailed study was made.

Tremolitic talc is produced by the R.T. Vanderbilt Co. near Gouverneur in St. Lawrence County, New York. Very selective mining techniques are required underground to maintain product quality control of this ore. This is not compatible with bulk hydraulic hoisting through a single pipe.

### Zeolites

Zeolites are hydrated silicates of aluminum and either sodium or calcium. Natural zeolites were formed by sedimentary processes. Some zeolites in

Nevada are associated with uranium. (Ref. 35). These deposits are generally small and not yet adequately defined but are mainly near-surface deposits at less than 300 ft. depth. They may be minable by hydraulic borehole mining from the surface.

## D2. Minerals too Hard for Hydraulic Mining but Feasible for Hydrotransport.

Other minerals were eliminated with respect to hydraulic mining because the ore is too hard to be broken by a monitor jet:

copper	limestone
feldspar	manganese (rhodochrosite)
fluorspar	potash
hematite (iron ore)	sulphur (rock matrix)
lead	trona (soda ash)
	zinc

However, some of these minerals can be considered for hydraulic transport. Prior experience with some of these ores is summarized below. However fluorspar, feldspar, and sulfur are not considered.\* The most highly ranked minerals will be discussed in Section 7.

### Iron Ore

Hematite is amenable to hydraulic hoisting after mechanical cutting. (Ref. 36 and 37). It is probably too hard for hydraulic mining. The Lengede mine in Germany hoisted iron ore hydraulically until its reserves were depleted and the mine closed in 1977. The amount of underground hematite in the U.S. is limited. The Lake Superior iron deposit in Michigan is the only one to pass the preliminary screening. Most U.S. reserves are taconite type ores and definitely too hard for hydraulic breaking (See Ref. 38).

Slurry pipelines are becoming more widely used for transporting iron ore in Brazil, Tasmania, Mexico and India. For this purpose the ore must be finely ground. There also must be provision for disposing of waste water at the delivery point.

Most iron ore from the Lake Superior district of Minnesota and Michigan is surface mined and is delivered by ship to Great Lakes ports. Slurry pipelines do not appear to offer significant economic potential in the Great Lakes area. If slurry pipelines became of interest, then hydraulic hoisting of coarse crushed iron ore from underground may also be applicable in some limited cases.

### Limestone

Limestone is too hard for hydraulic mining but it also can be transported hydraulically. However, most limestone mines in the U.S. now are surface mines. At present, limestone is pumped 17.6 miles as a slurry from a surface mine to a cement plant in Calaveras County, California (Ref. 39). The underground pipeline is more environmentally acceptable than trucks in this historic area.

\* Believed to be uneconomic

At some future date, hydraulic hoisting or transport of limestone from underground may become of interest. There are prospects for increased mining of high-calcium limestone underground in Illinois (Ref. 40). The state now has six shallow underground mines. (Drifts, adits from open pits, or inclines) Dry haulage may be preferable because of energy requirements for dewatering of slurry. Cement plants are now shifting from the wet to the dry process to save energy. (Ref. 41).

### Lead and zinc

Although lead-zinc ore is too hard to be broken by a monitor jet, it has been hydraulically hoisted from 450 m depth with lump sizes up to 50mm (Ref. 42).

### Copper

Copper concentrates can be hydraulically transported by slurry pipeline for 63.6 km in Turkey (Ref. 43). Also a 110 km pipeline for finely-ground copper concentrate is in Irian Jaya (Ref. 44) and a 27 km pipeline is in Bougainville (Ref. 45).

There are thirty major underground copper mines in the U.S. However the associated rocks are quartzite, monzonite, granodiorite and other hard types of igneous origin. The deposits are not applicable for hydraulic mining. In principle, the ore could be crushed underground and transported by pipe to the surface. However, this would require a water supply and a radical change from present transport methods. It also would require wet crushing and grinding on the surface. Major producing areas (eg. Arizona and New Mexico) are generally in regions of water shortage. The deposit in Butte, Montana is becoming depleted and noncompetitive.

### Manganese

The U.S. imports over 98% of its manganese which is required in iron and steel production. South Africa is the largest supplier. Eventually, (after 1990?), manganese may be available from manganese nodules recovered from the Pacific Ocean floor. The largest underground deposit of manganese in the U.S. is in Butte, Montana (Ref. 46 and 47). The ore is lower grade than South African deposits. It consists of hard ores including rhodochrosite (manganese carbonate) which occurs as a halo around the former copper deposits under Butte. Special beneficiation processes would have to be developed. Copper mining in Butte (The Anaconda Corp.) is very depressed now, but existing underground mine entries could provide access to the manganese ore. If the ore were crushed underground, it could be hoisted and transported to a mill hydraulically. The water would pick up copper sulphate which could be removed before recycling part of the water underground.

The data necessary to study the feasibility of this concept is not publicly available. There is no active program underway by industry to mine manganese. The Bureau of Mines is conducting studies to identify the resources available for inclusion in the Mineral Availability System.

## 7. RANKING OF DEPOSITS WHICH PASSED INITIAL SCREENING

### A. Ranking Criteria

In order to develop a relative ranking of the minerals in order of their amenability to hydraulic mining and transport, the set of rank selection criteria as shown in Table 7-1 were applied to various deposits. In each case the deposit was first evaluated and screened with respect to mineral properties to determine whether it could be hydraulically mined or not. These screening criteria were applied and finally rank selection criteria were used to evaluate the various deposits.

Ranking of deposits was generally based on factors in Table 7-1. The various minerals were ranked (somewhat subjectively) with respect to the items in Table 7-1. The result ranks them in the approximate order listed in Table 7-2. There are three groups: the first, for hydraulic mining and transport, the second, only hydraulic transport, and the third, unranked candidates for hydraulic transport.

A discussion of the various minerals and the factors affecting their relative ranking is given below. More detailed backup information is included in Appendix A.

### B. Discussion of Mineral Deposits

#### 1. Uranium sandstones

##### A. Reserves

An extensive National Uranium Resource Evaluation program (NURE) has been underway by the Dept. of Energy in recent years. Uranium reserves are located primarily in the western states (Ref. 48). Colorado and Washington have vein deposits in hard rock which are not hydrominable. The majority of U.S. reserves are in sandstones (Ref. 49) in the Grants mineral belt of New Mexico and in the Shirley, Gas Hills and Powder River Basins, and Northeast of Casper, Wyoming (Ref. 48). The \$50 per pound U.S. reserves were estimated to be 52% in New Mexico and 31% in Wyoming (January, 1978).

Australia has very large remaining reserves and could be dominant in setting world market prices (Ref. 52). However, one school of thought is that the U.S. must maintain its uranium productive capacity in spite of world markets. It appears that domestic uranium production as well as nuclear power will be subject to political and strategic considerations. At the moment uranium prices are depressed.

Experiments in hydraulic borehole mining of the Teapot sandstone near Casper, Wyoming showed success (Ref. 19). The water pressure required to cut the ore was less than 4500 psi. A sample of the ore had a confined compressive

TABLE 7-1

Selection Criteria for Ranking Mineral Deposits

Safety

1. Roof control
2. Roof caving appears possible

Health

1. Need to reduce manpower exposure to hazards (radioactivity, dust, etc.)

Environmental Impact

1. Recycling water will reduce pollution problem
2. Pipeline transport to mill is environmentally preferable

Recovery

1. Need improved recovery

Economics

1. Improved economics is crucial to compete
2. There is high water inflow to mine, requiring pumping in any case
3. Ore is soft; monitor production would be high
4. Selective mining or grade sorting not required

Dependence on Petroleum-Based Fuels

1. Diesel transport now used: should electrify transport

Strategic Importance

1. Mineral is strategic
2. Import dependence is high
3. Has export potential

Technology Applicability

1. High fraction of U.S. reserves amenable to hydraulic mining or transport

Risks of Hydraulic Mining

1. Water may dissolve ore, harming roof support
2. Water required may soften floor rock, affecting transport
3. Ore may dissolve, forming corrosive solution
4. Hardness of the ore may change as mining advances

TABLE 7-2

RANKING OF MINERALS

- A. Minerals in Order of Rank for Underground Hydraulic Mining and Hydraulic Transport.
1. Uranium sandstone - Wyoming
  2. Oil-bearing sands - California and Texas
  3. Sandstone - (St. Peter, at less than 300 ft. depth)
- B. Minerals in Order of Rank for Hydrotransport Only
1. Uranium - New Mexico (and Wyoming)
  2. Potash - New Mexico
  3. Trona - Wyoming
  4. Phosphates - Idaho
  5. Borates - California
  6. Oil-bearing sands
- C. Additional Unranked Candidates for Hydrotransport Only
1. Copper ore
  2. Limestone (shallow underground mines)
  3. Lead/zinc
  4. Manganese (rhodochrosite in Butte, Montana) (Ref. 82)
  5. Hematite - Michigan

strength of 4000 psi under a confining pressure of 200 psi (Ref. 26). One may estimate that the unconfined compressive strength might be below 3000 psi, if a core sample could be obtained.

On this basis, one can consider Wyoming sandstone as a potential candidate for underground hydraulic mining. However, the tested material was at depths of less than 100 ft. Therefore it is not assured that other Wyoming deposits at depths of 300 to 3500 ft. will be suitable. The range of hardness encountered in a single mine may prevent hydraulic mining in part of the deposit.

Data on uranium in the Exxon Highland underground mine (Ref. 51) indicates that the ore consists of soft, water-saturated and extremely unstable sediments. The host sandstones are fine to coarse-grained. The vertical interval of uranium is 110 to 180 ft. The rock strength averaged 500 psi but some was much weaker. The mine at a depth of 650 ft. operated from 1975 to 1980, when it was closed because of low uranium prices. The mine had major ground-control problems and used "Split-Set" friction roof bolts.

The mine was dewatered by 2000 gpm capacity pumps. The management believed that prior drainage of the orebody was very important to increase structure stability. The possibility of hydraulic borehole mining from underground seems to be feasible for this mine.

The Anaconda Corp. has located a large uranium deposit under Green Mountain near Jeffrey City, Wyoming which they hope to develop over the next ten years. Further data on the deposit and ore properties are needed before a study can be made of hydraulic mining feasibility. The shaft depth contemplated is 3500 ft. The conventional mine would hoist 1800 ft. to an adit, 20,000 ft. long, through which ore would be transported to the side of the mountain. An alternative would be to hydraulically hoist 3500 ft., then flow slurry by gravity down the mountain. The added cost of hydrohoisting an additional 1700 ft. would be offset by the savings in avoiding the necessity for the 20,000 long adit.

### C. Uranium sandstones in New Mexico

The Grants mineral belt in New Mexico is 95 miles long and 20 miles wide and produces nearly half the uranium oxide mined in the U.S. Most is from underground mines. The boom started in 1950, slumped in the 1960's and early '70s, then boomed again until the reaction to Three Mile Island after 1979. The price of yellow cake dropped to \$28.50 per lb. in 1980, less than half the price in 1976. Prices are predicted to decline during the 1980's. (Ref. 52 and 53). In 1978 there were 30 companies active in northwestern New Mexico (Ref. 54), but several have suspended operations recently because of depressed prices.

The area geology is described in a variety of reports (Ref. 55, 56, 57). In the Ambrosia Lake deposits, north of Grants, the uranium occurs mainly in the medium to coarse-grained Westwater Canyon sandstone member of the Morrison

formation. The ore is found at depths of 300 to 450 ft. near the Ambrosia dome, at 1200 to 1500 ft. several miles southeast of the dome (Ref. 57), and at depths near 3100 to 4000 ft. at the Gulf Minerals' Mt. Taylor mine at San Mateo. (Ref. 58). The Mt. Taylor reserves lie in a 6 mile long trend and are estimated at 128 million pounds of  $U_3O_8$ , which is 1/3 of the remaining reserves in the Grants belt (Ref. 59) or 22% of low-cost U.S. reserves. The grade is substantially above 5 lbs/ton. Two 3300 ft. shafts were completed in 1979 at a cost of about \$200 million. One shaft is 24 ft. and the other 14 ft. in diameter. (Ref. 60).

The strength of rock in the Mt. Taylor mine was 2730 psi in barren rock near the shafts and 8030 psi ( $565 \text{ kg/cm}^2$ ) for ore from a test slope (Ref. 61). Therefore the ore appears to be too hard and cannot be hydraulically mined by monitor jet. Jet cutting tests funded by Gulf Minerals tend to verify this conclusion.

It is planned to mine by drill-and-blast. A coarse fraction of 50% of the mill tailings may be returned to the mine for backfill. Since water inflow may exceed 7000 gpm, and must be pumped out of the mine in any case, it is expected that hydraulic hoisting and transport will be practical. Gulf Minerals is conducting development of a hydraulic transport system for use underground, primarily in driving haulageways. The crusher, mixer and centrifugal pump are rail mounted. They also are testing advanced high head pumps (e.g. Zimpro) for hydraulic hoisting of ore slurry in one stage to the surface.

At the small town of Crownpoint, N.M., northwest of Grants, a major uranium mine was planned by Conoco as a joint venture with Wyoming Mineral, a subsidiary of Westinghouse. The construction was terminated in early 1981 because of low uranium prices. The plan was to truck the ore 22 miles south to Prewitt, using about 40 trucks per day. (The original plan to build a mill near the mine was not approved.) The planned mine depth was 2200 ft. and had an estimated life of 20 years at a production rate of 1350 TPD. The reserves are at least 14.5 million pounds of  $U_3O_8$ . The area to be mined is 2.5 miles long by 2000 ft. wide.

It appears that a 22 mile pipeline to transport ore from the mine to the mill would be more economical than trucks. However, the problems of obtaining environmental approval for a buried pipeline are considered serious, because of radioactivity of the slurry and the need to pass through Indian lands.

The rock strength in the Conoco mine varies widely from 50 to 28,000 psi in haulage drifts, with most in the 2000 to 5000 psi range. (Ref. 62). The ore strength may be comparable. Therefore it is not considered practical to use hydraulic mining. The ore could be crushed underground and hydraulically transported to the mill. Water inflow to the mine is estimated to be 3800 gpm after 2 years, decreasing to 3000 gpm during the mine life. Water temperature is  $94^\circ\text{F}$ .

It was reported that the Conoco ore body is highly dispersed, "like raisins in a cake" and therefore it was believed that backfilling of stopes might not be necessary. This could be a crucial legal problem if radioactive mill tailings were to be used for backfill with the possibility of contaminating the uranium-bearing aquifer from which the ore was mined, or other aquifers supplying water to the town of Crownpoint.

Northeast of Crownpoint, the Phillips Uranium Corp. has completed the sinking of shafts at their Nose Rock Mine to depths of 3295 and 3215 ft. There are two shafts completed, and a third was planned initially (18', 16', and 14'). The proven reserves are more than 25 million pounds of  $U_3O_8$ .

Total production targeted is 2950 TPD, with 1750 TPD through Shaft #1 and 1200 through Shaft #3 (if completed). Figure 7-1 shows a sketch of a mine similar to the Nose Rock mine.

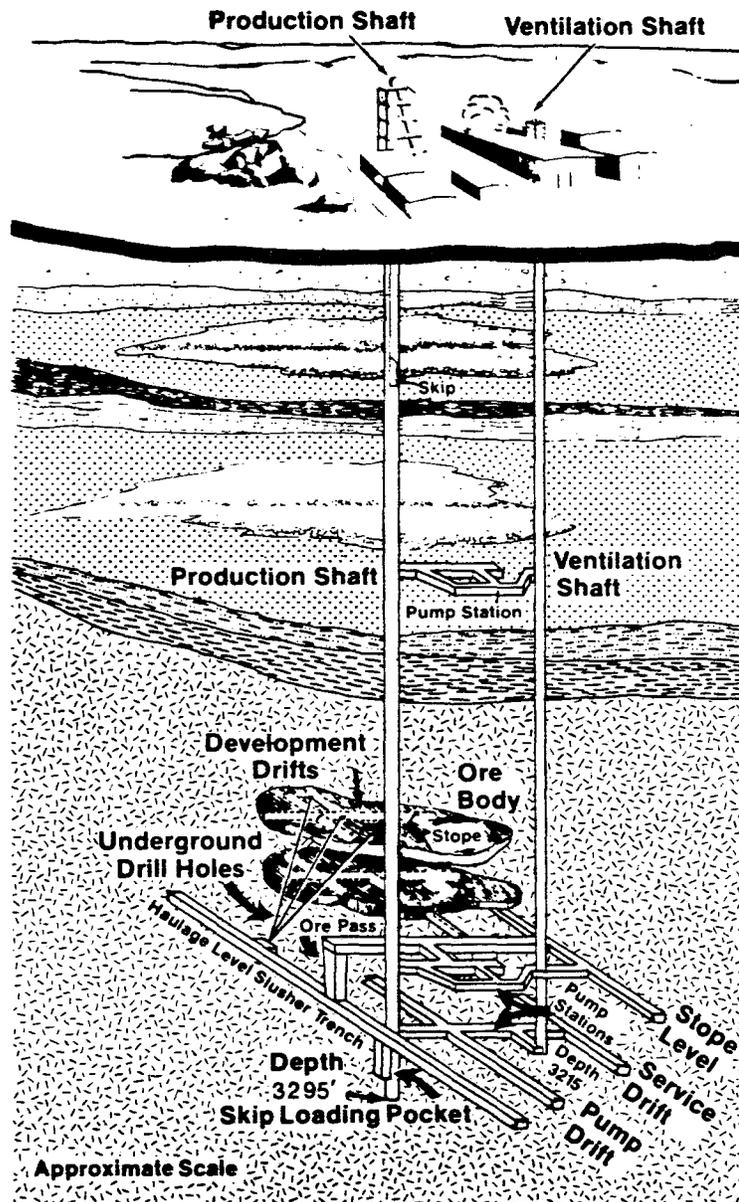
Water inflow is predicted to be 3000 to 6000 gpm at a temperature of 116°F. Backfill will be required to prevent roof caving and flooding of the stopes. As of December 1980, approval had not been obtained to use mill tailings for fill. The mine was put on standby status in 1981.

The ore strength is 300 to 1400 psi in the upper seam, which has low reserves, and 1800 to 2600 psi in the other two seams. This average strength would appear to put the ore in a strength category where hydraulic mining might be marginally applied. However variations of ore strength can be expected. We therefore conclude that hydraulic mining is unlikely, but that hydraulic transport and hoisting is technically feasible.

The three large deposits in the Grants mineral belt, associated with the Gulf, Conoco, and Phillips projects, have similar characteristics which are given in Table 7-3.

#### D. Uranium Deposit in Nebraska

In January 1981, an announcement was made by Kansas-Nebraska Natural Gas Company, Inc. of Hastings, Nebraska that its subsidiary, Wyoming Fuel Company, had discovered a significant uranium prospect (Crow Butte) in northwestern Nebraska. The "probable potential" reserves are estimated in excess of 25 million pounds of uranium oxide. The potential commercial mineralization occurs in an area measuring approximately six miles in length by one-half mile wide. Twenty eight drillholes have shown a grade times thickness in excess of 0.5 (i.e. 5 ft of at least 0.1%  $U_3O_8$ ) and thirty four show corresponding values of 0.1 to 0.5 grade times thickness. There is not adequate information available to assess the feasibility of hydraulic mining of this ore, although hydrotransport would appear feasible.



An artist's rendering of a mine similar to Phillips Uranium Corporation's Nose Rock project in Northwestern New Mexico.

Figure 7-1

TABLE 7-3

Characteristics of Large Uranium Mines near Grants, N.M. (Ref. 63)

Owner	Gulf	Conoco	Phillips
Mine Reserves, 10 <sup>6</sup> lb.	Mt. Taylor 128	(Plans deferred) 14.5+	Nose Rock (Standby Status) 25+ (25 in 1900 of 60,000 total acres)
Potential production rate, TPD	4200	1350	1750 (later 2950?)
Shaft diameters	24 ft. & 14 ft.	-	18 ft.. 14 ft. (and 16 ft?)
Shaft depth, ft.	3300	2200 (planned)	3295 and 3215
Water inflow, gpm	7000	3800-3000	6000-3000
Water temp., °F	126°F.	94°F	116°F
Distance, mine to mill	3 miles	22 miles	~1 mile
Investment to 1981	\$200 million+	\$35 million	\$140 million
Ave. comp. strength of ore	8030 psi	2000 to 5000 psi	1800 to 2600 psi
Range of strengths	?	50 to 28,000 psi	300 to 2600 psi +
Area of mine	6 mi. x 1 mi.	2.5 mi x 0.38 mi.	?

Some of the major problems encountered in underground mining of uranium in New Mexico are (Ref. 64):

1. The roof control is often difficult because of wet and/or weak sandstone. Conventional roof bolts may not hold well. The use of Split-Set roof bolts with wire mesh is becoming more common. There may be a problem of rust corrosion of the Split-Sets. Backfilling is often required to prevent flooding by upper aquifers and to improve ore recovery.
2. The mines may be wet and ore soft so that the "soupy" muck is difficult to pick up behind a roadheader (Dosco or Alpine). Improved roadheader design is desirable.
3. If roadheaders cannot be used, the drill-and-blast method requires more manpower in an area with a shortage of adequately-trained miners and of high labor turnover.
4. Haulage by conveyor is only practical in a dry mine. Usually slushers are used in stopes, or shuttle cars with roadheaders.
5. Fans of exploration drillholes are drilled from underground to explore for ore and to drain water from the formation. This is important to dry the rock for improved strength and roof control. However, there can be a dust problem with roadheaders, requiring water or steam sprays.
6. In deep mines, there is high temperature of the water inflow, requiring refrigeration of air to obtain an acceptable working temperature.
7. The escape of radon gas from the ore requires very high ventilation airflow. Sealants to hold radon in the rock formations may be of interest.

All the above problems relate primarily to the mining operations in New Mexico and still will persist if hydraulic transport were used on the haulage level in these mines. Therefore hydraulic transport will have to be evaluated primarily on its economic merits.

## B2. Oil-bearing Rocks

### A. The Resources

The U.S. has extensive resources of petroleum in depleted oil fields and heavy crude oil and tar sand deposits.

In 1979 about 10% of all crude petroleum produced in the world was from heavy crude and tar sands. It has been estimated (in 1979) that in 20 years heavy crude and tar sands will account for one third or more of total petroleum production. (Ref. 65). The oil-in-place quantities of heavy crude and tar sands in the world are at least ten times larger than discovered conventional oil resources.

Approximately 300 billion barrels of light, medium and heavy crude oil and tar sands will remain in the ground in the U.S. after recovery of petroleum by primary, secondary and enhanced oil recovery (EOR) techniques.

It is well known that present primary and secondary methods for recovery of oil from wells leave approximately 50 to 70% of the oil in the ground. It is estimated that U.S. heavy crude oil in place (12-21-77) was approximately 110 billion barrels (Ref. 65, p.95). It is estimated that approximately 107 billion stock tank barrels of heavy crude oil will remain in U.S. reservoirs with existing technology, economics and political climate. Approximately 48% of the heavy crude has an API gravity between 20°-25°, and 52% has API gravity less than 20°. An additional 200 billion barrels of light and medium crude oil with API gravity above 25° will remain in U.S. reservoirs, making a total of about 300 billion barrels of light, medium and heavy crude which is now or will become available for recovery by mining methods after enhanced oil recovery systems have been used. Also, mining may be preferable to secondary or tertiary recovery because it will permit a higher total recovery of the resource.

The potential exploitation of this resource of about 300 billion barrels of petroleum appears to be receiving relatively little attention in the U.S. in comparison with major efforts on oil shale and synthetic fuels from coal. By comparison, in Canada there are two major tar sand operations in the Athabasca area and a total of 45 active experimental recovery projects in Alberta and Saskatchewan for tar sands and conventional heavy oil, including 30 pilot in situ thermal recovery programs.

Prior U.S. studies of oil mining (Ref. 66, 67, 68, 69, 70) have not taken into consideration the possibility of hydraulic mining or hydraulic transport of oil sands. Hydraulic methods are particularly suited for safe mining and transporting of gassy ores like coal and oil sands. They are adaptable to remote control and to safe mining underground without roof support.

Hydraulic mining and hydrotransport are also applicable to large scale surface mining of oil and tar sands. Hot water is presently used for processing of Canadian tar sands.

Oil sands with overburden of less than 150 ft. and possibly up to 500 ft. or more are amenable to surface mining. With overburden depths of 150 to 500 ft., it may be possible to stimulate production from oil sand by using steam injection through pipes directed outward and upward into the oil sand formations from mined tunnels located in the underlying rock. For depths greater than 500 ft., this system also may be considered, but in addition other in-situ production methods are possible which require high pressures (injection of gas, water or combustion products). Sufficient depth is required in these cases to avoid hydraulic fracture of the formation.

In all cases of overburden in excess of 150 ft. to 500 ft., underground mining of the oil sands by mechanical or hydraulic means and transport to surface or underground processing equipment is possible. The use of borehole hydraulic mining from underground drifts either below, within, or above the oil sand deposit is a possibility. In order to minimize subsidence and to avoid surface disposal, the sand tailings may be returned to the mined out zone.

Experience to date in recovery of synthetic crude oil from Canadian tar sands has indicated that open pit mining methods may only permit recovery of one-sixth of the total in-place bitumen resource in the surface mineable area. Problems of water supply and tailings and sludge disposal are severe. Tailings ponds containing clay and bitumen are a hazard to bird life. In situ recovery studies show that cyclic steam displacement may recover only 20% of the original bitumen resource. Severe problems exist with respect to water availability and disposal of waste liquids underground. It may be expected that many of these problems will limit exploitation of oil sand deposits in the U.S. unless adequate research is conducted to find solutions.

A major effort will be required to identify deposits in the U.S. of oil sands remaining in oil fields and heavy crude deposits which are or will become available for oil recovery by surface or underground mining and to screen them in order to identify the most feasible and applicable hydraulic mining and processing techniques for each deposit. Present mining methods and also advanced technology, including surface and underground hydraulic mining and transport and partial or complete underground processing, should be considered. Research requirements should be identified which will permit effective development of oil sand resources by mining methods.

If oil sand deposits can be found which have secondary mineral content, the economics may be affected. Examples are oil sand deposits where other materials may be recovered as byproducts, such as uranium, glass sands, foundry sands, heavy minerals, or sulfur.

In studying the economics of hydraulic mining and borehole mining from underground, it would be desirable to compare alternate in situ processes, including the use of hot water and chemicals for extraction, either from the surface or underground.

The comparative environmental impact of water purification and reclamation processes will be critical to selection of a preferred recovery method.

#### B. Reserves of Oil-Bearing Rocks

Table 7-4 shows data on the reserves of oil in oil-bearing rocks in five deposits in four states. The depth varies from 850 to 1,500 ft. and the oil deposit thickness from 20 to 200 ft. Detailed data on the properties of the oil bearing rock are not available and would require access to drilling data. However, the rocks include sandstones, dolomite, and shales, some of which are believed to be poorly consolidated or fractured.

Data on these deposits may be found in the Golder report, Reference 66, (pp. 123-195), in which underground mining of these deposits by conventional methods was considered. The features of these deposits which are critical to the feasibility of mining the oil hydraulically are:

1. Presence of relatively competent rock formations in or near the oil-bearing formation in which entries can be developed for transport and control of remote mining operations.

TABLE 7-4  
DATA ON OIL BEARING ROCK DEPOSITS

Field	State	Reserves 10 <sup>6</sup> bb1	Ave. Depth ft.	Thickness ft.	Area acres
Circle Ridge (Tensleep)	Wyoming	44.1	900-1200	110	260
Circle Ridge (Phosphoria)	Wyoming	16.7	850	110	640
Casmalia	California	100	1000	200	2090
Yates	Texas	1000	1500	220	Large
Irma	Arkansas	51.5	1150	20-27	2166

2. The gas emissions must be low and the formation gas relieved by drainage prior to mining. Gas dilution by air ventilation must be possible, and no blasting can be allowed. The spark hazard due to sparks in a siliceous formation would be severe unless all mining operations are remotely-controlled and sealed from the manned entries.
3. Oil seepage from the formation into entries must be acceptably low.
4. The formation should not have large faults or excessive dip.

It appears that the safety aspects are too hazardous to provide technical feasibility for mining of the Circle Ridge, Casmalia, or Yates fields by either present or hydraulic methods.

The Irma field can use the drainage with steam method developed at Yarega in the USSR. The Wheeler Ridge field may be applicable for gravity drainage as discussed in Ref. 66 or for inverted hydraulic borehole mining as discussed below.

#### C. Examples of Movable Oil Sand Deposits

Several studies have been made of the feasibility of mining oil by surface or underground methods (Ref. 66, 67, 69, 71, 72).

The simplest method of mining involves driving entries below or in the oil-bearing formation and drilling holes for gravity drainage. This has been practiced by Conoco in Johnson County, Wyoming (Ref. 73). The light oil of 28° API gravity drains through horizontal drillholes 248 to 1700 ft. long entries.

A study of the gravity drainage process was made by Golder Associates (Ref. 66). An example was studied which was based on the Wheeler Ridge Field in Kern County, California. The parameters of the oilfield are summarized in Table 7-5.

The top of the oil-bearing deposit is 1000 ft. to 1310 ft. below the surface and the average thickness of the pay zone is 170 ft. Proven acreage as of 1974 was 620 acres with oil remaining in place of 93 million barrels. The gas to oil ratio in 1976 was only 139 cubic feet of gas per barrel of oil. The low production rates have been due to high viscosity of the oil and low permeability of the formation.

In order to recover the oil by underground gravity drainage, it would be necessary to drill many closely-spaced drainage holes (e.g., closer than 50 ft. at the ends of drill holes up to 250 ft. long). There is no proven method for predicting the percent recovery attainable which will be limited by the

TABLE 7-5

DATA ON WHEELER RIDGE OIL FIELD

(Ref. 88)

Permeability (millidarcies)	Approx. 800
Porosity (%)	Approx. 32
Oil Gravity	22° API
In-Place Grade (bbl/T)	0.28
Depth to Top of Oil (feet)	
Minimum	1000
Maximum	1310
Thickness of Oil Zone (feet)	170
Dip of Oil Zone	Asymmetrical Anticline--Dips Vary
Overlying Rock	
Type	Sand, Sandy Clay, Clay, Sandstone, Alluvium
Formation Name	San Joaquin-Etchegoin, Tulare
Age	Pliocene to Recent
Underlying Rock	
Type	Siltstone with interbedded Sandstone
FM Name	Fruitville
Age	Upper Miocene
Oil-Bearing Rock	
Type	Sandstone interbedded with Siltstone
FM Name	Santa Margarita (Coal Oil Canyon Zone)
Age	Upper Miocene

permeability and viscosity.

As an alternate, we can consider hydraulic mining the oil-bearing sand and transporting it to the surface as a slurry to permit surface processing. The feasibility of hydraulic mining such a mineral remains to be demonstrated. The ore at depth may be stronger than the unconsolidated ore previously tested by surface borehole mining. (Ref. 17). The use of manned hydraulic monitor jets within the oil formation is ruled out because of safety problems, such as the gas evolution. This also rules out other underground mining methods to be combined with hydrotransport, unless the mining is by remote control. However, one can consider hydraulic borehole mining from entries driven in competent rock below or above the deposit. The location below is preferred because it would permit gravity flow of slurry from the deposit to the entries. This would be more reliable and require less pump energy than using a jet pump as in hydraulic borehole practice from the surface.

For safety, the boreholes which would be drilled upward from underground would have to be cased to the bottom of the deposit. This will prevent gas emission, it would prevent washout and caving during mining, and permit sealing after ore excavation. If desirable, tailings from the ore processing could be reinjected into the cavities. This would avoid surface disposal and help prevent subsidence. The possibility exists for vat leach processing of ore underground to extract part or all of the oil prior to backfilling the cavities with tailings. This would obviate the necessity for transporting all the sand to a surface mill. However, the operation of an oil extraction operation underground remains to be demonstrated and its safety is in doubt.

Hydraulic mining by a borehole method is desirable because it does not expose men directly to the oil-bearing formation and to the associated hazard of fire and explosion. It also permits development with entries of small size, since their size is not determined by ore haulage requirements.

### B3. Sandstone

Sandstone is mined in various parts of the country for foundry sand, glass sand and oil well frac sand. The St. Peter sandstone in Minneapolis is tunnelled by hydraulic mining at water pressures below 300 psi and low production rates, (8.7 TPH) with hydrotransport. (Ref. 73 and 74 ). The unconfined compressive strength varies from zero to 2800 psi. The depth is typically 100 ft., which is less than the 300 ft. minimum depth which we set as a screening criterion. Oil well frac sand is surface-mined in the Jordan sandstone of Minnesota. Foundry sand is mined underground from the St. Peter sandstone in Iowa by the Martin-Marietta Corp. The mine at Garnavello, Iowa is next to the Mississippi River and is a drift mine with less than 200 ft. of overburden. The ore is blasted and hauled to a crusher. (Ref. 75). Experiments by the Bureau of Mines (Ref. 76) have shown that the sandstone could be disintegrated by a monitor jet at 300 gpm and 900 psi if the nozzle was close (a few feet) from the face. However, visibility and safety require the operator to be more remote from the face, or protected.

A preliminary economic comparison of hydraulic mining and hydraulic trans-

port with conventional mining and transport indicate comparable costs of product, in the neighborhood of \$3 to \$4 per ton (See Section 9 below). Therefore further economic studies are warranted which should account for new equipment costs and for relative maintenance costs in the Martin-Marietta mine.

This mine ships much of its product 200 miles to a large customer. However, pipelining of the product 200 miles is not considered practical.

There is another underground sandstone mine operated by UNIMIN in Crystal City, Missouri. However, most sandstone mines are surface mines or drift mines with less than 300 ft. of overburden. There does not appear to be any broad application for hydraulic mining or hydraulic transport of sandstone from underground mines more than 300 ft. deep.

The Pennsylvania Glass Sand Corp. in Berkeley Springs, W. Va. has used surface hydraulic mining for 20 years to break up soft unconsolidated sandstone after blasting. This appears to be a good application for monitor jets, except in northern regions during the winter where ice formation is a problem.

#### B4. Potash

Potash is mined underground as sylvinite and polyhalite near Carlsbad, New Mexico by seven producers (Ref. 77). Reserves are 100 million short tons. Total U.S. production in 1976 was 2.2 million metric tons, about 40% of domestic demand. The U.S. production is 95% consumed by the fertilizer industry. Major imports of fertilizer are from Saskatchewan, Canada primarily into the northern agricultural states (Illinois, Iowa, Indiana, Minnesota, Ohio and Wisconsin). Carlsbad product supplies fertilizer mainly to the southern and southeastern states.

Canadian potash producers can capture northern fertilizer markets by shipping potash by freighter or ocean-going barge to Florida and returning phosphate to ports in western Canada.

A study was made of the feasibility of pipelining potash from Saskatchewan to a port at Vancouver (Ref. 78). Tests showed that potash can be transported as a slurry with KCl brine or with crude oil. However, the pipeline was not built.

By 2000, U.S. production of potash is projected to decline, supplying less than 10% of U.S. consumption (Ref. 79). Domestic consumption is projected to double to 11 million metric tons. In the future, Utah reserves in the Paradox Basin could provide a major new supply source (Ref. 80) to supplement declining production from New Mexico. Texasgulf is active in solution mining near Moab, Utah. Eventually solution mining may be applied to deep deposits in Montana.

Potash has an average compressive strength of only  $288 \text{ kg/cm}^2$  (4100 psi) (Ref. 27), but with variations from 420 to 4650 psi. Its Mohs' hardness of 2 to 2.5 is similar to that of halite (rock salt). Potash is believed to be too

hard for hydraulic mining.

A recent study was made in Germany of the possibility of hydraulic hoisting of potash from underground (Ref. 81). It was concluded to be economically justifiable when expanding production. A hydraulic hoist system with pipes for the fine fraction (0 to 4 mm) can be added in an existing shaft with minimum disruption of skip operation. The economics are improved if hot brine is piped underground to dissolve KCl during the hoisting process. We have made a cost study of a system which recirculates brine at ambient temperature as the slurry carrier medium (See Section 9).

#### B5. Trona

Trona is a sodium carbonate ( $\text{Na}_2\text{CO}_3 \cdot \text{NaHCO}_3 \cdot 2\text{H}_2\text{O}$ ). It has a crystalline appearance and is usually light to dark brown. Its hardness ranges from 2.5 to 3 on the Mohs' scale and it has a specific gravity of 2.1. Trona has an uniaxial compressive strength of around 8000 psi (563kg/cm<sup>2</sup>). It is water soluble (Ref. 82).

The trona beds extend over more than 1300 square miles in southwestern Wyoming. The reserves are over 50 billion metric tons (Ref. 83). Production was 7.5 million metric tons in 1979 (90% by mining) and the same in 1980. (Ref. 84). Trona is mined underground near Green River and Rock Springs, Wyoming. The rapid growth of mining is due to a phaseout of synthetic soda ash plants in the U.S. (Ref. 85). Tenneco Oil Co. is opening a new mine by 1984. The FMC Corp. mines 4.8 million TPY by blasting at a depth of 1500 ft. in a 10 ft. seam. The Stauffer Chemical Co. mines 3 million TPY by blasting and by continuous miner at 850 ft. depth. The Allied Chemical Corp. mines by blasting, by longwall, and by room-and-pillar methods at 1600 to 1900 depth in a flat seam of 8 to 11 ft. thickness (Ref. 82). Texasgulf mines 1.9 million TPY with continuous miners. The ore is softer than that of Allied Chemical (8,000 psi) or of the FMC mine.

The Stauffer Chemical Co. trona has a uniaxial compressive strength of 6435 psi (44.1 MPa) (Ref. 101).

It is concluded that trona is too hard to break with a monitor jet. However it might be transported from underground by water or by a brine solution. Since one refining process (the sesquicarbonate process) requires initial solution in water, one could consider starting the solution process during hydrotransport, as proposed for hydraulic hoisting of potash (Ref. 81). The use of water underground and its possible effect on roof control could pose a safety problem.

The second refining process produces monohydrate by initial calcining before the ore is dissolved and is now the dominant process (Ref. 85). However, it would not be practical to calcine underground prior to hydraulic transport.

FMC is developing solution mining of trona and intends to add 1 million TPY capacity by 1984. Vulcan Materials and Allied Chemical Corp. also are experimenting with solution mining. These developments are based on using

special solvent liquids (caustic solutions) through boreholes from the surface. The estimated cost savings of 25% in production could bear on the future of Wyoming soda ash in world markets.

Trona mining is effectively done by longwall or continuous miners. In these cases, there is no major problem of mine safety or health except nuisance dust in cutting, haulage and skip hoisting. For drill-and-blast mining there is a health problem where ANFO is used. However blasting is becoming less used. There is no problem of water inflow or waste water disposal from the mines.

Trona does not face threat from imports and is extensively exported. Cost competition is important.

The processing mills are generally within one mile from the mine and therefore truck haulage is practical. Pipelining would not aid greatly in surface transport. Trona is partially soluble in water and produces solutions which are corrosive. Hydrotransport would require special pipe materials.

As a conclusion, we can identify no major advantage for hydraulic hoisting and hydrotransport of trona as a main transport system. However, by analogy with potash, (Ref. 81), there may be cases where existing mine skips are at the limit of capacity. In that case, increase in production rate could be obtained by installing hydraulic hoisting in an existing shaft at reasonable capital investment and with minimal disruption of skip operation.

#### B6. Phosphates (Ref. 86)

Eighty four percent of U.S. phosphate production (50.7 million TPY) is from surface mines in Florida (Ref. 87) and North Carolina.

Phosphate production in Florida and North Carolina is mainly by surface mining, in some cases with hydrotransport to the mill. Borehole mining experiments have been conducted in North Carolina by Dresser Industries and by FMC Corp.

In Florida, hydraulic borehole mining experiments were conducted in St. Johns County by the Bureau of Mines in 1980. The depth of the phosphate bed is 200 to 300 ft. The possibility of mining this deposit by underground methods is remote. The adjacent blacky limestone forms the Florida aquifer and would pose some problems of mine flooding and of contamination of water in the aquifer. Total U.S. production of phosphates is 60 million TPY (Ref. 88). Western production (mainly in Idaho, Montana and Utah) is 10% of the total and about half of that is used for production of elemental phosphorus and the rest for fertilizer. Most western production is from surface mines (Ref. 89). The western production is assumed to be constant at less than 8 million TPY to the year 2000 (Ref. 90).

Western phosphate ore is classified as main bed if the grade is 31 to 32%  $P_2O_5$ , and as furnace shale if the grade is 24 to 26%  $P_2O_5$ . Main bed ore is calcined to reduce hydrocarbon levels before it is used in wet acid plants. The furnace shale is used in electric furnaces to produce elemental phosphorus. It is also beneficiated to produce a 30 to 32%  $P_2O_5$  product for wet-process phosphoric acid manufacture (Ref. 91). Phosphate rock is digested with sulfur-

ic acid to produce phosphoric acid and a waste impure gypsum.

The underground "Maiden Rock Mine" south of Butte, Montana was shut down in 1965 to 1968. The phosphate bed is 35 to 40 ft. thick of which more than 24 ft. is reported to be soft material. The Cominco-American underground mine produces 200,000 TPY from a rock seam 4 ft. thick of strength 15,000 to 20,000 psi at a depth of 300 to 400 ft. The seam dip is 30° to 60°. The reserves are 6 million tons. Mining tests in the Douglas mine near Drummond, Montana (now closed) indicated the ore had a Mohs' hardness of 3 to 4 (Ref. 92). This ore is clearly too hard for hydraulic mining. The possibility of hydraulic hoisting exists, depending on the availability of water.

The deposits of phosphate rock in the Western Phosphate Field of Caribou, County, in southeastern Idaho have been surface mined since 1945. Production was 6 million tons in 1975. There is evidence of groundwater flow systems in most of the phosphate formations (Ref. 93).

A study of the Diamond Creek open pit mine estimated up to 1670 gpm of water inflow into each panel of the mine. The plan for the underground mine assumes 2000 gpm will be provided by a pipeline from the nearest available source.

Western phosphate varies from soft, friable, altered phosphatic shale to hard, tightly cemented, unaltered phosphatic rock (Ref. 94).

In general it may be concluded that surface mining will predominate for phosphate production and there is no urgent need to develop improved underground methods for mining the western deposits of phosphate rock at this time. It is only the near-surface deposits that are oxidized enough for phosphatic acid production. The deeper rock is not useable and too hard for monitor jet mining (Ref. 95) (See also Ref. 96 and 97).

#### B7. Borates

Borates have long been mined in Death Valley, California. They are widely used in the fiberglass, glass, and ceramic industries, as well as in detergents. The worlds largest borax mine is an open pit mine at Boron, California. It contains reserves of 100 million tons of 25% B<sub>2</sub>O<sub>3</sub> ore (Ref. 98) which is 43% of U.S. reserves. Total U.S. production of boron contained in boron compounds in 1978 was 242,000 tons, 52% of world production (Ref. 99).

From 1976 to 1979, American Borate Corp. has developed the underground Billie mine at Death Valley (Ref. 100). The proven ore body is 5000 ft. long, several hundred feet wide and in places over 300 ft. thick. The reserves in the Death Valley area approach 10 million tons of ore having over 20% B<sub>2</sub>O<sub>3</sub> content. The total resource is estimated at 45 million tons. The ulexite, colemanite and probertite ore in the Billie mine is from 400 to 1200 ft. deep. The planned production rate is 600,000 TPY, or 1800 to 2800 TPD for a life of 20 to 25 years.

The unconfined compressive strengths of the ore are (Ref. 100):

ulexite - 2000 to 3000 psi (140 to 211 kg/cm<sup>2</sup>)

colemanite - 5000 psi (352 kg/cm<sup>2</sup>)

probertite - 20,000 psi (1408 kg/cm<sup>2</sup>)

Ulexite occurs as a halo surrounding the tincal ore body and it is only the ulexite which appears soft enough to consider hydraulic mining. However, ore of over 10,000 psi strength must be cut for production mining by roadheaders.

The mine water inflow is only 20 gpm, so all mine water is now hauled in by truck. The colemanite ore is hauled by truck 30 miles to the processing plant at Lathrop Wells, Nevada. The probertite and ulexite are trucked directly to a mill at Drum, California. Selective mining is important which is not very compatible with a single hydrohoist system. However, gravity separation could be conducted under roof at the mine surface. Mine water inflow of 20 gpm would have to be supplemented by water from other sources, such as Lathrop Wells, Nevada.

The mine uses a cut-and-fill stoping method to obtain high recovery and to prevent surface subsidence, as required by the National Park Service. The minus 2 inch fill of shale is dry placed by dumping down raises and spreading to the stopes. Four foot head room remains on top of the filled stopes. The calcareous shale fill attains a high strength of 750 psi when 7% water is added and it is compacted to 85% of maximum compaction. Any water which mixes with the ore tends to harden and make a type of cement.

It is concluded that the shortage of water in Death Valley, the adverse effects of water on ore, and the need for selective mining and transport make it undesirable to consider hydraulic transport of borates from underground in the Billie mine.

## 8. TECHNOLOGY OF HYDRAULIC TRANSPORT AND HYDRAULIC HOISTING

### A. Pressurization Systems

The process of hydraulic transport generally includes:

1. Disintegration of mineral by monitor jet or by mining machine or by blasting and crushing.
2. Slurry formation by adding water to obtain the desired concentration.
3. Pressurized transport of slurry through a hose or pipe by gravity, jet pump, centrifugal pump or feeder system.
4. Wet crushing or grinding as needed for processing and separation of ore from tailings
5. Dewatering of ore and disposal of water and tailings.

The reliability of a hydrotransport or hydrohoist system depends primarily on its pressurization system, which have usually been centrifugal pumps or positive-displacement pumps. Centrifugal pumps are used for high flow, low-head applications (typically not over 100 psi pressure rise per stage). Positive-displacement piston pumps are used for high head, low-flow applications and, since they require check-valves, the particle size generally cannot exceed one millimeter. They are used for transporting fine mineral slurries over long distances or up deep shafts where pressures over 1000 psi are needed.

### B. High-Head Pumps and Feeders

For example, Wilson-Snyder piston pumps are used on the Black Mesa pipeline for finely-ground coal. Piston pumps of the types used for pumping drilling mud in oil and gas well drilling can be modified for slurry pumping. Examples include the Wirth pumps used for fine coal hoisting, coal preparation plant tailings, and for chalk slurry for cement production. The latter system has operated since 1964 in transporting chalk slurry over a 5 km distance through a 400 mm pipe. (Ref. 101). Wirth pumps are sold in the U.S. by MidContinent Corp., which supplied pumps for the Calaveras limestone pipeline (Ref. 39).

When coarse particles over 1 mm must be handled at high pressures, then various other slurry pressurization systems can be considered, whose common element is "batching." High speed centrifugal pumps in series, or positive displacement pumps, deliver relatively clear water at high pressure behind a batch of slurry in a pipe or chamber and push it as a slug through a pipe, either horizontally or vertically. Two or three pipes or chambers can be phased in operation to provide nearly continuous delivery. Examples of a pipe feeder system are the Japanese Hitachi Hydrohoist and the German Siemag Pipe Feeder. The Hitachi system is used in hydrohoisting coal of plus 0.75 mm size in the Sumagawa mine (Ref. 102) and for transporting bauxite slurry (Ref. 103 and 104). A Siemag pipe feeder was very successfully used for raw coal (0 to 60mm) from a depth of 850 m. in the Hansa hydromine (Ref. 105).

These systems require valves to close on slurry at much lower frequencies than the check-valves of a positive-displacement pump, and therefore are more reliable. By proper design and cycle timing, only one valve per chamber has to close on slurry. The Siemag system loads and unloads each pipe chamber in opposite directions to achieve this goal. It is successful in achieving a solids-to-water ratio by volume of 1:2.

Another approach to the high-head application is the separation of a batch of slurry from the pressurizing liquid by a flexible barrier. Examples are the Zimpro high pressure hydraulic exchange pumps (Ref. 106) which are used for corrosive, abrasive sludges and slurries. They use a diaphragm bag in a vertical cylindrical chamber to separate the internal pressurizing oil from the external slurry. The bag is normally of Neoprene, but chlorinated butyl rubber can be used for acidic slurries (Ref. 107). The only moving parts in contact with slurry are the check valves and the diaphragm bags. The discharge pressure can be up to 3000 psi. A small unit for 15 gpm of ore slurry at 2000 psi has been developed. A 200 gpm unit is being operated in Sierra Leone, Africa in pumping rutile slurry of +150-28 mesh size at pressures of 400 to 500 psi. With time, the pipe will be lengthened to 3 mi. and the pressure increased to 1000 psi (Ref. 108).

Experiments with a small Zimpro single stage pump to hoist uranium slurry are being planned by Gulf Minerals in their Mt. Taylor mine in New Mexico (Ref. 109) where the head requirement will be over 3300 ft. of slurry.

Engineering work on a 500 gpm Zimpro pump has been completed (Ref. 110). This development shows promise of being applicable to hoisting of coarse abrasive ores from deep underground mines when equipment of the desired size can be proved reliable.

Another type of pump for high-head applications is the Mitsubishi Mars pump (Ref. 111). This uses a reciprocating oil pump to pressurize oil in a chamber directly in contact with a slurry. The low oil density helps maintain separation of oil to prevent slurry from entering the oil circuit. Only check valves operate in slurry. This type of pump is used in mines, in ore treatment, and for transport of concentrates and tailings. It is used mainly for finely ground slurries because the check valves do not work well on coarse slurries.

Wirth has developed a piston diaphragm pump which has been tested on quartz sand slurries of 30% by weight with a top particle size of 3mm. Pressures up to 120 bars (1750 psi) have been achieved with no valves or diaphragms being replaced after 1000 operating hours.

Another approach to solids transport is to inject mechanically a slurry into a flowing pipeline carrying high pressure water. An example is the Kamyr high pressure feeder (Ref. 112). It was developed for handling wood pulp and wood chips, but has been modified for other materials. It is a rotating pocket feeder where each pocket delivers a batch of slurry into the flow. The rotor provides the check valve action so that wear is apt to be significant except for fine slurry of relatively low abrasivity like low ash coal. Hard facing of the rotor and stator components improves the wear life. Recent tests in the

U.S. and U.K. Have demonstrated the feeder's ability to handle coarse coal (to 100mm) and coarse coal refuse (to 37mm) at rates up to 200 metric tons per hour. Pressure capability is to 350 psi at present, with higher pressures up to 1500 psi under development for reduced feed rates.

### C. Low-Head Pumps

Transport of coarse slurries approximately horizontally in underground mines or on the surface can be provided by centrifugal pumps. The pumps for handling coarse lumps are generally lined with hard alloys (not rubber). Manufacturers in the U.S. include: A.S.H.; Barrett, Haentjens & Co. (Hazelton pumps; Galigher; Georgia Iron Works; Ingersoll-Rand (Cameron Pump Div.); Joy Manufacturing Co.; Lightning Industries, Inc.; Pettibone Corp.; Thomas Foundries; Warman, and others. All U.S. slurry pumps are single-stage units. However, two-stage units of large size for coarse coal have been developed in the U.S.S.R. (Ref. 2 and 4).

In addition to these centrifugal pumps, a new type of dry solids feeder is the helical inducer pump being developed for D.O.E. by Foster-Miller Associates of Waltham, Mass. (Ref. 113). It uses a ventilated helical rotor inducer as a solids injector, followed by one or more boost pumps. These pumps are self-regulating and do not require variable speed drives.

The potential advantage of this type of pump is that pumps can operate at a constant speed but accept a variable solids flowrate with no requirement for a mixing tank or a sump. Ventilation at the inducer isolates each line section from the next, permitting transient flows to be handled without cavitation. Further development to apply these pumps to uranium slurry transport is now underway. An advantage of this pump is that no mixer tank is needed and it therefore may become easier to couple the solids output of a continuous miner by flexible hose into a pipeline.

### D. Airlift

Airlift hydraulic hoisting requires two pipes with a downward gravity flow of liquid in one leg which overcomes friction in hoisting a flow in the other leg where the average density is lowered by compressed air injection. The vertical hoist height is limited because of the large volume expansion of the injected air as the slurry rises. Therefore high lifts in a mine require two or three airlift stages, with sumps as intermediate levels. A three-stage airlift for coal was used for a 725m lift of coal in the USSR (Ref. 1). Airlift is most applicable when all water for slurry formation comes from the surface so its full gravity head is available. It is not applicable in a deep mine where mine inflow water is obtained at the lowest elevation.

A disadvantage of an airlift is the low energy efficiency as compared to slurry pumps. Also, the shaft must generally be deepened by 20 to 50% of the lift height to obtain sufficient head for operation.

### E. Jet Pumps

Jet pumps for slurry develop pressure by aspirating a slurry into a high velocity water jet which forces it through a diverging diffuser where kinetic energy is converted to pressure. The jet pump has low-efficiency and limited lift height, generally less than 300 feet. Therefore its main use in underground mining is to pick up a slurry from a shallow sump and move it with a small pressure rise. It can have application in coupling the output of a slurry mix tank to the inlet of a centrifugal pump. It also is used in hydraulic borehole mining systems to lift the slurried ore.

The Department of Energy in cooperation with Ingersoll-Rand Corp. has developed a jet pump injector to feed coal into a pipeline.

### F. Evaluation of Pump Systems

An analysis of the state of development and potential performance of various slurry transport systems indicated that the following should be assumed as the most applicable for our potential mines:

1. Hydraulic transport of minerals underground in the nearly level haulageways should be by centrifugal slurry pumps in series. Estimates were based on the use of Warman pumps.
2. Hydraulic transport of minerals on the surface for up to 20 mile range should also be by centrifugal slurry pumps with pump stations every 4 to 5 miles.
3. Hydraulic hoisting of minerals from deep depths of 2000 to 3500 ft. should be by a 3-pipe feeder system similar to the Siemag system used in the Hansa hydromine.

## 9. ECONOMIC ANALYSIS

### A. Cost Estimation Models and Common Assumptions

In order to determine the potential economic advantages of hydraulic mining and transport, and of hydrotransport alone, cost estimates were prepared for hypothetical mine transport systems to permit comparing the proposed hydraulic systems with conventional systems.

The purpose is to study the hydraulic system feasibility of some suitable minerals and estimate the difference between costs of transport for a hypothetical hydraulic transport system and an idealized conventional transport system. Those items or activities which are different for the two systems are considered. The result is the relative cost differences rather than the absolute costs. (An exception is the costs per barrel of oil in Section 9-F, where all mining and oil sand processing costs are included).

Except where noted: the common assumptions which apply to all mine models are:

1. Each uranium mine is assumed to operate on a three-shift basis for 300 days per year with a 20 year life. The mill in each case operates 24 hours per day for 300 days per year. However, for oil sands, operation is 350 days per year.
2. Cost estimates for conventional mine equipment, supplies and equipment operation are based on the "STRAAM Handbook" (Ref. 114), using costs for 1975 to 1979, extrapolated to mid-1981. Modifications for costs of underground rail haulage and the method for estimating shaft sinking costs are discussed in Section C3 below.
3. In all eight uranium mine cases, two shafts are available for hoisting and servicing. Conventional hoisting is sized for 50% excess capacity. For hydraulic hoisting, the main hoist shaft is replaced by a second service shaft which is installed with hoisting capability of only 50% of nominal production to provide standby capacity. It also hoists waste rock which comprises 25% of the ore production. The slurry pipes are installed in a third small shaft of 7 ft. diameter which is bored during mine development and used for muck removal.
4. Production in all the uranium mines (Cases 1 through 8) is achieved by continuous miners with a production of 200 tons of ore and 50 tons of waste per shift\*. To keep the evaluation simple, all underground transport has been designed for maximum length of travel (2.05 mi. or 3.5 mi.). All tonnages are given in metric tons.

### B. Hydraulic Hoisting and Transport for Uranium Mines in New Mexico

Table 9-1 shows the basic data assumed for eight different mine models, for which details are given as Cases 1 through 8 in Table 9-2. Four of the cases (1B, 2B, 5B and 6B) are calculated for a different distance from mine to mill of 20 miles instead of 5 miles.

\*Continuous miners are not yet widely used in uranium mining but are under development to reduce manpower required. The eight uranium mines in New Mexico have been analyzed for transport costs only. Therefore the method of mining does not affect cost estimates in these cases. It does affect Case 9 below.

TABLE 9-1 : DESIGN POINTS FOR COST ESTIMATING UR NIUM MINES IN NEW MEXICO

CASE NO.	PRODUCTION RATE, TPD*	SHAFT DEPTH M.	SHAFT DEPTH FT.	HAULAGE METHOD	AREA OF MINING MT.	KM	MAX. MAIN HAULAGE DISTANCE (A)	DISTANCE FROM MINE TO MILL (B)		
1	1750	700	2296	Locomotive	3.5 x 0.6	5.6 x 1	1.75mi (2.8 km)	5mi. 8km	20mi. (32km)	1
2	1750	700	2296	Hydraulic	3.5 x 0.6	5.6 x 1	1.75mi (2.8 km)	5mi. 8km	20mi. (32km)	2
3	1750	1000	3280	Locomotive	3.5 x 0.6	5.6 x 1	1.75mi (2.8 km)	5mi. 8km		3
4	1750	1000	3280	Hydraulic	3.5 x 0.6	5.6 x 1	1.75mi (2.8 km)	5mi. 8km		4
5	4500	700	2296	Locomotive	6 x 1	10 x 1.6	3mi (4.8 km)	5mi. 8km	20mi. (32km)	5
6	4500	700	2296	Hydraulic	6 x 1	10 x 1.6	3mi (4.8 km)	5mi. 8km	20mi (32km)	6
7	4500	1000	3280	Locomotive	6 x 1	10 x 1.6	3mi (4.8 km)	5mi. 8km		7
8	4500	1000	3280	Hydraulic	6 x 1	10 x 1.6	3mi (4.8 km)	5mi. 8km		8
9										9
10										10
11										11
12										12
13										13
14										14
15										15
16										16
17										17
18										18
19										19
20										20
21										21
22										22
23										23
24										24
25										25
26										26
27										27
28										28
29										29
30										30
31										31

\* All tonnages are in metric tons and are abbreviated T

TABLE 9-2  
BASIS FOR COST ANALYSIS OF MINES WITH  
CONVENTIONAL OR HYDRAULIC HOISTING (MINE LIFE = 20 YR.)

Case No.	URANIUM, (New Mexico)												URANIUM (Wyoming)	OIL SANDS (Calif.)	POTASH (N.M.)	TRONA (Wyoming)				
	1A	1B	2A	2B	3	4	5A	5B	6A	6B	7	8	9	10	11	12	13	14	15	16
1 Hydraulic Mining?	No												No	Yes	No	Yes	No	No	No	No
2 Type of Mine Hoisting & Transport	Conv.	→	Hydr.	→	Conv.	Hydr.	Conv.	→	Hydr.	→	Conv.	Hydr.	Conv.	Hydr.	Gravity	Hydr.	Conv.	Hydr.	Conv.	Hydr.
3															Drain					
4																				
5 Production Rate of Ore, metric tons/day	1750	1750	1750	1750	1750	1750	4500	4500	4500	4500	4500	4500	1750	1750		29,500	10000	10,000	10000	10,000
6 Production Rate of Waste Rock, metric tons/day	435						1120						435	435	2950	2950	0	0	0	0
7 Shaft Depth, Meters	700	700	700	700	1000	1000	700	700	700	700	1000	1000	200	200	300	300	300	300	500	500
8																				
9 Haulage Method	Loco.	Loco.	Hydr.	Hydr.	Loco.	Hydr.	Loco.	Loco.	Hydr.	Hydr.	Loco.	Hydr.	Loco.	Hydr.	Pilin Pipes	Hydr.	Belt	Belt	Belt	Belt
10																				
11 Max. Main Haulage, Mi.	1.75						3						1.75							
12																				
13 Area of Mine;																				
14 Length, Mi.	3.5						6						3.5							
15 Width, Mi.	0.6						1						0.6							
16																				
17 Main Shaft Dia. Ft.	18	18	14	14	18	14	24	24	18	18	24	18	19'21"	21'	19'21"	19'21"	22	16	22	16
18 Service Shaft Dia. Ft.	14	14	14	14	14	14	18	18	18	18	18	18	17'19"	17'19"	17'19"	17'19"	16	16	16	16
19 Third Shaft Dia. Ft. (for shaft muck, and hydrohoist)	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
20																				
21 Mine Water Inflow, gpm	3500						9000						3500	3500			0	0	0	0
22																				
23 Distance, Mine-to-Mill, Mi.	5	20	5	20	5	5	5	20	5	20	5	5	5	5	5	5	0	0	0	0
24																				
25 Backfill Mine?	Yes												No	No	No	No	No	No	No	No
26																				
27																				
28																				
29																				
30																				

Fig. 9-1 shows a schematic flow diagram of the type of hydraulic transport system assumed for the eight model uranium mines which are based on geology in the Grants, N.M. area. This flow diagram was used as a basis for estimating capital and operating costs of the hydraulic ore transport system for comparison with the conventional transport system. A discussion of the technical characteristics of each system and its major components is given below.

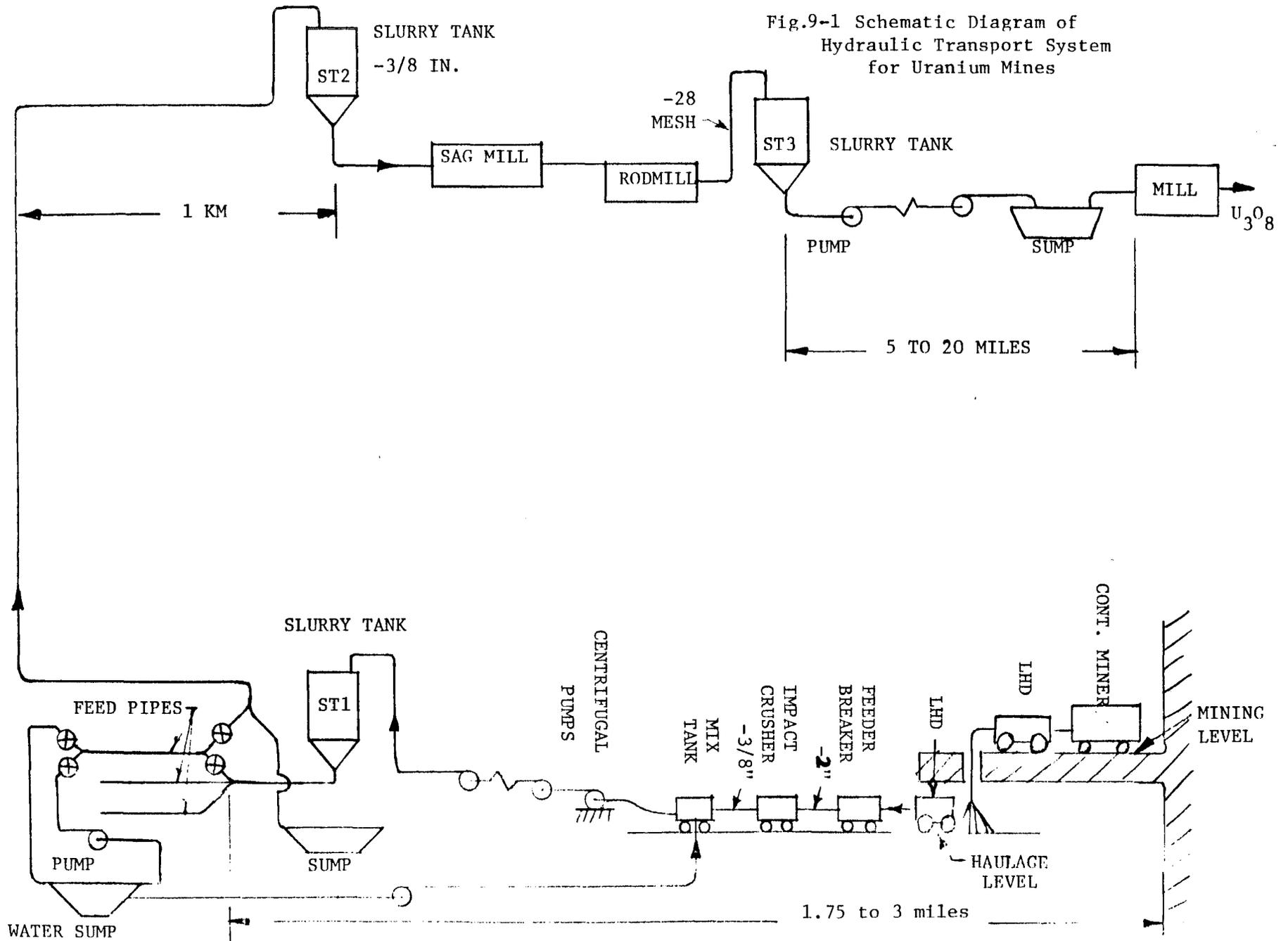
The common features of all the mines are:

1. The ore in all cases is mined on an upper level about 50 ft. above the haulage level by continuous mining machines and is hauled by load-haul-dump (LHD) vehicles to ore passes. Ore feeds by gravity directly into ore cars for conventional transport, or into storage heaps near the mobile slurry formation system which is track mounted for the hydraulic system. The ore in this case is loaded by LHD into the feeder breaker of the hydrotransport system.

As shown in Figure 9-1, the general features of the hydraulic transport systems are:

1. The slurry formation system comprises four main units which are rail mounted. They are a feeder breaker (FB) (fed by LHD), which reduces run-of-mine ore to minus 2 inch size, an impact crusher (IC) which reduces size to minus 3/8 inch size, a mix tank (MT) where mine inflow water is mixed with the crushed ore to produce a slurry of 25% average weight concentration, and a heavy duty centrifugal pump (assumed to be made by Warman) which is the first stage of the underground hydrotransport system.
2. The slurry flows in polyethylene pipe installed parallel to a rail track running along the long mine axis (See mine layouts in Figures 9-2, 9-3, and 9-4 of next Section C3 below) with booster pumps installed as needed along the pipe length. One pipe from each end of the mine feeds slurry into a 1000 m<sup>3</sup> elevated slurry tank near the main shaft which provides gravity feed to the hydraulic hoist.
3. The hydraulic hoist consists of a three-pipe feeder system similar to the system used for hoisting run-of-mine coal (minus 100mm) in the Hansa hydromine in Dortmund, West Germany in the period 1977 to 1980 (Ref. 105). The feeder consists of three pipes, each 150 m long. Each pipe has two valves at each end to permit loading slurry by gravity from the slurry tank (St 1) into the pipe while draining the water in the pipe to a sump, then high pressure water is admitted to force the 150 m long slug of slurry up the vertical pipe toward the surface. The charging and feeding of the three pipes

Fig.9-1 Schematic Diagram of Hydraulic Transport System for Uranium Mines



are phased to approach a continuous flow of slurry up the hoist pipe, with minimal dilution of the slurry. Each pipe is charged and discharged in opposite directions, so only one valve for each pipe must close on slurry and therefore be subjected to the resultant wear. (This feature differs from the Hitachi Hydrohoist, which charges and feeds in the same direction).

At the surface, the hoist flow continues for one kilometer from the shaft where the main surface transport station is located. The slurry flows into an elevated 1000 m<sup>3</sup> slurry tank (St 2) at this point.

4. The slurry tank ST 2 acts as a settling tank to separate -28 mesh material into a parallel circuit and to gravity feed the +28 mesh - 3/8 inch slurry to a grinding plant to reduce it to -28 mesh for remixing with the overflow from the settling tank. The grinding is by a semi-autogenous grinding mill (SAG) followed by a rod mill. Both these units would normally be located at the head end of the ore processing mill. However they are located ahead of the surface pipeline in order to reduce pumping power and wear of the pipeline.
5. The concentrated fine slurry from the wet rod mill is pumped into a slurry tank ST 3 where it is mixed with the overflow from the settling tank ST 2 and then fed by gravity into the surface transport system. For the mines with a transport distance of 5 miles to the mill, surface transport is by a group of centrifugal pumps connected in series in a single pump station at the head of the pipeline. For the mines with 20 miles to the mill, surface transport is by four pump stations five miles apart. The surface pipeline is buried at shallow depth and where it crosses critical areas, a concentric outer pipe (assumed one mile long) is installed for safety against the possibility of leakage.

At the mill, the -28 mesh slurry feeds into a pond which has enough capacity to hold a 5 day output of the mine. Provision is made to dewater the slurry to optimum feed concentration for the mill, and to process the excess water separately for the uranium recovery, water treatment and disposal.

## C. Basis for Cost Estimates of Transport in Uranium Mines

### C1. Capital Costs of Hydraulic Transport

A discussion is given below of the basis used for estimating the capital costs for equipment comprising the hydraulic transport systems. The item numbers refer to the Tables 9-3 and 9-4.\*

\* (Where brand names are mentioned they are intended as identification for estimating purposes only and do not necessarily constitute an endorsement by the authors or by the Bureau of Mines).

TABLE 9-3  
ESTIMATES OF HYDRAULIC TRANSPORT CAPITAL COSTS - (COSTS IN \$K)

Item No.		2A				2B				4				6A				6B				CASE 8			
		Quantity		Unit Cost	Total Cost	Quantity		Unit Cost	Total Cost	Quantity		Unit Cost	Total Cost	Quantity		Unit Cost	Total Cost	Quantity		Unit Cost	Total Cost	Quantity		Unit Cost	Total Cost
1	LHD's for ore loading to feeder breaker	3	55TPH	50	150	3	55TPH	150	3	55TPH	150	3		225	3		225	3		75	225	3		75	225
2	Feeder-Breakers (Stamler)	2	55TPH	50	100	2		50	100	2		50	100	2		75	150	2		75	150	2	40TPH	75	150
3	Impact Crushers (1-stage cage type) with drive	2	55TPH	70	140	2			140	2			140	2			200	2			200	2	140TPH	100	200
4	Mix tank	2	55TPH	5	10	2			10	2			10	2			10	2			10	2	50TPH	5	10
5	Add'l cost of water collection system to supply to slurry				30				30				30				50				50				50
6	Centrifugal pumps and drives	12		20	240	12	240	20	240	12		20	240	20		400	20				400	20	153' head	20	400
7	Rail cars to support above components	8		3	24	8		3	24	8		3	24	8		24	8				24	8		3	24
8	Slurry Pipe (Driscopipe 8600)	20,000	6"	5.85	117	20,000	6"	5.85	117	20,000	6"	5.85	117	33,300	8"	7.33	244	33,300	8"	7.33	244	33,300	8"	7.33	244
			ft.	160psi			ft.	160psi			ft.	160psi			ft.	110psi			ft.	110psi			ft.	110psi	
9	Valves (with spare liners)	4		0.5	2	4		0.5	2	4		0.5	2	4		0.5	2	4		0.5	2	4		0.5	2
10	Underground electrical equipment for slurry pumping (50% of pump costs)				120				120				120				200				200				200
11.	Slurry tank (ST2) at hoist, including emergency dump (\$30/m <sup>3</sup> for excavation)	1			70	1			70	1			70	1			130	1			130	1			130
12.	Hydraulic hoist system (3-pipe feeder) including controls and electrical equipment	1	12"		6500	1	12"		6500	1	12"		6,915	1	14"	8400	8400	1	14"	8400	8400	1	14"	8925	8925
			700m				700m				1,000m				700m				700m				1000m		
13.	Surface pipe, mine to slurry tank	1km	3280'	15/ft	50	1km	3280'	15/ft	50	1km	3,280'	15/ft	50	1km	3280'	18/ft.	60	1km	3280'	18/ft.	60	1km	3280'	18/ft.	60
14.	Surface slurry tank (ST2)	1	500m <sup>2</sup>	20	20	1	500m <sup>2</sup>	20	20	1	500m <sup>3</sup>	20	20	1	1000m <sup>3</sup>	30	30	1	1000m <sup>3</sup>	30	30	1	1000m <sup>3</sup>	30	30
15	Surface rod mill (extra cost to locate at mine)			30	30			30	30			30	30			50	50			50	50			50	50
16.	Slurry tank (ST3) after crushing and grinding	1	500m <sup>3</sup>	20	20	1	500m <sup>3</sup>	20	20	1	500m <sup>3</sup>	20	20	1	1000m <sup>3</sup>	30	30	1	1000m <sup>3</sup>	30	30	1	1000m <sup>3</sup>	30	30
17	Centrifugal pumps on surface	6		50	180	28		30	840	6		30	180	6		40	240	28		40	1120	6		40	240

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TABLE 9-3 (CONT'.)

Item No.	2A			2B			4			6A			6B			CASE 8		
	Quan- tity	Unit Cost	Total Cost	Quan- tity	Unit Cost	Total Cost	Quan- tity	Unit Cost	Total Cost	Quan- tity	Unit Cost	Total Cost	Quan- tity	Unit Cost	Total Cost	Quan- tity	Unit Cost	Total Cost
18.																		
	Surface electrical equipment for slurry (50% of pump cost)		90			420			90			120			560			120
19.	Surface Pipe	5 ml. 10"	317	12ft.	10" 12ft.	1267	5mi.	10" 12ft.	317	5mi.	12" 15ft.	396	20ml. 12"	15ft.	1584	5mi.	12" 15 ft	396
20.	Slurry storage pond and slurry dewatering system at mill	1	200			200	1		200	1		450	1		450	1	450	450
21.	Underground slurry control sys- tem and console	1	150			150	1		150	1		100	1		100	1	100	100
22.	Surface slurry control system and console	1	200			225	1		200	1		250	1		275	1	250	250
23.	(TEC) Total equipment costs		8760			10725			9175			11761			14294			12286
24.	Freight costs-10% of TEC		876			1072			917			1176			1429			1229
25.	(TDEC) Total delivered equipment cost		9636			11797			10092			12937			15723			13515
26.	Installation labor (40% of TDEC)		3854			4719			4037			5175			6289			5406
27.	(TDPC) Total depreciable plant cost		13490			16516			14129			18112			22012			18921
28.	Engineering & Contingencies (20% of TDPC)		2698			3303			2826			3622			4402			3784
29.	Total Capital Investment		16188			19819			16955			21734			26414			22705
29A.	20 year life equipment invest- ment		14379			16790			15146			18924			21978			19894
29B.	10 year life equipment invest- ment		1497			2717			1497			2245			3872			2245
29C.	5 year life equipment invest- ment		312			312			312			565			565			565

TABLE 9-4

ANNUAL OPERATING COSTS FOR HYDRAULIC MINES

Item No.	2A		2B		4		6A		6B		Case 8		
	Quantity	Unit Cost	Quantity	Total Cost									
	Cash Costs:												
	Electric power installed (max):												
30.	Haulage level (KW)	1575		1575	2700		2700		2700		2700		
31.	Hoist	772		772	1100		1985		1985		2837		
32.	Surface	447		1789	447		1150		4600		1150		
33.	TOTAL KW	2794		4136	4247		5835		9285		6687		
34.	Electric Power @ 5c/kwh			670		993		1019		1400		2228	
35.	Labor cost per year:											1605	
36.	No. of men	11		18		11		11		18		13	
37.	Man-shifts per year	9900		16200		9900		9900		16200		11700	
38.	Labor costs @ \$15.44/hr			1223		2001		1223		1223		2001	
39.	M & R @ 5%-Line 27(1)			675		826		706		906		1101	
40.	Cash operating costs per year			2568		3082		2948		3529		5330	
41.	Non-cash Depreciation:												
42.	20-year life			719		840		757		946		1099	
43.	10-year life			150		272		150		225		387	
44.	5-year life			62		62		62		113		113	
45.	Sub-total non-cash			931m		1774		969		1284		1599	
46.	Annual operating costs			3499		4976		3917		4813		6929	
47.	Cost/ton of Ore			6.66		9.48		7.46		3.57		5.13	
48.	Metric tons per day			1750		1750		1750		4500		4500	
49.	Depth, m			700		700		1000		700		700	
50.	Distance to mill, mi.			5		20		5		5		20	

(1) Line-27>equals  
Line 29 ÷ 1.2

- Item 1. One LHD is used on the haulage level to load ore into the feeder breaker for each underground slurry system. One spare is provided. There are two slurry systems.
- Item 2. The feeder breaker is based on a custom made Stamler unit capable of reducing run-of-mine ore to -2 inch size.
- Item 3. A cage-type rotary impact crusher is used to reduce ore to -3/8" size.
- Item 4. A mix tank is provided with a screen and low pressure water injection system to mix slurry to a concentration of 25 wt.%.
- Item 5. Provision is made for a mobile mine water collection system to provide water for slurry formation to the mix tanks at each end of the mine.
- Item 6. The centrifugal pumps are electrically-driven with adjustable sheaves for speed selection. There are 10% spares provided.
- Item 7. The components FB, IC, MT and CP are each mounted on rail cars for mobility along the main track on the mine centerline. They are moved infrequently so no locomotive is assigned or capitalized.
- Item 8. The slurry is transported in polyethylene pipe. Costs are based on Driscopipe 8600.
- Item 9. There is one slurry valve at the end of each slurry line to throttle flow into the slurry tank ST 1. 100% spares are provided for these valves.
- Item 10. The additional cost of electrical equipment for slurry pumps is estimated at 50% of the pump costs.
- Item 11. The slurry tank ST 1 of 1000 M<sup>3</sup> capacity near the hoist is a vertical axis steel tank installed in an excavated pocket 35 m high by 12 m diameter. Excavation costs are estimated at \$100 K and equipment cost at \$30K. Provision is made for settling slurry and gravity feeding concentrated slurry to the pipe feeder. Water overflow is clarified by flocculation underground to less than 4 gm/liter of solids to permit use in the high pressure water pumps of the hydraulic hoist system. A separate emergency dump is provided in the shaft sump.
- Item 12. The cost of the hydraulic hoist system is based on a detailed cost estimate prepared by Hitachi for Hydrohoist systems for coal. These estimates were made for the Colorado School of Mines Research Institute in 1975 (Ref. 103). The costs have been corrected to 1981 costs by using equipment inflation

factors by the U.S. Bureau of Mines (Ref. 114). The costs have been corrected for variations in hoist height in the various cases. The major components of each system are: 3 horizontal feed pipes, 3 high pressure water pumps (with 1 spare), one vertical plastic-lined hoist pipe, necessary valves, and an underground control room, with instrument console and controls. (Compare German SIEMAG hydraulic hoist estimates for potash on page 96, based on Ref. 81).

- Item 13. The hydraulic hoist pipe is extended on the surface for 1-kilometer to the location of the grinding mill and surface transport station.
- Item 14. An elevated surface slurry tank (ST 2) is located next to the grinding plant. It is similar to the underground slurry tank ST 1, and has provision for bypassing excess water past the wet grinding plant, then mixing it into slurry tank ST 3 for transport to the mill in the slurry pipeline.
- Item 15. An additional cost is assessed for location of the grinding mill in a building at the head of the pipeline instead of within the main mill.
- Item 16. Slurry tank ST 3 is an elevated tank like ST2 fed by gravity from the rod mill and feeding by gravity into the pumps of the surface transport system.
- Item 17A. Five centrifugal pumps are used in series for the 5 mile transport distance to the mill.
- Item 17B. For the 20 mile transport cases, centrifugal pumps are used in series at each of four pump stations 5 miles apart.
- Item 18. The cost of electrical equipment for the surface transport system is assumed to be 50% of the cost of the pumps and motors used in each system.
- Item 19. The pipeline uses steel pipe.
- Item 20. At the mill, the pipeline feeds slurry into a slurry storage pond with a capacity of 5 days mine production. This is necessary to assure continuity of mill operation in case of failure of the mine surface transport systems. The slurry pond must be plastic lined to prevent water loss. Provision is made for thickening slurry to feed to the mill and treating overflow for uranium recovery, water treatment and disposal.
- Item 21. The control of the underground slurry system is independent of the hoist. It includes electromagnetic flowmeters, remote pressure indication and microprocessor controls.

- Item 22. The control of the surface pipeline can be independent of the hoist. It includes flow and pressure instrumentation and emergency dump provisions in case of pipeline leakage.
- Item 23. The total equipment cost (TEC) is the sum of items 1 thru 22.
- Item 24. The freight and delivery cost is 10% of TEC.
- Item 25. Total delivered equipment cost (TDEC)
- Item 26. Installation labor is assumed to be 40% of TDEC.
- Item 27. Total Depreciable Plant Cost (TDPC).
- Item 28. Engineering and contingencies are assumed to total 20% of TDPC.
- Item 29. Total Capital Investment (TCI).
- Item 29A. The depreciation of capital investment is derived by assuming a life of various capital items. All hydraulic mine equipment is assumed to have 20 year life except for:
- Item 29B. 10 year life items
  - Item 1 LHD's
  - 2 Feeder-breakers
  - 3 Impact crushers
  - 6 Centrifugal pumps and drives
  - 17 Surface centrifugal pumps and drives
- Item 29C. 5 year life items:
  - Item 8 Slurry pipe
  - 9 Valves
  - 13 Surface slurry pipe

The total initial capital investments for each group of equipment items are summarized in lines 29A, 29B, and 29C, which are used to determine depreciation costs in Table 9-4.

## C2. Operating Costs of Hydraulic Transport

The operating costs of the hydraulic transport systems are estimated below in major categories:

1. Labor
2. Supplies and electric power
3. Equipment operation (includes repair parts, fuel, lube, and tires)

### Labor

The average labor rate for mine and plant personnel is estimated as follows. It is based on a rate of \$5.89 per hour in July 1975, plus 35% in fringe benefits. The base rate is adjusted by the inflation indexes quoted by the Bureau of Mines (Ref. 114) from 1975 to 1979, extrapolated to mid-1981. Fringe benefits are assumed to increase to 61% in 1981, making a total labor cost of \$15.44 per hour.

### Supplies and electric power

The cost of supplies for hydraulic transport includes only electric power at a cost of 5 cents/kw-hr. Mining is on a 2 shift basis, with maintenance on a third shift. The transport system operates 16 hours per day to supply the mill which operates 24 hrs. per day.

### Equipment Operation

The equipment operation cost for hydraulic transport consists of 95% repair parts and 5% lubrication. The total of the equipment operation cost per year is assumed to be 5% of the initial Total Equipment Costs (Line 23 in Table 9-4). Therefore over a 20 year mine life, an amount equal to the Total Equipment Costs is expended on equipment operation, primarily in repair parts.

The following assumptions are made regarding uranium mines:

1. The mine water collection and supply system for the hydraulic transport system will require additional costs over the mine water collection system for the conventional mine. In the hydraulic case, the water is supplied to the rail-mounted slurry mixer system, which moves from time to time. In the conventional case, it is collected at one point at the shaft sump. The mine inflow water is assumed to be 2 gpm per TPD production of ore (i.e., 3500 gpm for 1750 TPD and 9000 gpm for 4500 TPD).
2. The electrical distribution systems costs for the hydraulic ore transport system will be in addition to those for the rail haulage system, which are decreased relative to the conventional case because no ore is hauled by rail (only waste rock is handled dry in all cases).
3. In all cases, the mill tailings are normally disposed of on the surface. If mine stopes are backfilled, it will be by gravity hydraulic transport of sandfill from the surface for both the hydraulic and conventional mines. Therefore no cost differences are associated with backfilling.
4. When comparing hydraulic and conventional mines, the cost of the conventional mine system includes the additional cost of a bigger shaft and larger skip to handle all the ore as well as waste rock. In all cases, the waste rock is transported by rail and skip. The additional cost of ore cars, rail, power, etc. underground, and the cost of truck haulage on the surface is included for the conventional mines.

### C3 - Capital & Operating Costs for Conventional Transport

Capital and operating costs were determined for the following cases in Table 9-2 for comparison with data generated by the STRAAM Handbook (Ref. 114).

<u>Case</u>	<u>Mineral</u>	<u>Location</u>	<u>Tons/day</u>	<u>Depth</u>	<u>Surface haulage/distance</u>
1A	Uranium	Grants	1750	700m	5 mi.
1B	Uranium	Grants	1750	700m	20 mi.
5A	Uranium	Grants	4500	700m	5 mi.
5B	Uranium	Grants	4500	700m	20 mi.

The costs for cases 1A, 1B, 5A and 5B were calculated for the conventional haulage system. These included all items which differ from the hydraulic transport system; in particular, road and shaft construction, hoisting, underground rail haulage and surface truck haulage.

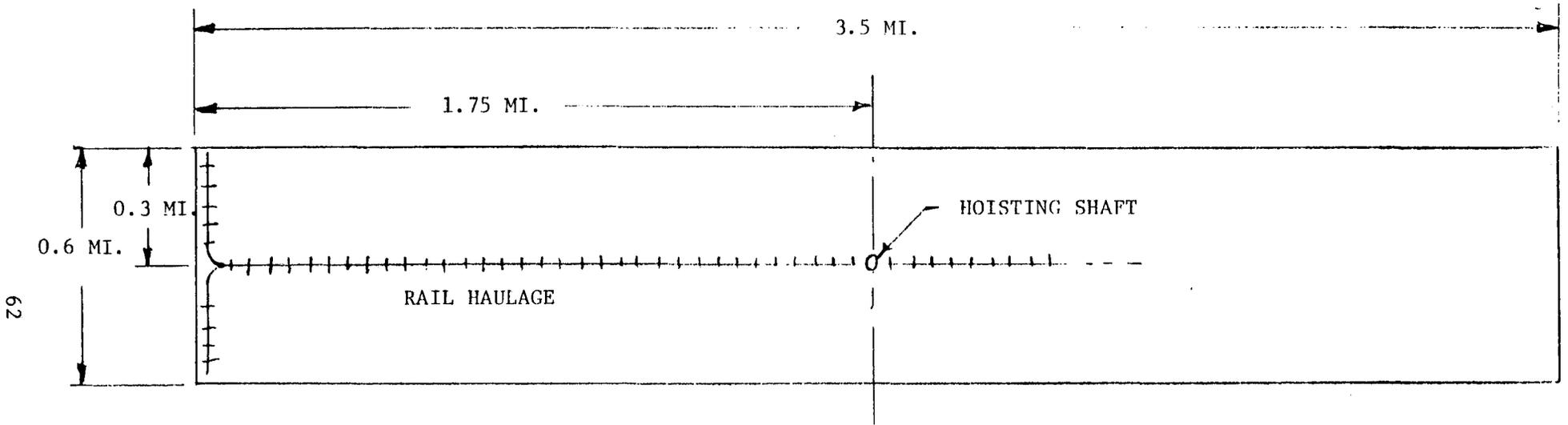
Figures 9-2, 9-3, and 9-4 show schematic diagrams of a conventional haulage system for eight uranium mines based on the geology of the Grants, N.M. area. This generalized mine design was used to estimate the operating parameters and subsequently the equipment specifications, capital costs and operating costs for the system.

For the generalized design considered, ore is mined using continuous mining machines with LHD haulage. The ore is transferred through ore passes directly into railcars located on the main haulage level about 50 feet below the ore level. The capacity of the cars is 8 tons and there are 10 cars in each train being pulled by a 12 ton diesel locomotive. The ore is hauled to the production shaft, located at the center of the property, where it is dumped into ore loading pockets, transferred into either 10 ton or 12 ton skips and hoisted to the surface. The skips empty into temporary storage bins at the surface which discharge into 35-ton off-highway trucks for transport to the mill.

The capital and operating costs for the equipment used solely for conventional haulage were obtained based upon the design specifications, quotes and estimates from manufacturers and various empirical estimation parameters representative of similar equipment types and operating conditions.

The detailed cost analysis of conventional uranium haulage systems provided estimates which were compared with the results of the methods of analysis in the STRAAM Handbook (Ref. 114). The STRAAM curves were checked with respect to both the capital and operating cost components of transport subsystem costs for underground Diesel rail haulage, skip hoisting and surface transport by 35 ton dump trucks.

The STRAAM methods were found to be generally appropriate for estimating conventional costs with the exception of underground Diesel rail haulage. In this case, the operating cost estimates were found to be unrealistically high since they had been derived primarily from small mines with very small rail cars (1 to 2 tons) (Ref. 115), whereas our estimates assume 12 ton locos, pulling strings of ten 8 ton cars, as used in the Gulf Mt. Taylor mine.



All dimensions in miles

Figure 9-2

Mine Layout for Transportation Design  
Conventional Cases 1, 9

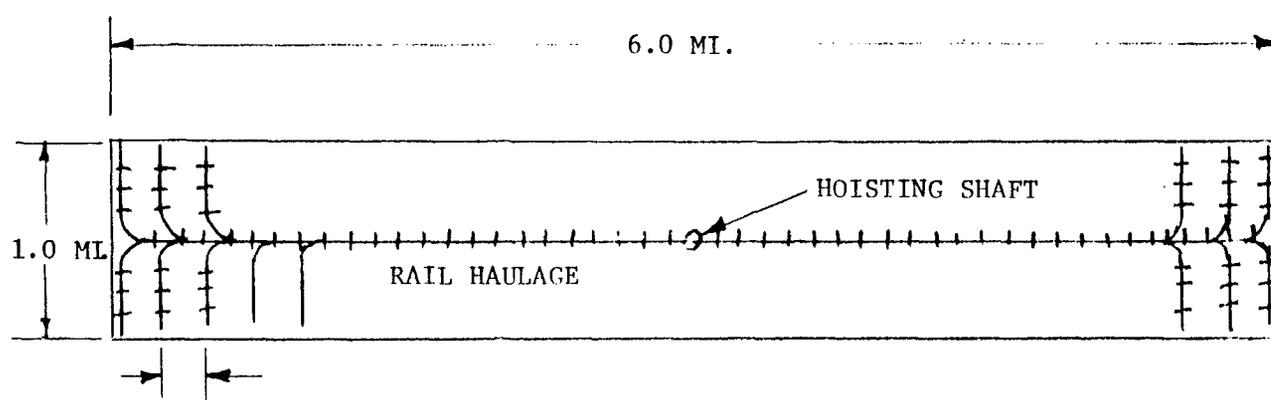


Figure 9-3

Mine Layout for Transportation Design  
Conventional Case 5

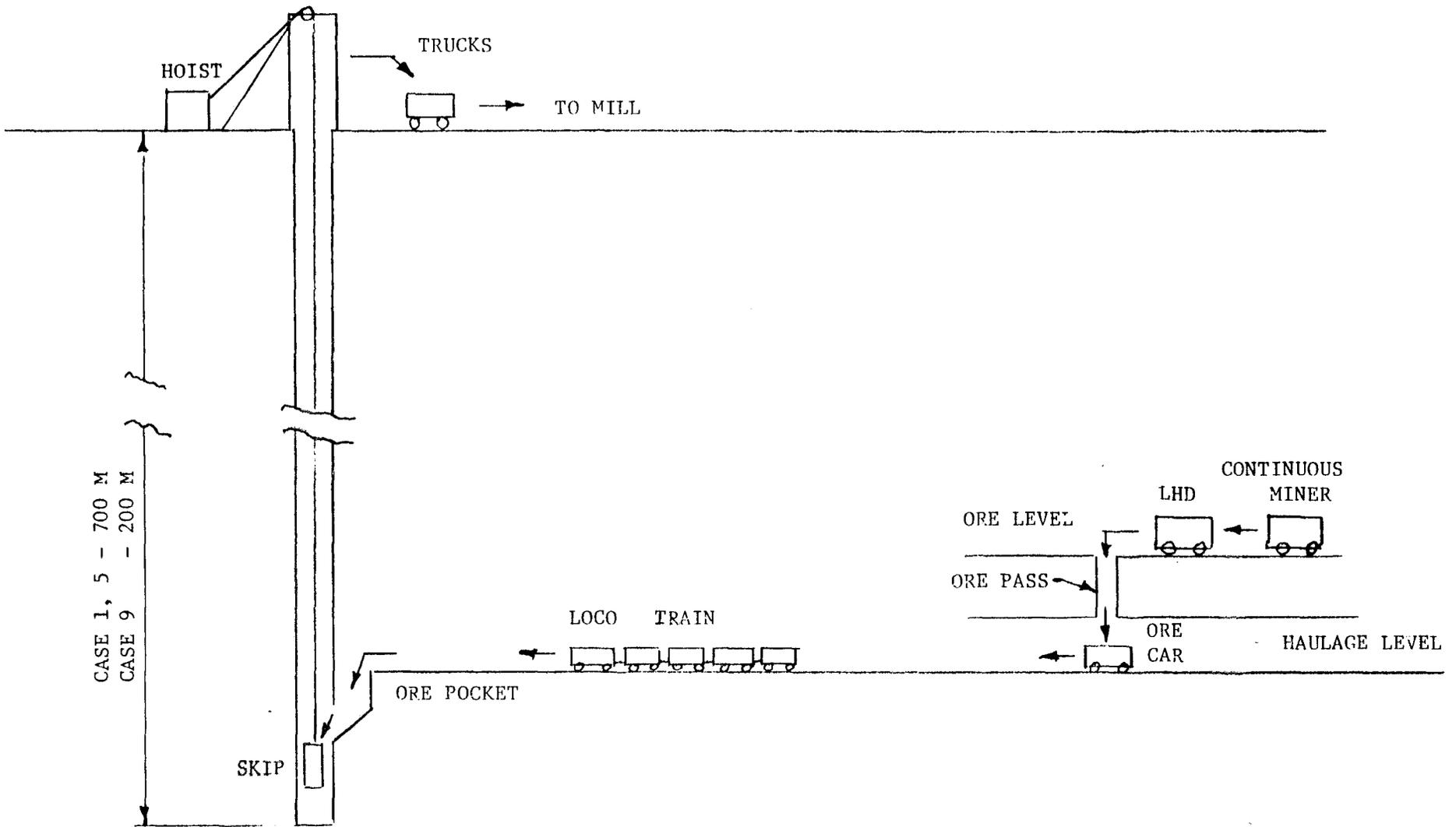


FIGURE 9-4  
Schematic Diagram of Conventional Haulage  
System for Uranium Mines

Therefore the STRAAM methods were assumed, but with the cost estimates for labor for Diesel rail haulage reduced by 50%.

In all cases the STRAAM data were corrected to mid - 1981 costs using the deflator values for each cost component for 1975 to 1979, extrapolated to 1981.

In using the STRAAM curves to estimate hoist system capital costs, it was found that the STRAAM-generated costs were within 10% of the independent engineered costs if the shaft diameters assumed as a basis for analysis in Table 9-2 were taken to be inside diameters and each overall diameter was increased by three (3') feet to provide for an 18" lining, when entering the STRAAM analysis. This assumption leads to shaft sinking costs, which are more realistic for the wet, difficult ground conditions in the Grants, New Mexico region. One of the advantages of hydraulic hoisting is to permit a smaller diameter shaft and thereby to save on shaft capital costs. It is assumed that for the small hydraulic mines (Cases 2 and 4), the hoist shaft needs to be only 14 ft. instead of 18 ft. in wide diameter. For the large hydraulic mines (Cases 6 and 8), the hoist shaft needs to be only 18 instead of 24 ft. in inside diameter. Conventional costs include only the increase over the shaft cost for the hydraulic case.

#### D. Uranium Transport Cost Comparisons

The capital and operating costs, together with transport costs per ton of ore are summarized in Table 9-5 for conventional transport and in Table 9-6 for hydraulic transport. A graph showing the transport costs per ton vs. production rate is shown in Figure 9-5. It may be seen that:

1. The conventional transport costs for the small (1750 TPD) mines (1A, 2 and 1B) from \$9.40 per ton for 700 m depth to \$9.84 for 1000m depth, increasing to \$11.32 for 20 mi distance to mill at 700 m depth.
2. The hydraulic transport costs for the small (1750 TPD) mines (2A, 4 and 2B), vary from \$6.66 per ton for 700 m depth to \$7.46 for 1000m depth, increasing to \$9.48 for 20 mi distance to mill at 700m depth.
3. The conventional transport costs for the large (4500 TPD) mines (5A, 7 and 5B) vary from \$8.33 per ton for 700 m depth, to \$8.64 for 1000m depth, increasing to \$9.20 for 20 mi distance at 700m depth.
4. The hydraulic transport costs for the large (4500 TPD) mines (6A, 8, and 6B) vary from \$3.57 per ton for 700m depth, to \$3.78 for 1000m depth, increasing to \$5.13 for 20 mi distance at 700 m depth.
5. Comparison of costs shows that hydraulic transport is up to 29% less costly than conventional transport for the 1750 TPD mines and up to

TABLE 9-5

## SUMMARY - NEW MEXICO URANIUM MINES - CONVENTIONAL TRANSPORT

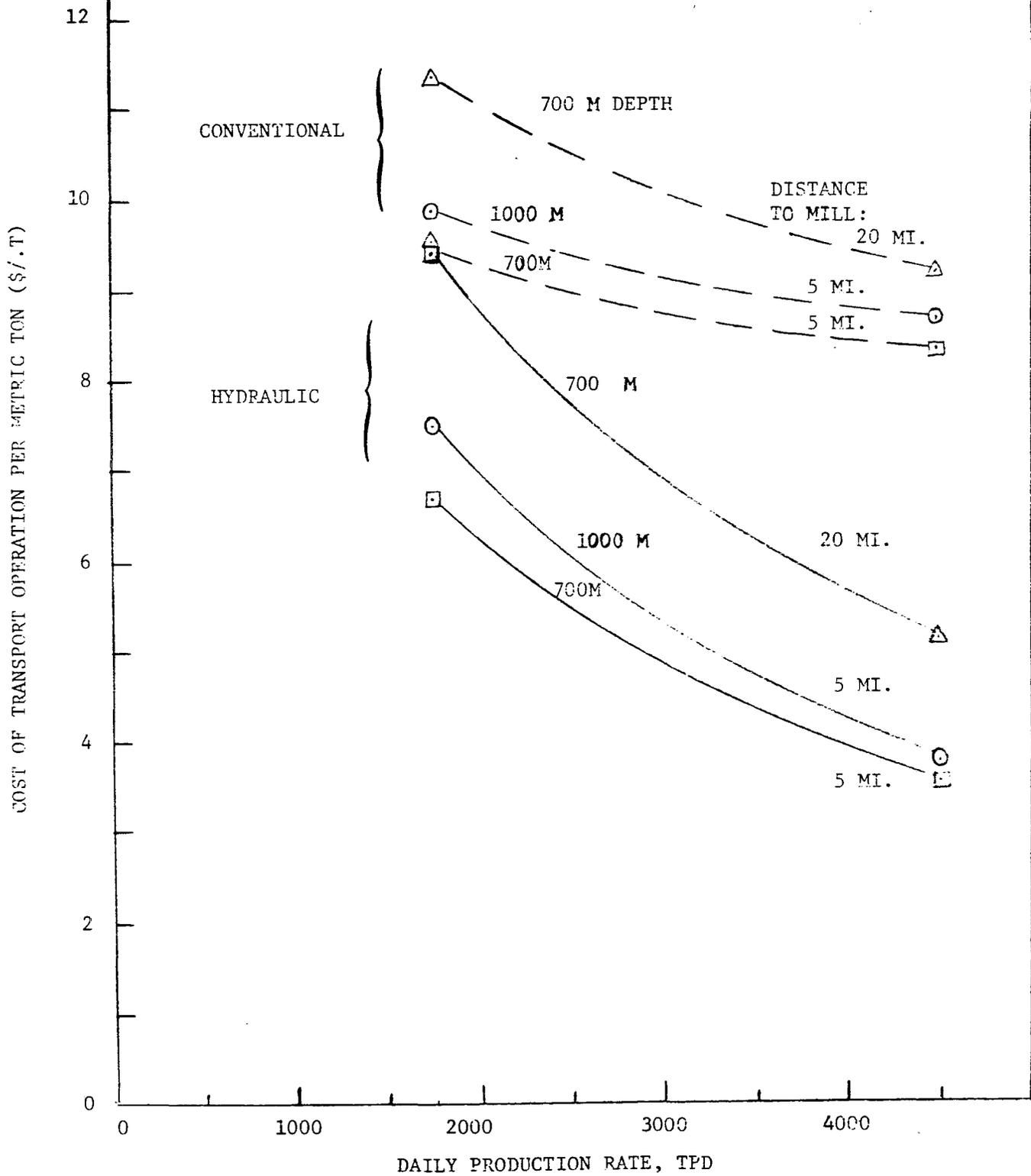
	1A	1B	3	5A	5B	7
Depth, m	700	700	1000	700	700	1000
TPD	1750	1750	1750	4500	4500	4500
TPY - 300 DPY (000)	525	525	525	1350	1350	1350
Distance to mill,m	5	20	5	5	20	5
Total Capital Investment (\$000)	11,761	15,244	13,945	21,152	25,825	25,042
Annual Operating costs (\$000)						
· Cash	3,876	4,340	4,001	9,424	10,170	9,640
· Non-Cash	<u>1,057</u>	<u>1,604</u>	<u>1,166</u>	<u>1,824</u>	<u>2,249</u>	<u>2,018</u>
- TOTAL	4,933	5,944	5,167	11,248	12,419	11,658
Cost/Ton Ore	\$9.40	\$11.32	\$9.84	\$8.33	\$9.20	\$8.64

TABLE 9-6

## SUMMARY - NEW MEXICO URANIUM MINES - HYDRAULIC TRANSPORT

	2A	2B	4	6A	6B	8
Depth, M	700	700	1000	700	700	1000
TPD	1750	1750	1750	4500	4500	4500
TPY - 300 DPY (000)	525	525	525	1350	1350	1350
Distance to mill, mi.	5	20	5	5	20	5
Total Capital Investment (\$000)	16,188	19,819	16,955	21,735	26,415	22,704
Annual Operating Costs (\$000)						
• Cash	2,568	3,802	2,948	3,529	5,330	3,774
• Non-cash	<u>931</u>	<u>1,774</u>	<u>969</u>	<u>1,284</u>	<u>1,599</u>	<u>1,333</u>
- TOTAL	3,499	4,976	3,917	4,813	6,929	5,107
Cost/Ton Ore	\$6.66	\$9.48	\$7.46	\$3.57	\$5.13	\$3.78
Savings by hydraulic method, %	29	16	24	57	44	56

FIG. 9-5  
 ESTIMATED COST OF OPERATION  
 OF HYDRAULIC TRANSPORT  
 SYSTEM PER METRIC TON OF ORE



57% less costly for the 4500 TPD mine with 5 mile distance to the mill. For 20 mile distance,hydraulic transport can be 16% less costly for a 1750 TPD mine and 44% less costly for a 4500 TPD mine.

Additional savings may be made with hydraulic transport if it is established that the mine pumping system for removing drainage water can be reduced in capacity because the hydraulic transport system normally utilizes most of the water inflow.

## E. Inverted Borehole Hydraulic Mine for Uranium in Wyoming

### E1 - Hydraulic Mine Estimates (Case 10):

The hypothetical uranium mines in Wyoming (Cases 9 and 10) were analyzed using assumed geological and hydrological conditions similar to those for the Highland Mine (Exxon) located 60 miles northeast of Casper, Wyoming, in the Powder River Basin. This mine was closed in 1980. The roof and ore are soft, water-saturated and extremely unstable sediments (Ref. 51).

Rock at Highland averaged 500 PSI in uniaxial compressive strength and some was considerably weaker. It is believed that the ore can be mined hydraulically. Timber and shield tunneling has been used with experimental use of wire mesh and "Split-Set" friction roof bolts for roof support.

The weak rock makes roof control difficult and it is desirable to remove workers from the ore zone. Therefore our Case 10 is designed to remove all workers from the ore level and to mine by hydraulic borehole mining through boreholes from the haulage level upward into the ore level. The ore is then transported as a slurry in pipes to the main pipe system, to the hoist shaft and to the mill.

The reasons for assuming upward drilling of boreholes instead of downward are:

1. Borehole mining from underneath haulageways would lead to subsidence and high expense in roof control of haulageways located above mined out cavities.
2. Gravity would aid in slurry flow, and jet pumps would not be needed in the borehole mines.
3. If mined cavities were hydraulically backfilled, excess water could be drained by gravity through each cased and capped borehole, and then clarified underground to provide water for monitor jet pumps.

The presence of water in cavities above the haulageways of course presents a hazard in case of roof failure, cracking, or fault development. Therefore careful roof inspection is required to detect incipient failure in time to grout the roof zone affected. Borehole casings will be grouted in place.

The Wyoming uranium mines in Cases 9 and 10 are modeled after the similar Cases 1A and 2A in the New Mexico area, except that the shaft depth in Wyoming is only 200 m. (656 ft.) instead of 700 m. (2296 ft.). The uranium mineralization is assumed to be dispersed through beds with a vertical interval of 33.5 m (110 ft.) to 55 m (180 ft.) and averaging 44 m. (145 ft.) in thickness.

A production rate of 1750 tons/day for 300 days per year is assumed for the Case 9 which would lead to a production of 1.15 million pounds per year of  $U_3O_8$  at a grade of 0.10%. The waste rock from haulage tunnel development is assumed to be hauled by locomotive and hoisted by skip in both Cases 9 and 10. The amount of ore to be mined conventionally is assumed to average an equivalent of 3.37 ft. thickness out of the 145 ft. total thickness of the mineralized zone. The borehole miner will be less selective in mining the ore than for the

conventional mining. It will miss some ore between cavities and will include some waste rock of low grade which will mix with the ore. It is assumed that the borehole miner removes 3.86% by weight of the mineralized zone with an average grade of 0.08%, as compared to 2.31% removed for the conventional mine with a grade of 0.10%.

Therefore, if the conventional mine production rate is 1750 TPD, the borehole mine has to mine 2333 TPD to produce the same uranium output (neglecting any differences in mill recovery and costs). In both the conventional Case 9 and hydraulic Case 10, there is assumed to be waste rock of 25% of the ore production (435 TPD) which is separately hauled conventionally. In both cases this waste rock is transported by locomotive and hoisted by skip.

Based on borehole mining experiments by Flow Industries in uranium and oil sands (Ref. 17 and 19) it is assumed in Case 10 that each borehole jet will mine 40 metric tons per hour of ore using a water flowrate of 500 gpm at a pressure of 2000 psi. The assumed production rate of 2333 TPD can be met by three borehole miners operating 19.5 hours per day (an availability of 80%) and each mining 780 TPD. A fourth jet miner section is provided for standby.

In Cases 9 and 10, it is assumed that the mine is developed by one tunneling machine driving a 10 ft. diameter circular drift with cut-outs for drill stations every 60 ft. (Driven conventionally.) Each tunnel entry is spaced 600 ft. on centers from the next. In the borehole Case 10, two drilling stations 60 ft. apart are located in each of the last three cut-outs and one borehole miner operates in each of the three cut-outs. It requires six drill holes in a "fan" as shown in Figure 9-6 to permit mining any ore in the pairs of cavities marked A, B, or C.

Cavity A is a vertical cylinder 50 ft. in diameter by 145 ft. high. Cavity B includes at least the 180° upper section of a 50 ft. diameter cylinder at an angle of 30° from vertical and about 145 ft. long. Cavity C includes at least the 180° upper sector of a 50 ft. diameter cylinder at an angle of 60° from vertical and about 230 ft. long. In Cavities B and C, ore below the centerline can also be mined if a flume channel is washed away to permit slurry flow.

After small exploration drillholes are drilled and logged, the plan for borehole mining is made to remove about 17% of the potentially reachable volume in Cavities A, B, and C. The six boreholes of 12 inch diameter are bored at the approximate angles indicated, or at an angle to intercept more ore, depending on exploration drilling results.

The angular rotation rate and axial motion of the jet nozzle and possibly its flowrate will be programmed to disintegrate and wash out approximately 17% of the potentially reachable cavity volume, which is in turn 22.7% of the entire ore zone, for a total removal of 3.86% of the ore body.

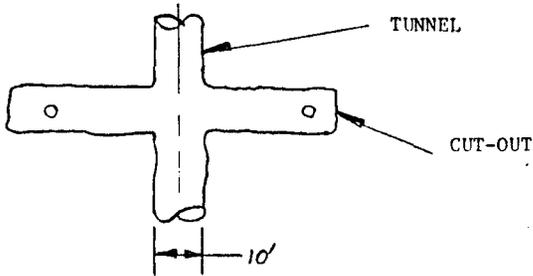
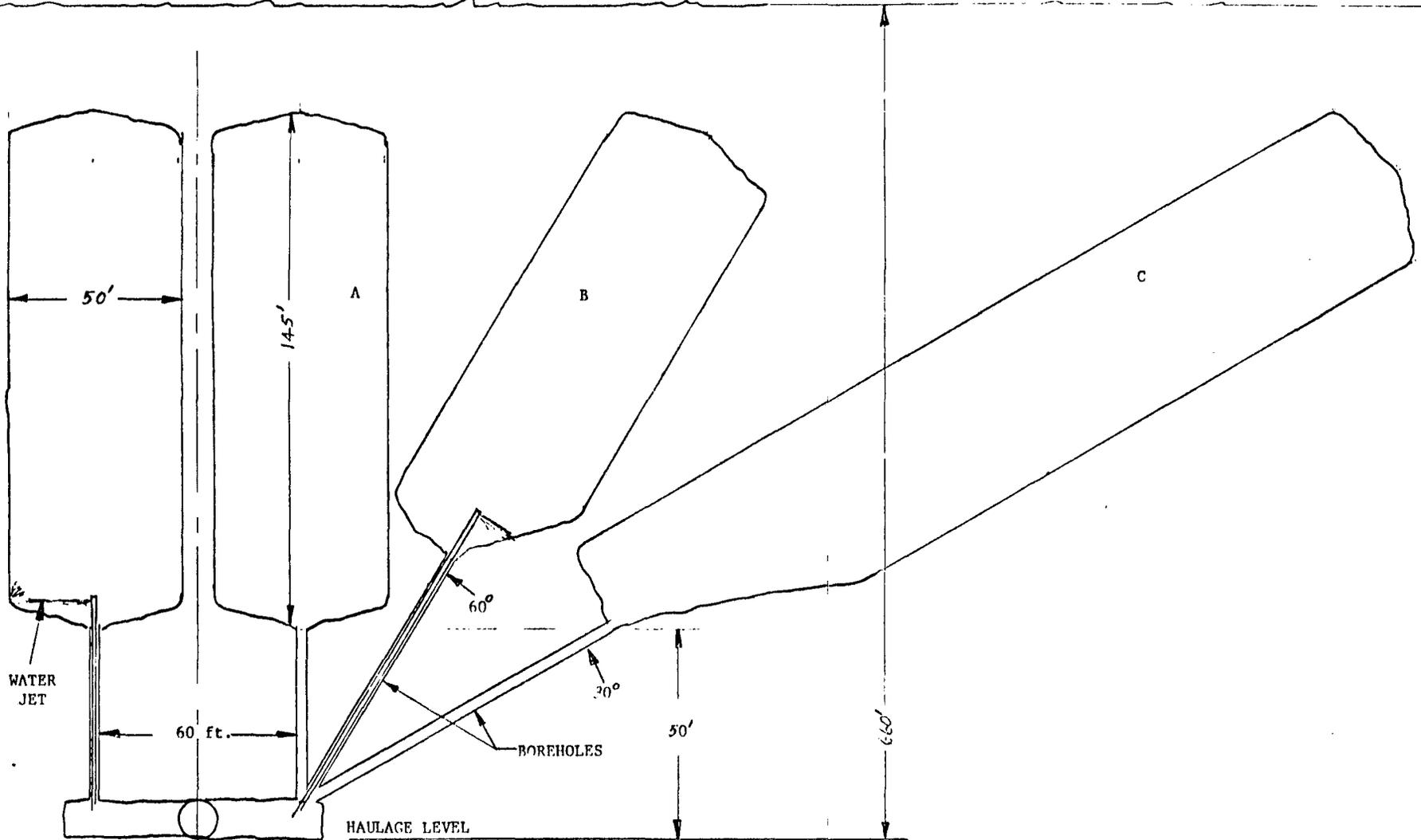


FIG. 9-6 : SCHEMATIC OF VOLUMES WHICH CAN BE MINED BY INVERTED BOREHOLE HYDRAULIC MINING.

The total potential volume minable through the six boreholes is

$$2 \left[ 145 + \frac{145}{2} + \frac{230}{2} \right] \frac{\pi}{4} (50)^2 = 1,305,062 \text{ ft}^3$$

This is 22.7% of the total ore zone. We assume we selectively mine 17% of this volume or 221,000 ft<sup>3</sup> which is  $221,000 \times \frac{2.3(62.4)}{2200} = 14,420$  metric tons for each 60 ft. of tunnel advance.

- o The time for three borehole miners to mine out one 6-hole advance of 60 ft. is then  $\frac{14420}{2185} = 6.6$  days.
- o The time for the tunneling machine to advance the entry 60 ft. at 300 ft. per month is 6 days.

Therefore the tunneling machine can approximately keep up with the mining rate of 3 borehole miners.

The tunneling machine in an advance of 60 ft. covers an associated mine area of 600 ft. wide by 60 ft. in 6 days. Therefore the total mine area of 3.5 x 0.6 mi. could be tunneled in a time of 27 years. Our assumed area of mine of 3.5 x 0.6 mi. is then larger than needed for 20 year life by 35%. The borehole miners require six holes of 12 in. diameter totaling 1560 ft. in length (from 195 to 390 ft.) to be drilled in each fan every 6.6 days. This is a total of 71,000 ft. of hole per (300 day) year. Each hole (2068 per year) must be cased to 50 ft. depth and has an average length of 260 ft. The slurrified ore from each borehole miner will flow by gravity down to the haulage level where a rail mounted centrifugal pump system carries it a maximum of 2.05 miles to the shaft sump for hoisting. The hydrohoist lifts the slurry 200 meters (656) ft. and then a surface pump station carries it 5 miles to the mill.

In the conventional mining case, we assume 2.31% of the total ore volume is mined in a time of about 24 years. A 600 ft. wide by 60 ft. wide by 60 ft. long block contains 340,530 metric tons, of which 7866 tons is mined. At a mining rate of 1750 TPD, it takes 4.5 days to mine this block. The number of 60 ft. long blocks in a 3.5 x 0.6 mi. mine is 1626. The total time to mine the entire area is then 24.4 years.

The estimated cost of capital equipment for the borehole hydraulic mine (Case 10) is given in Table 9-7. The operating costs are estimated in Table 9-8. The total cost of mining and delivering ore to the mill is \$12.16 per metric ton. As for the non-hydraulic mining case, this does not include administrative, milling, water collection, secondary recovery, or reclamation costs. The costs of the water collection system in the hydraulic mine have been assumed to equal the costs of the water drainage and disposal system for the non-hydraulic mine.

TABLE 9-7 - CAPITAL COST ESTIMATES  
INVERTED BOREHOLE HYDRAULIC MINING OF URANIUM (WYOMING)

(Case 10)

Quantity Required	Item	Characteristics	Unit Cost (\$K)	Total Capital Cost	Life yrs.	Cost per yr. (\$K)
4	Borehole miners	12" x 400'	\$500	\$2,000	10	200
4	Miner Drive and controls		200	800	10	80
4	500 gpm water pump	2000 psi	200	800	10	80
20,000 ft.	Steel water pipe		\$10/ft.	200	10	20
12	Centrif. slurry pumps & drives	1700 gpm	20	240	10	24
20,000 ft.	Slurry pipe, plastic	6"	\$5.85/ft.	117	5	23
8	Valves, slurry	6"	0.5	4	5	1
1	Slurry tank at hoist incl. emergency dump		80	80	20	4
1	Hydraulic hoist system (3-pipe feeder) incl. controls	12" 200m	5700	5700	20	285
5 mi.	Steel slurry pipe	10"	\$12/ft.	317	20	16
6	Surface pumps	1700 gpm	30	180	20	9
1	Water supply system	1700 gpm	100	100	20	5
2	Rotary drill & casing rig (underground)	12" x 400'	300	600	20	3
2	Locos for waste rock	12 ton	73	146	15	10
2	Locos to move equipment	12 ton	73	146	15	10
4	Cars, material transport (For slurry pumps)	8 ton	8	32	10	3
20	Cars for waste rock	8 ton	10	200	10	20
	Rail	4.7 mi.	\$200/ton	82	10	8
1	Hoist, skip	10' dia x 5', 200HP	784	784	30	26
1	Headframe, etc.		784	784	30	26
1	Truck, for waste rock	35 ton	293	293	7	42
1	Shaft	21' x 660'	\$3360/ft.	2,218	30	74
1	Shaft	19' x 660'	\$3040/ft.	2,006	30	67
1	Shaft	17' x 660'	\$2720/ft.	1,795	30	60

TABLE 9-7 (Cont')

Quantity Required	Item	Characteristics	Unit Cost (\$K)	Total Capital Cost	Life yrs.	Cost per yr. (\$K)
1	Underground electrical system (water & slurry pumps)		220	220	30	7
1	Surface elec- trical system (slurry pumps)		90	90	30	3
1	Installation of 5 mi. surface slurry pipeline		80K/mi.	400	30	13
3	Main fans	500,000cfm	112	336	10	34
2	Main fans	250,000cfm	56	112	10	11
4	Aux. fans	50,000cfm	11	44	10	4
1	Shaft station (with control system)		1000	1000	30	33
	SUB-TOTAL			21,480		1,171
	+ 15% Contingency			3,222		176
	TOTAL			\$25,048		1,374
	Depreciation @ 525,000 t/yr					\$2.62 per metric ton

TABLE 9-8 OPERATING COSTS  
INVERTED BOREHOLE HYDRAULIC MINING OF URANIUM (WYOMING)

(CASE 10)

	Costs per year	
	(\$K)	
<u>Borehole miners (three)</u>		
Labor: 6 MS/day (15.44/hr)	222	
Power: 0	0	
Maintenance: 6% of Capital	120	
TOTAL		342
 <u>Underground pumps, water &amp; slurry</u>		
Labor: 3 MS/day	111	
Power: @ 5¢/kw-hr	760	
Maintenance: 6% of Capital	62	
TOTAL		933
 <u>Hydraulic hoist system</u>		
Labor: 6 MS/day	222	
Power: @ 5¢/kw-hr	220	
Maintenance: 6% of Capital	342	
TOTAL		784
 <u>Surface pumps, slurry</u>		
Labor: 4 MS/day	148	
Power: @ 5¢/kw-hr	107	
Maintenance: 6% of Capital	11	
TOTAL		266
 <u>Hoist</u>		
Labor: 4 x 3 = 12 @19.44	444	
Power: 200 hp @ 60%, 16 hr/day	21	
Maintenance: 6% of Capital	47	
TOTAL		512
 <u>Rail Haulage (Waste rock only)</u>		
(2 locos and 20 cars)		
Labor: 2 x 2 x 2 shifts = 8 MS/d	296	
Loco operating (incl. 43 gal/d fuel)	32	
Loco maintenance	10	
Track maintenance	50	
Car maintenance	20	
Traffic control	4	
TOTAL		412
 <u>Trucks (Waste rock only)</u>		
Labor: 4.5 MS/d	166	
Fuel, 13 gal/hr.	62	
Maintenance: 6% of Capital	18	
TOTAL		246

TABLE 9-8 (Cont.)

<u>Fans</u>	Costs per year (\$K)	
Main Fans: 1100 KW, 24 hrs.	396	
Maintenance: 6%	17	
TOTAL		413
<u>Roof Support (haulageways only)</u>		
Labor: 8 MS/d	296	
Materials	150	
		446
Sub-Total		4354
+ 15% contingency		653
TOTAL Operating Cost/yr		\$5,007 K
Annual tonnage		525,000
Operating Cost per metric ton		\$9.54
Depreciation (from Table 9-6)		\$2.62
Total Cost per metric ton		<u>\$12.16</u>

## E2 - Non-Hydraulic Mine Estimates (Case 9)

Case 9 is a theoretical uranium mine located in Wyoming with similar geology and rock properties to the Exxon Hydraulic mine (Ref. 51). The depth of the mine is 200 meters and boundary dimensions are 3.5 miles x 0.6 miles. The production rate is 1750 tons of ore and 435 tons of waste per day. The haulage distance from the mine to the mill is 5 miles. To obtain the overall mining production cost, several aspects of the mine design were more closely defined, in particular the dimensions of the producing sections and support pillars. Details of the design, equipment selection procedure, and the costs are calculated for all direct mining functions, including mining, underground haulage, hoisting, surface haulage, ventilation, ground support, and shaft and road construction. Not included are administrative, milling, water pumping, secondary recovery, and reclamation costs.

The overall development scheme consists of mining utilizing either room-and-pillar or slot mining techniques with continuous mining machines. The mined ore is transported from the face with LHD vehicles, transferred through ore chutes to rail cars located on a haulage level about 50 feet below the ore zone. The cars are pulled by diesel locomotive to a central production shaft and emptied into 5 ton skips which are hoisted to the surface. 35 ton off-highway trucks transport the ore from the shaft to the mill at 5 mile distance.

The roof rock in the mined sections is supported by "Split Set" rock bolts, wire mesh and timbering as required. Additional support will be provided by backfilling the mined out sections with mill tailings. The cost of backfilling is not included in this section.

The capital cost estimates are given in Table 9-9. The operating cost estimates are given in Table 9-10. It should be noted that the non-hydraulic mine has four shafts, whereas the hydraulic mine needs only three.

TABLE 9-9  
CAPITAL COSTS  
Non-Hydraulic Mining of Uranium (Wyoming), Case 9

Quantity Required	Item	Characteristics	Unit Cost (\$K)	Total Capital Cost (\$K)	Life (years)	Cost per year (\$K)
4	Continuous miner		500	2000	15	133.3
4	LHD	3 yd <sup>3</sup>	235	940	4	235
3	Loco	12 t	73	219	15	14.6
70	Cars	8 t	10.4	728	10	72.8
4.7 mi.	Rail	5016/yd	\$200/ton	82	10	8.2
2	Hoist	10' dia. x 5' 200hp	784	1568	30	52.3
2	Headframe, etc.		784	1568	30	52.3
3	Trucks	35t	293	879	7	125.6
4	Roofbolter		200	800	10	80
1	Shaft	21' x 660'	\$3360/ft	2218	30	73.9
2	Shaft	19' x 660'	\$3040/ft	4013	30	133.8
1	Shaft	17' x 660'	\$2720/ft	1795	30	59.8
5 mi.	Roads*	50' wide	\$100K/mi	500	30	16.7
3	Main fans	500,000cfm	112.5	338	10	33.8
2	Main fans	250,000cfm	56.2	112	10	11.3
8	Aux. fans	50,000cfm	11.2	90	10	9
1	Shaft station		1800	1800	30	60
1	Underground clear. syst.		220	220	30	7
1	Surface electr. syst.		90	90	30	3
				19,960		1182
				+ 15% Contingency		177
				TOTAL Capital Cost		1359
				22,954		
				Depreciation @525,000 t/yr		\$2.58 per metric ton

\*The capital cost is the additional cost of the road required to haul ore by truck.

TABLE 9-10

## OPERATING COSTS (\$K)

Non-Hydraulic Mining of Uranium (Wyoming), Case 9

	Cost per year (\$K)	
<u>Hoists</u>		
Labor: 4 x 3 = 12 @\$15.44/hr	\$444.7	
Power: 200 hp @ 60%, 16 hrs/day, 5¢/kwh	21.5	
Maintenance: 6% of Capital	<u>94</u>	
Total per hoist	560.2	
2 hoists		\$1,120.4
<u>Rail Haulage</u>		
Labor: 2 x 2 x 3 = 12 man-shifts/day	444.7	
Loco Operating (incl. 43 gal/day fuel)	48.0	
Loco Maintenance	16.0	
Track Maintenance	17.8	
Car Maintenance	32.0	
Traffic control Maintenance	<u>6.4</u>	
	623.9	623.9
<u>Trucks</u>		
Labor: 15 x 3 = 4.5	166.7	
Fuel: 13 gal/hr	62.4	
Maintenance: 6% of Capital	<u>17.6</u>	
Total per truck	246.7	
2 Trucks operating		493.4
<u>Continuous Miner</u>		
Labor: 2 x 3 = 6	222.3	
Power: 280 kw @ 60%, 20 hrs, 5¢/kw hr	50.4	
Maintenance: 6% Capital	<u>30.0</u>	
Total per miner	302.7	
3 miners operating		908.1
<u>LHD</u>		
Labor: 1 x 3 = 3 man-shifts/day	111.2	
Fuel: 4 gal/hr x 20 hrs	24.0	
Maintenance: 6% Capital	<u>14.1</u>	
Total per LHD	149.3	
3 LHD's operating		447.9
<u>Roof Bolters</u>		
Labor: 2 x 3 = 6	222.3	
Fuel: 2 gal/hr x 20 hrs	12	
Maintenance: 6% capital	<u>12</u>	
Total per bolter	246.3	739

TABLE 9-10 (Cont.)

		Cost per year (\$K)	
<u>Fans</u>			
Main	Power: 1100 kw, 24 hrs	396	
	Maintenance: 6%	16.9	
Aux:	Power: 550 KW, 24 hrs	198	
	Maintenance: 6%	4.7	
		<u>615.6</u>	615.6
<u>Roads</u>			
	10% of Construction cost/yr		50
<u>Roof support supplies</u>			
	bolts: 150,738 per yr	602.9	
	wire mesh: 228,000 ft <sup>2</sup> per year	28.5	
	10" x 10" timbers: 981,509 bd-ft/yr	296.4	
		<u>927.8</u>	927.8
	Sub-Total		5,926
	+ 15% contingency		<u>889</u>
	Total Operating Cost		\$6,815 K/yr
	1750 x 300 = 525,000 ton/yr		\$12.98/metric ton
	Depreciation (from Table 9-8)		<u>2.58</u>
	Total cost per metric ton		\$15.56

### E3 Comparison of Hydraulic and Non-Hydraulic Mining of Uranium (Wyoming)

Comparison of Tables 9-8 and 9-10 shows that the estimated hydraulic mining and transport costs were \$12.16 per metric ton, which is 22% less than the similar costs of \$15.56 per metric ton for the non-hydraulic mine. The comparison does not take into account the relative costs of water drainage and pumping for the two cases because the water inflow is very site-specific and is variable with time during the mine life. However, it is clear that the capital and operating costs for mine drainage can be reduced by removing water with the hydraulic transport system.

F. Inverted Borehole Hydraulic Mine for Oil Sand at Wheeler Ridge, Calif.

F1. Assumptions

Cases 11 and 12 in Table 9-2 refer to a specific deposit of oil sands in Wheeler Ridge Field, in Kern County, California. The reference Case 11 is based on a proposed method of oil recovery using gravity drainage from the oil sand into underground mine openings. The reference case is described in the Golder Associates report on oil mining (Ref. 66).

From the standpoint of underground hydraulic mining, the deposit has desirable characteristics, including:

1. The oil sand is 170 ft. thick and can be reached by simple drilling from underground openings in the underlying rock beds which are relatively competent and permit maintenance of openings at reasonable cost.
2. The competency of the oil-bearing sands is low and would probably be minable by a monitor jet from a borehole mining device.
3. The field occupies 620 proven acres with estimated oil in place of 93,000,000 barrels.

The present oil content is estimated to be 0.28 bbls per ton of 22° API gravity heavy crude oil. The top of the oil sands is 1000 to 1310 ft. below the surface.

There was no recorded gas production until after injection of 27,337,000 Mcf of gas during a nine-year pressure maintenance program in the 1960's. The gas to oil ratio in 1976 was only 139 cubic feet of gas per barrel of oil. Data available indicate a porosity of 32% and permeability of 800 millidarcies.

Underlying the sands is the upper Miocene Fruitvale formation. It is comprised of siltstone with interbeds of very fine-to-coarse-grained sandstone. Indications are that these formations are relatively competent and contain impermeable bands which would be suitable for mine development.

The mine development is assumed to be the same for Cases 11 and 12. Mine development is on a single level in rock 50 ft. below the oil sands. A double entry layout is used to assure good ventilation. Drifts are 12 ft. wide by 10 ft. high. The rock is assumed to have a strength of about 5000 psi, without serious jointing or faulting.

It is assumed that the borehole monitor jet will cut out a volume 50 ft. in diameter by 170 ft. high at a rate of 40 TPH. The water flow is 500 gpm at 2000 psi. The amount of sand removed per borehole is 333,000 ft.<sup>3</sup> or 23,600 metric tons (at density of 156 lb/ft<sup>3</sup>) containing 6600 bbl of oil at 0.28 bbl/ton.

In order to produce 6600 bbl of oil per day for comparison with the Golder study (Case 11) we must mine an average of 1.25 borehole cavities per day and recover 80% of the oil in the surface processing plant. The production rate

must be 29,500 metric tons per day. Assuming each borehole miner mines 40 TPH for 21 hours per day (3 shifts) a total of 35 operating borehole miners are required, plus 5 spares, for a total of 40. All borehole miners must be operable from underground in a 10 ft. high drift. Similarly the drill rigs for boring and casing 12 inch I.D. boreholes must operate in a 10 ft. high drift.

Each drillhole will be cased through the first 50 ft. of rock with a 12 inch I.D. casing to accept the borehole mining tool. The slurry mined by the rotating monitor jet will be piped through plastic gathering lines to the shaft sump where it will be hydraulically hoisted to the surface and one mile to the mill. Hydraulic backfilling is not planned and tailings will be pumped to a surface disposal area. Water from the tailings slurry will be recovered on the surface, clarified to less than 100 mg/liter and returned underground for use by the borehole jets.

The mine and mill will operate 350 days/yr, 3 shifts per day, for an annual production of  $6600 (350) = 2.31 \times 10^6$  bbl of oil. Note that this 350 days per year and 3 shift operation is in contrast to 300 days per year and two shifts of operation in other mining cases analyzed. It is assumed because of the high oil sand mining rate required and the need to keep the surface processing plant operating continuously.

#### F2 Cost Analysis

The costs for the reference gravity drainage case are derived from the Golder Associates study (Ref. 66) for the Wheeler Ridge Field. This is based on producing 6600 barrels per day by drainage of oil into drifts driven below the oil-bearing zone. A treatment plant is used underground to separate oil/water, oil/gas and oil/solids at a capital cost of \$1 million. The Golder estimate of total production cost was \$10.86 per barrel, based on 1978 costs. Assuming cost escalation at a rate of 8.5% per year, the mid-1981 costs would be \$13.87 per barrel of oil.

The costs for the inverted borehole hydraulic mine of oil sand are based on similar assumptions as for the hydraulic mining of uranium in Wyoming (Case 10) discussed in part E above, but a factor of 16.8 higher ore production rate per day on 3 shifts with 35 borehole miners. The other major difference is that the fractional volume of oil-bearing zone to be mined is much higher (54.5%) than the fractional volume of uranium bearing zone (3.86%) which is selectively mined. Each inverted borehole in oil sand is 50 ft in diameter by 170 ft. high and holes are on 60 ft square centers, so the volume of oil sand removed permits 54.5% recovery. With uranium, the tunnel entries are 600 ft on centers, with some slanted boreholes, whereas in oil, the boreholes must be more nearly vertical to achieve high recovery and the tunnels must be approximately 120 ft on centers, requiring 5 times as much tunnel development for the same mine area.

Each 60 ft. advance of a tunnel, requires drilling two 220 ft holes and mining two cylindrical volumes 50 ft in diameter by 170 ft high.

The costs for the hydraulic borehole mine for oil sands are derived on a basis comparable to the assumptions in the Golder report for the Wheeler Ridge gravity drainage case. The costs are estimated in Tables 9-11 and 9-12 on the basis of 1981 costs.

The largest cost items are \$88.5 million for a surface oil sand processing plant, \$20 million for 40 borehole miners and \$18 million for a hydraulic hoist system. The total cost is estimated to be \$39.96 per barrel, including 15% per year of the capital cost for interest and profit. This compares to \$13.87 per barrel estimated for the gravity drainage method, which however was based on an oil yield of 50% which was "more of an assumption than an estimate" (Ref. '66, p. 195).

If the borehole mine utilized backfilling to minimizing subsidence, the costs would increase at least \$6 per barrel to about \$46 per barrel.

### F3 Underground Processing of Oil Sands

A potential method to reduce the cost of the borehole mining process would be to avoid the costs of hoisting the slurry, surface processing the ore and disposing of waste sand on the surface or by backfilling. In concept, one way of accomplishing this would be to install underground mobile processing equipment which would separate oil from the hydromined slurry and return the sand tailings into adjacent mined out cavities. This underground processing equipment could depend on hot water or chemical extraction of oil. The use of preheated water in the borehole monitor jets can also be considered. Since these processes have not been developed, it is not possible to estimate costs. However, it is clear that large savings would be possible if underground processing were feasible.

It may be noted that the Golder study concluded that:

- Underground operations involving direct mining cannot be contemplated at this time with adequate confidence in their safety or economic feasibility. There is no obvious way of improving this situation markedly by any readily identifiable research or test project.
- Underground operations involving drainage of oil offer important attractions. Such projects would have the favorable features of low capital requirements and minimum environmental impact. Considerable further study is needed, however, to establish with confidence the potential yields to be expected from such operations.

Borehole mining should permit a higher oil recovery than gravity drainage and more rapid oil extraction. Potential safety problems may be overcome by keeping the oil slurry in a closed system at all times. Therefore, further investigation of the underground oil processing concept is desirable in comparison

with the gravity drainage process. The hydraulic mining and transport of oil sand slurry to the surface for processing does not appear to offer big economic advantages over other underground mining methods for oil sands, such as direct stoping, block caving or the shatter and drain method, which are estimated to produce oil at costs of \$20 to \$60 per barrel (Ref. 66). However, it may offer much greater safety if the oil sand can be mined remotely and the slurry can be kept in a closed system at all times. Therefore borehole mining of oil sands from underground may provide a method of underground mining of acceptable safety.

TABLE 9-11 CAPITAL COSTS

Inverted Borehole Hydraulic Mining of Oil Sands (Wheeler Ridge, Calif.)

Quantity Required	Item	Characteristics	Unit Cost \$K	Total Capital Cost \$K	Life Cost yrs. per yr \$K
	Exploration & Feasibility		2500	2500	20 125
40	Borehole Miners	12" x 220'	500	20,000	10 2000
40	Miner drives & controls		200	8,000	10 800
40	500 gpm water pumps	2000 psi	200	8,000	10 800
200,000'	Steel water pipe		\$10/ft	2,000	10 200
120	Centrif. slurry pumps & drives	1700 gpm	20	2,400	10 240
200,000'	Slurry pipe			1,170	5 230
80	Valves		0.5	40	5 8
1	Slurry tank at hoist		80	80	20 4
1	Hydraulic hoist system		18,000	18,000	20 900
1 mi.	Steel slurry pipeline		600	600	20 30
12	Surface pump		30	360	20 18
1	Water supply system		1,000	1,000	20 50
20	Rotary drill & casing rigs	12"x220'	300	6,000	20 300
20	Locos for waste rock	12t	73	1,460	15 97
20	Locos to move equipment	12t	73	1,460	15 97
40	Cars for pump trans- port	8t	8	320	10 32
200	Cars for waste rock	8t	10	2,000	10 200
1	Hoist, skip for waste rock	2.7x10 <sup>6</sup> tm/d	7,700	7,700	20 385
1	Headframe, etc.		7,700	7,700	20 385
10	Truck, waste rock	35t	293	2,930	7 420
1	Shaft	24'x1200'	\$5000/ft	6,000	20 300
1	Shaft	21'x1200'	\$3360/ft	4,032	20 202
1	Shaft	19'x1200'	\$3040/ft	3,648	20 182

Table 9-11 (Cont.)

Quantity Required	Item	Characteristics	Unit Cost (\$K)	Total Capital Cost (\$K)	Life yrs.	Cost per year \$K
1	Underground elect. sys- tem (slurry pumps)		2200	2,200	30	73
1	Surface electr. system		900	900	30	30
1 mi.	Installation of Surface slurry pipe		80k/mi.	80	30	3
1	Ventilation for system			4,000	10	400
1	Oil sand pro- cessing plant	29,500 TPD	\$3000 per daily ton	88,500	20	4,425
1	Shaft station (with control system)		1,000	1,000	30	33
Sub-Total				203,540		12,969
+ 15% Contingency				30,531		1,945
TOTAL				\$234,071		\$14,914K
Depreciation @10.3MTPY						\$1.45 per metric ton
Depreciation @ 2.31x10 <sup>6</sup> bbl / yr						\$6.46 per bbl

TABLE 9-12 OPERATING COSTS

Inverted Borehole Hydraulic Mining of Oil Sand (Wheeler Ridge, Calif.)

	Costs per year		
		\$K	
<u>Borehole miners (40)</u>			
Labor: 70 MS/d (15.44/hr)		3026	
Power: 0		0	
Maintenance: 6% of Capital		1200	4226
<u>Underground pumps, water &amp; slurry</u>			
Labor: 10MS/d		432	
Power: @ 5¢/KW-hr		7,600	
Maintenance: 6% of Capital		624	8656
<u>Hydraulic hoist system</u>			
Labor: 24 MS/d		888	
Power: @ 5¢/KW-hr		2,200	
Maintenance: 6% of Capital		1,080	4168
<u>Surface pumps, slurry (1 mi.)</u>			
Labor: 6 MS/d		222	
Power		214	
Maintenance		22	458
<u>Hoist</u>			
Labor: 24 MS/d		888	
Power:		315	
Maintenance: 6% of Capital		462	1665
<u>Rail Haulage (waste rock only)</u>			
20 Locos and 240 cars			
Labor: 80 MS/d		3458	
Loco operating		320	
Loco Maintenance		500	
Car Maintenance		200	
Traffic control		40	4518
<u>Trucks (waste rock)</u>			
Labor: 45 MS/d		1945	
Fuel : 13 gal/hr		620	
Maintenance: 6% of Capital		176	2741

TABLE 9-12 OPERATING COSTS (CONT.')

<u>Fans</u>	<u>Cost per year (\$K)</u>	
Maintenance: 4400 KW, 24 hrs	1584	
Maintenance: 6% of Capital	240	1824
<u>Roof support (haulageway only)</u>		
Labor: 45 MS/d	1945	
Materials	1500	1946
<u>Processing Plant @ \$0.50 per ton</u>		5162
<u>Waste Disposal and Reclamation</u>		1000
<u>Environmental</u>		<u>400</u>
Sub-Total		36764
+ 15% contingency		5515
Total Operating Cost/yr.		\$42,279
Annual production		2.31 x 10 <sup>6</sup> bbl/yr
Depreciation (from Table 9-11)		\$6.46
Allowance for interest & profit (15 % of capital investment)		\$15.20
Total Cost Per Barrel		\$39.96

### G. Hydraulic Mining of Sandstone in Iowa

The St. Peter sandstone is found at shallow depths along the Mississippi River from Minneapolis to Iowa. The Martin-Marietta Corp. operates an underground mine for foundry sand at Garnavillo, Iowa. The depth of mining is less than 200 feet and the seam thickness varies from 50 to 20 ft. Much of the product is shipped 200 miles for use in casting of farm machinery. The present conventional mine uses blasting with a room-and-pillar mining method. The rooms are 88 ft. on centers and are 38 ft. wide by 20 ft. high at the present mining faces, leaving pillars 50 ft. square.

An approximate cost comparison was made of the conventional and hydraulic mining methods, assuming an increase of the production to 2100 TPD during 14 hours per day for 250 working days per year for 10 years. It is assumed that the working front in the mine is 1400 ft. wide with 16 entries and a maximum distance from the face to the portal of 1.5 miles. (The present distance is 3/4 mile.

Experiments in hydraulic mining by the Bureau of Mines have shown that the sandstone can be disintegrated at 40 TPH. We shall assume 40 TPH from each of 4 monitors which normally operate 14 hrs/day with 93% availability. They each require 400 gpm of water at 900 psi from a 300 hp pump. There will be 5 pumps, including one as a spare. There will be two separate and independent systems, each with one water pump, 1.5 miles of steel water pipe, two monitors, two jet pumps to pick up slurry, two slurry pumps (and a spare), and 1.5 miles of plastic slurry pipe. The slurry pumps will handle a 15 wt.% slurry concentration and transport it 1.5 miles (maximum) to the wash plant through plastic pipes. The water will be clarified to less than 100 mg/liter of siliceous solids in order to prevent excessive wear of the water pumps and monitor nozzles. Water will be recovered and pumped through high pressure steel pipe back to the faces.

The comparison assumes that costs for washing the sand and for water clarification are the same in both cases. Tables 9-13, and 9-14 show the capital and operating costs, respectively, estimated for the hydraulic mine. It is seen that the hydraulic mining and transport costs are estimated to be \$3.56 per short ton.

An estimate of the present costs for conventional mining and transport at a lower production rate, using substantially depreciated equipment, indicate a cost in the neighborhood of \$3 per ton. However, if new conventional equipment were purchased at 1981 prices to expand to a production rate of 2100 TPD, the cost of mining and transporting the sandstone would be higher.

Based on data in Ref. 114 with costs escalated to 1981, the costs for capital equipment and operating costs for mining by the drill-and-blast method and for transport by truck an average distance of 3/4 mile were estimated as shown in





Table 9-6. This includes the cost for a compressed air system to supply air drills for blasting. It also includes an estimate of the increase in ventilation system costs required because of the need to clear fumes and dust from blasting and the exhaust fumes from the operation of Diesel trucks used for haulage underground. The hydraulic mining and transport system is electrically powered and is estimated to require only one/sixth the air flow (2100 m<sup>3</sup>/min) for ventilation. The conventional case includes the additional costs for crushing the conventionally-mined ore, since hydraulic mining disintegrates the ore to minus 30 mesh adequately. The added costs are estimated to be \$1.5 million for capital cost of a crushing plant, plus \$10,000 per month for its operation. It should be noted that in no case have costs other than for mining, transport and crushing been included. Costs of mine development, surface facilities, ore washing and drying and shipping are not included.

A comparison of Tables 9-5 and 9-6 shows the estimated hydraulic costs of \$3.56 per ton which is 22% less than the costs of \$4.59 per ton estimated for the conventional system. It therefore appears that hydraulic mining and transport may have economic advantage as well as health and safety advantages in sandstone mining. More detailed cost estimates are needed for each specific case.

TABLE 9-6

Sandstone Mining - Conventional, Room-and Pillar  
(based on Ref. 114, escalated to 1981)

A. Capital Equipment Costs: (\$K)

Mining equipment (drills, jumbos, etc)	\$1127
Haulage trucks	664
Compressed air system for drilling	212
Additional ventilation system 12,600m <sup>3</sup> /min (for blasting and Diesel truck operation)	400
Crushing plant	<u>1500</u>
Total Capital Investment	\$3903

B. Operating Costs \$K per year (250 days)

Room-and-pillar mining	948
Truck haulage	443
Compressed air operations	130
Additional ventilation operations	185
Crushing plant operations	<u>120</u>
Total Operating Costs	\$1826

Amortization of capital investment (@ 15%)	<u>585</u>
Total Costs/Yr	\$2411

Production per year	525,000 tons
Mining and transport costs per ton including added vent. and com- pressed air	\$4.59 per ton

H. Hydraulic Hoisting of Potash in New Mexico and Trona in Wyoming

H1. Potash

a. Assumptions

A comparison was made of the cost of increasing the potash hoisting capacity of an existing mine by a new shaft and skip, or by hydraulic hoisting through a drilled borehole. The assumptions are:

1. Additional ventilation is required with either alternative.
2. Mine depth is 300 meters (comparable to Carlsbad, New Mexico deposits).
3. Production rate is 10,000 TPD or 3,000,000 TPY, based on 2 shift operations for 300 days per year for 20 years. Maintenance is performed on the third shift.
4. Ore reaches shaft as minus one inch from a feeder breaker and belt transport.
5. The conventional mine uses skip hoisting. On the surface the ore is screened to 3/8", the oversize is crushed to 3/8" and then slurried to 35 percent concentration by weight by adding KCl brine.
6. The hydraulic mine has screens and crushing equipment underground to produce minus 3/8" material and slurrify it with brine which is brought down a drillhole from the mill (not preheated). The hydraulic hoist will be a 3-pipe feeder system, like the Hansa Hydromine system made by SIEMAG.
7. The slurry enters the mill for scrubbing. The mill returns brine underground at ambient temperature.
8. All pipe will be plastic-lined steel pipe for corrosion and erosion protection.
9. A plastic-lined slurry sump must be provided at the shaft to hold all the slurry in the hoist in case of power failure or line breakage.

In order to make a cost comparison, it is assumed that only the portion of costs associated with hoisting will be compared, assuming an existing mine with two shafts already at full capacity. Conventional hoisting requires a new shaft, while the hydraulic system could be put in an existing shaft or the pipe could be installed in a drillhole (which we assume).

A separate engineering analysis of the conventional hoist capital and operating costs showed that they were within about 10% of the STRAAM values which are therefore used for the comparison.

b. Conventional hoist costs

The annual conventional hoisting capital costs are estimated to be:

Shaft sinking and shaft facilities	\$4,421K
Hoist system	<u>\$9,166K</u>
TOTAL	\$13,587K

The conventional hoist operating costs are estimated to be:

Labor	\$301K
Supplies	\$656K
Equipment operation	<u>\$ 97K</u>
TOTAL	\$1054K

Assuming straight line depreciation of the hoist system capital investment over 20 years, the depreciation is \$679K per year.

The total hoisting cost per ton of ore is then found:

Operating Cost	1054K
Depreciation (20 yr)	<u>679K</u>
TOTAL	\$1733K

Annual tonnage, 3,000,000

Conventional hoisting cost per metric ton \$0.58

c. Hydraulic hoist costs

The costs for hydraulic hoisting potash are estimated as follows.

The capital costs are derived from estimates made by Burghardt (Ref. 81) for expansion of potash mining capacity in German mines. He estimates 1979 total investment costs for a SIEMAG pipe feeder system for 300 TPH of potash from 800 m depth as \$8,940K DM. This includes \$1520K DM for crude salt screening and feeding. Assuming a conversion rate of 1.60DM per U.S \$ in 1979, and escalating by 16% to mid-1981, the cost becomes \$6480K. The required capacity of 10,000 TPD requires 16 hour per day operation of a 625 TPH system. We assume that capital cost goes up as the square root of capacity, so the cost is corrected to

$$\frac{625}{300} \times 6489K = \$9353K$$

The correction for a reduction of depth from 800 m to 300 m is assumed as in Table 9-3, Cases 6 and 8 to be \$475K per 300 m of depth, which leads to a cost of \$8560K for the hydraulic hoist system at 300 m depth. This cost is for a larger capacity but lower depth system than for the uranium hydraulic hoist in Case 8 of Table 9-3.

We assume that the hydraulic hoist requires only a drill hole to install the hoist pipe at a cost of approximately \$500K. The total capital investment is then:

Hydraulic hoist system	\$8560
Drill hole for hoist pipe	<u>500</u>
TOTAL	\$9060

The operating cost for the hydraulic hoist is based on Burghardt's estimate of 8 KW-hr/tkm and electric cost of 5¢ per KW-hr. The annual operating costs are estimated to be:

Electrical energy	\$360K
Labor - (3 men @ 15.44/hr)	222K
Equipment operation (5% of capital investment per yr.)	<u>453K</u>
TOTAL CASH COST	\$1035K

The depreciation is assumed to be straight line for 20 years or \$453K per year.

The total hoisting costs per ton of ore are then

$$\frac{1035 + 453}{10,000(300)} = \$0.50 \text{ per metric ton}$$

This estimated cost of 50¢ per metric ton is 14% lower than the 58¢ cost estimated above for conventional skip hoisting, which is assumed to require an additional 22 ft. diameter hoist shaft, instead of a drillhole.

It is seen that the capital investment needed to add a hydraulic hoist (\$9060K) is 33% less than that required to add the new shaft and skip hoist (\$13,587K), it being assumed that the necessary additional ventilation capacity is available in both cases.

As pointed out by Burghardt, the use of hot brine as the carrier medium instead of cold water, would permit integration of the hot dissolving process with hydraulic hoisting. This would reduce the added investment needed in the processing plant for dissolving the increased production.

## H2. Trona

A cost comparison was made of the cost of hoisting trona in Wyoming by skip or by hydraulic means. The assumptions are similar to those for potash hoisting except for a greater mine depth:

1. Mine depth is 500 meters.
2. Production rate is 10,000 TPD or 3,000,000 TPY, based on 3 shift operations for 300 days per year for 20 years.
3. Ore reaches shaft as minus 1 inch from a feeder breaker and belt transport.
4. The conventional mine uses skip hoisting thru a 22 ft. shaft. There will also be a 16 ft. shaft. On the surface the ore is screened to minus 3/8", the oversize is crushed to minus 3/8" and then slurried to 35 percent concentration by weight by adding saturated solution.
5. The slurry enters the mill where it is treated by the Wyoming Trona process.
6. The hydraulic mine has screens and crushing equipment underground to produce minus 3/8" material and slurrify it with brine which is brought down a drillhole from the mill. The hydraulic hoist will be a 3-pipe feeder system in a 7 ft. shaft.
7. All slurry pipe will be plastic-lined steel pipe for corrosion and erosion protection.
8. A plastic-lined slurry sump must be provided at the shaft to hold all the slurry in the hoist in case of power failure or line breakage.

The annual conventional hoist costs are derived from the STRAAM data as for potash above and are summarized here:

Capital costs:	
Shaft sinking and shaft facilities	\$7,369K
Hoist system	<u>\$9,166K</u>
Total Capital investment:	\$16,535K

Operating costs (2 shifts):	
Labor	301K
Supplies	656K
Equipment operation	97K
Depreciation	<u>827K</u>
Total op. costs including depreciation	\$1881K

Annual tonnage 3 x 10<sup>6</sup>

Conventional hoisting cost per metric ton: \$0.63

The annual hydraulic hoist costs are derived as above for the potash case but with the capital cost increased by \$320K to account for the 500 m instead of 300 m depth.

The hydraulic system costs are:

Capital costs:	
Hydraulic hoist system	\$8880K
Drill hole for hoist pipe	<u>833K</u>
TOTAL	\$9713

Operating costs (2 shifts):	
Electrical energy	360K
Labor (3 men @ 15.44/hr)	222K
Equipment operation (5% of capital investment per year)	485K
	<u>\$1067K</u>

Depreciation 485

Total hydraulic hoisting costs per ton of trona ore are:

$$\frac{1067 + 485}{10,000(300)} = 0.50 \text{ per metric ton}$$

This cost of 50¢ per metric ton is 21% lower than the cost of 63¢ estimated above for skip hoisting of trona through a new shaft.

The added capital investment needed to add the hydraulic hoist (\$9713K) is 41% less than that required to add the new shaft and skip hoist (\$16,535K), it being assumed that additional ventilation capacity is available in both cases.

## 10. POTENTIAL HEALTH AND SAFETY EFFECTS

### OF HYDRAULIC MINING AND TRANSPORT

#### A. Mine Dust and Radon Daughters

The most severe health problem facing the mining industry in general is the control of respirable mine dusts. This is of greatest concern in the uranium mining industry because of the hazard of deposition of radioactive radon daughter products in the lungs of workers and of those exposed to the effects of mill tailings dumps.

The International Atomic Energy Agency in 1968 published a code entitled "Radiation Protection in the Mining and Milling of Radioactive Ores" (Ref. 118). It covers the occupational hazards in mining and milling of uranium. Research on minerals health and safety is conducted by the Bureau of Mines (Ref.120). A review paper on radiation hazards in uranium mining and milling has been prepared (Ref. 121 ).

In present underground mining practice in uranium sandstones, a mine is generally dewatered in advance of mining in order to obtain the better structural strength associated with dry rock as an aid to roof control. However this tends to cause more dust when the ore is broken. Therefore water or steam sprays may need to be used locally to control dust. In any case, high ventilation airflow is used for dilution of radon gas, which is emitted by the broken ore and rock formations. The application of hydraulic mining would tend to increase water content in the adjacent sandstone and negatively affect roof control but improve dust control. Keeping the sandstone moist will also hinder diffusion of radon gas into the mine openings. If the radon could be sealed into the rock, the airflow required for ventilation could be reduced.

In coal seams, water infusion in advance of mining is used to reduce respirable dust generation. By analogy, dust generation in uranium mines could be reduced by minimizing the degree of prior dewatering of the uranium ore formations, which are usually aquifers.

The emission of dust and radon from ore during loading, hauling and dumping in underground uranium mines could be avoided by transporting the ore as a slurry in pipes. However, dust and radon exposure of miners in the stopes would not be reduced unless the ore were soft enough that a hydraulic mining method could be applied.

#### B. Avoiding Diesel Exhaust

Underground uranium mines now sometimes use Diesel powered equipment such as LHD units for transporting ore to the main haulage system.

If a main haulage rail system were in part replaced by hydrotransport, (no hydraulic mining) the LHD units would still be required. Only if an alternate section haulage were developed for use with hydraulic mining would there be a reduction of Diesel exhaust pollution of the air. For example, the use of gravity fluming of ore from the stopes to the main haulage hydrotransport system could prevent this air pollution, and also be more economical. The question of radon evolution from open flume flow of uranium slurry has not been considered.

#### C. Noise

Very little research has been conducted on the generation of noise by hydraulic mining or transport systems. However, if hydraulic borehole mining were used underground, the jet noise of ore disintegration would occur in a closed cavity and not reach the miners. Therefore, the noise associated with drilling and blasting or continuous mining machines would be avoided. If monitor jets are used directly in the stopes, provision should be made to protect miners from the jet noise, which can exceed acceptable levels.

#### D. Safety Against Roof Falls

New Mexico sandstone mines generally have weak, wet roof rocks. Therefore, when miners conduct drill-and-blast or continuous mining operations, the roof must be supported by roof bolts, Split Sets, wire mesh, or other methods. These methods generally do not completely prevent roof falls. Therefore, there is an incentive to remove the men from the stopes and to use remote-controlled mining methods, such as hydraulic borehole mining.

The problem of roof falls also exists in main haulageways. In principle, the use of hydrotransport for main haulage should permit the use of smaller transport vehicles for service and therefore allow smaller entries, which are less prone to roof falls.

#### E. Control and Automation Effects on Safety

Conventional mining systems are batch-processing systems which are not easy to measure or control. They are labor intensive and therefore subject to human error, which often causes accidents and adversely affects safety. Hydrotransport systems, on the other hand, are amenable to measurement, control, and automation with central computer supervision which can be designed to improve mine safety. The hydrotransport systems for main haulage, hoisting, and for haulage to the mill can be integrated into a single quasi-steady flow system, mainly within closed pipes. One of the most serious accidents which can be invisulized would be a failure of the hoist pipe. This would require catching slurry in the main hoist sump, but would not cause a severe safety problem.

11. ENVIRONMENTAL IMPACTS OF  
HYDRAULIC MINING AND TRANSPORT

A. Uranium Mining

A review of legal regulation of environmental aspects of noncoal mining has been prepared by Cook (Ref. 117).

The Bureau of Mines has an extensive program on minerals environmental research and development (Ref. 120). Several of the programs relate to uranium mining, milling, and tailing disposal. A bibliography on uranium mining and milling studies is available from NTIS (Ref. 122). It includes 170 abstracts for the period 1964-81.

A Code of Practice entitled "Management of Wastes from the Mining and Milling of Uranium and Thorium Ores" was published by the International Atomic Energy Agency in 1976 (Ref. 123). It deals with environmental effects from mining through production of uranium concentrate (normally "yellow cake"). It does not deal with occupational hazards in mining or milling (See. Ref. 118).

The New Mexico state policies and requirements for management of uranium mining and milling have been published (Ref. 119 ). Volume I, the Executive Summary of this report, stresses the need for a well drilling program in order to allow the development of New Mexico uranium resources to be optimal relative to the water resource in the San Juan Structural Basin.

One concern is that increased mine dewatering in the Grants mineral belt may impair existing water allocations in the San Juan Structural Basin. Part of the land area involved belongs to the Navaho Indian Tribe. Other study participants include the New Mexico Bureau of Mines and Mineral Resources, New Mexico State Engineer, U.S. Geological Survey, and the U.S. Department of Energy.

In order to predict the effect of mine dewatering on the groundwater supply, drilling of 4 to 44 wells may be required.

The five volumes of this study are as follows:

- Volume I - Executive Summary, SAND 79-0973;
- Volume II - Water Availability in the San Juan Structural Basin, SAND 78-1331;
- Volume III - Adverse Effects of Uranium Mining and Milling on the Physical Environment, SAND 78-1332;
- Volume IV - The Supply of Electric Power & Natural Gas Fuel as Possible Constraints on Uranium Production, SAND 79-7105
- Volume V - State Policy Needs for Community Impact Assistance, SAND 79-7093.

Volume III of the Sandia Study points out that: "...uranium mining and milling are currently the most significant sources of radiation exposure to the public from the entire uranium fuel cycle, far surpassing other stages of the fuel cycle such as nuclear power reactors or high level radioactive waste disposal."

The potentially hazardous substances associated with uranium mining and milling are the radionuclides radon-222, radium 226, lead-210, polonium-210, uranium 238, uranium 234, and compounds of the stable elements selenium, arsenic, molybdenum, vanadium and lead (Ref. 125). The public health concern is for the possibility of exposure to very low concentrations but over long (10 to 50 year) periods of time.

In 1981, a U.S. District Court in Washington, D.C. ruled that a regional environmental impact statement for uranium development in New Mexico's San Juan Basin was not justified and that the site - specific environmental impact statements for specific uranium projects are appropriate.

The environmental impacts of underground hydraulic mining and transport of uranium include the effects on ground water hydrology in the vicinity of the mine and the effects on surface and ground waters of the disposal of mine waste rock and of tailings and of liquid wastes from the milling process. Water management must provide for controlling these environmental impacts to meet all legal requirements including radiological health requirements. The tailings and waste liquids contain radioactive components and often toxic chemicals such as selenium. These hydrological effects are not unique to hydraulic mining and transport. Conventional mines must also dispose of mine drainage water and stabilize mill tailings and ore stockpiles to minimize air pollution (by fugitive dust) or water pollution (by surface water leaching of tailings dumps or ore stockpiles).

The environmental effects of hydraulic borehole mining near-surface deposits of uranium and phosphate ores has been studied under a Bureau of Mines contract (Ref. 126). Borehole mining has the potential of draining water from an adjacent aquifer, with a slight possibility of dissolving contaminants and reinjecting them into an aquifer. If borehole cavities from uranium mining are backfilled to reduce subsidence, the slurry for backfill should not contain the fine slime component of mill tailings which includes most of the radioactive and chemical pollutants. These slimes could contaminate an adjacent aquifer. Backfilling should be with washed coarse tailings or with other sand fill material. Methods of chemically solidifying the backfill can be considered as a means of stabilization to reduce the possibility of aquifer pollution.

In New Mexico and Wyoming the natural rate of evaporation from tailings ponds exceeds the rainfall, so tailings piles normally do not discharge liquid wastes except by percolation into the ground. However, provisions must be made

to handle surface water from storms without failure of tailings dams or dikes and to prevent rain water leaching which might release radioactive contamination. Solid tailings must also be stabilized against wind erosion.

Tailings dumps are a source of radon gas released by diffusion. Wind-blown tailings and external gamma radiation may also be problems. Covering the pile by addition of two feet of overburden material can stabilize the tailings.

Dissolved toxic materials, such as selenium or radium decay products, are generally part of the waste liquid in tailings ponds. Unless controlled, they can then percolate into ground water or be discharged to surface streams (Ref. 124).

The Environmental Protection Agency on November 24, 1980 published a proposed National Groundwater Protection Strategy. Draining of water into an underground uranium mine significantly modifies the ground water flow in the aquifers below the water table where uranium was deposited. The lowering of the phreatic surface of water in the vicinity of the mine exposes rocks to non-saturated conditions. This can cause increased oxidation and dissolution of radiochemical and toxic materials from the ore. Also, radium-226 and toxic minerals are leached from ore particles suspended in the mine water. However, mine drainage water in excess of that required for mine and mill processes can be chemically treated adequately for agricultural or potable use.

The water used for hydraulic transport and hoisting can in part be used to slurry backfill tailings which may be returned from the mill to the mine. This would relieve many of the water pollution problems of surface disposal of the tailings. However, one must ensure that enhanced contamination of ground waters does not result.

The effects on surface subsidence are also not unique to hydraulic mining, but are common to underground mining by other methods. If backfilling is required, hydraulic backfilling is a likely choice of method, because, if desired, water returned to the mine with fill slurry can be partially separated underground (e.g., centrifugally) for use in the hydrotransport process. It is only when hydraulic mining or borehole mining is applied with planned roof caving and without backfilling that increased impacts on surface subsidence can be expected.

There are also environmental effects due to temporary or permanent closing of hazardous surface openings to underground uranium mines. The current depression in the uranium industry makes this problem more relevant in New Mexico and Wyoming, where several mines have been closed. After requesting approval for water to operate a 1300 st/d uranium processing mill at Prewitt, N.M., Conoco made the decision to close down their mine project at Crownpoint after expenditure of \$35 million.

## B. Water Rights

The availability of water is the most critical necessity for hydraulic mining and for hydrotransport. The need for the legal availability of water is just as important as its physical availability, particularly in the dry western states. A strategy for requiring water rights for western mining has been discussed by Green (Ref. 116). The key element is to acquire water rights as soon as possible and to have the plan approved by a water court or state engineer. The "consumptive use" of water can be minimized by recycling mine water. Fortunately, many uranium deposits are in aquifers so availability may be less of a problem than the environmental problems of disposal without injury to other water users.

## 12. CONCLUSIONS

A. A review of experience in operational monitor jet mining of coal indicates that the monitor jet pressure required is from 0.5 to 2 times the unconfined compressive strength of the coal. The lower range applies to brittle, highly fractured material and the higher range to a more tight coal without cleat development. By applying these criteria to other minerals and assuming monitor jet pressures which are practical (not over 3000 psi), we conclude that minerals which have an unconfined compressive strength below 1500 to 3000 psi can be considered as likely candidates to be hydromined underground. This may include some unconsolidated uranium sandstones (Wyoming), oil-bearing sands (California and Texas) and other weak sandstones (e.g., the St. Peter sandstone of Iowa.). However, the properties of ores at a particular site cannot be inferred from regional averages or generalizations. Therefore, the properties required for hydraulic mining must be determined for each specific site. Consideration must also be given to the potential variability of ore physical properties through a deposit before selection of the ore disintegration method for a mine. For these reasons, research on the monitor mining feasibility of various underground ore deposits is desirable.

B. An evaluation of U.S. minerals which are probably too hard to be hydromined but which could be hydraulically transported from underground mines at depths of 300 to 3500 ft. indicates the following possible candidates:

1. uranium sandstone (New Mexico)
2. potash (Carlsbad, N.M.)
3. trona (Wyoming)
4. phosphate rock (Idaho or Montana)
5. borates (California)
6. copper ore (Arizona)
7. limestone (Illinois)
8. lead/zinc ore (Missouri)
9. manganese ore (rhodochrosite in Montana)
10. iron ore (hematite in Michigan)

An evaluation of the relative ranking of these minerals indicates that uranium sandstones in New Mexico and possibly Wyoming are the most likely candidates for hydrotransport and hydrohoisting.

C. Comparisons of the costs of hydraulic and conventional transport of uranium ore from 700 to 1000 m underground to a surface mill at a range of 8 kilometers (5 mi.) indicate substantially lower costs for the hydraulic

method at mine production rates of 1750 to 4500 metric TPD, the savings increasing from 29% to 57% with the mine production rate in this size range. for a mine depth of 700 m and distance to the mill of 5 miles (8 km). With the same conditions, but a distance of 20 mi (32 km) to the mill, the cost savings increase from 24% to 56% in the production rate range of 1750 to 4500 TPD.

Hydraulic transport and hoisting of uranium ore can be effectively used in large underground uranium mines where the ore is too hard for hydraulic mining and must be broken by blasting or continuous mining, and can have a major effect on the safety, health and economics of mine transport.

D. For soft, unconsolidated ores like some Wyoming sandstones and some oil-bearing sandstones, there is the possibility of mining the ore by hydraulic borehole mining from underground entries driven in competent adjacent rock formations. This system can use hydrotransport of ore to the surface. It appears to have major advantages with respect to health and safety of underground workers because the ore can be handled in closed pipe systems. Therefore, the health hazard of radon gas from uranium and the explosion hazard of gases from oil sands could be reduced. The choice of location of the haulage-ways below or above the ore zone requires more detailed analysis for each deposit.

E. A comparison was made of the costs of underground up-raise borehole hydraulic mining and transport with conventional mining and transport of uranium from a 1750 TPD mine at 200 m depth in Wyoming with a distance of 8 km (5 mi.) to the mill. The hydraulic method is estimated to require 22% lower costs per ton, not including cost savings in mine dewatering. The inverted borehole hydraulic mining would remove all men from exposure to the safety and health risks (primarily roof falls and radon) in mine stopes, and would reduce the release of radon during underground transport. The use of up-raise borehole hydraulic mining has great potential for improving the safety, health and economy of underground uranium mining.

F. A comparison was made of the costs of underground inverted borehole hydraulic mining and transport of oil sands with the underground gravity drainage method of oil recovery which had been studied by Golder Associates. The hydraulic method has estimated costs of about \$40 per barrel, compared to the 1981 costs of about \$15 per barrel for gravity drainage, which perhaps optimistically assumes 50% recovery of oil. The hydraulic method may provide a method of improved safety for underground mining, although it cannot compete economically with gravity drainage or with surface mining of oil sands from appropriate deposits.

G. A comparison of costs for hydraulic mining and transport of foundry sandstone in Iowa showed a potential cost saving of about 22% below conventional costs for a production rate of 2100 TPD.

H. Potash in New Mexico has potential for hydrohoisting from underground as a method for increasing the production rate of existing mines without sinking new shafts, when conventional skip hoisting capacity is at its limit. The hydraulic hoist can be installed with minimal disruption of normal skip operations. Trona in Wyoming is also a possible candidate for hydrohoisting. The cost of additional capacity by hydrohoisting is estimated to be 14% less than by conventional hoisting for potash and 21% less than by conventional for trona.

### 13. RECOMMENDATIONS

A. Research is needed to establish a relationship between monitor jet hydraulic mining potential and the properties of uranium ores. This will require underground hydraulic mining experiments with short duration tests in existing mines to be correlated with physical properties of ores as determined from underground measurements, from samples obtained underground, and from core samples. The potential importance of hydraulic mining to improved safety, health and economy of uranium mining makes it important to conduct this research on uranium ore deposits, particularly in Wyoming where soft, weak ore exists which may be amenable to hydraulic mining.

B. A research program should be implemented to demonstrate the feasibility of up-raise borehole hydraulic mining from underground to improve the safety, health and economy of underground uranium mining in soft uranium ores. A design study should first be made to optimize the size, power and other design parameters of a demonstration up-raise borehole mining tool which would be broadly adaptable to various mining conditions. The borehole miner should make maximum use of the same up-raise boreholes as are drilled underground for ore exploration and for mine dewatering, and it may be equipped with a radiation detector to aid in selective mining. Tests should be conducted in an appropriate mine with soft uranium ore which would simulate conditions in a major uranium mine.

#### 14. REFERENCES

1. W.C. Cooley, "Survey of underground Hydraulic Coal Mining Technology", Final Report by Terraspace Inc. to Bureau of Mines on Contract H0242031, October 15, 1975 (NTIS, PB-251, 492).
2. W.C. Cooley and V. Ter-Minassian, "Survey of Surface Hydraulic Mining Technology", Final Report by Terraspace Inc. to Bureau of Mines on Contract J0265016, July 30, 1976.
3. W.C. Cooley and R.R. Faddick, "Review of Russian Data on Hydrotransport of Coal", Terraspace Inc. Report for Bureau of Mines on Contract J0265016, December 15, 1976.
4. W.C. Cooley, "Survey of Foreign Technology for Stowing in Underground Coal Mines," Final Report by Terraspace Inc. to Bureau of Mines on Contract J0275941, May 30, 1978.
5. W.C. Cooley, "Survey of Foreign Technology for Hydrotransport of Coarse Coal," Final Report by Terraspace, Inc. for Skelly and Loy under Dept. of Energy Contract, June, 1981.
- 6A. W.C. Cooley, "Translations of Foreign Hydrotransport Technology, Vol. 1 - German Technology," Prepared by Terraspace Inc. for Skelly and Loy under Dept. of Energy Contract, June 1981.
- 6B. W.C. Cooley "Translations of Foreign Hydrotransport Technology, Vol. 2 - Russian Technology," Prepared by Terraspace Inc. for Skelly and Loy under Dept. of Energy Contract, June 1981.
7. J. F. Wilkinson, "Water Mines, Transports Soviet Coal," Coal Age, pp. 68-74, March 1978.
8. Li Hai Jou, "Test on High Pressure Water Jet and Hydraulic Coal Winning," in "Hydraulic Coal Mining in China," Proc. of Hydraulic Coal Mining Seminar, Colorado School of Mines, Nov. 1-2, 1979.
9. J. Wakabayashi, "Slurry Pumped 3000 ft. Vertically," Coal Age, pp. 84-87, June 1979.
10. H. Maurer, "Applications and Possibilities of Hydraulic Transport in Coal Mining," VDI - Berichte 371, 1980 (Translated from German by Terraspace. Inc. 1980).
11. A.W.T. Grimley, "Underground Coal Mining Using the Hydraulic Method," Can. Inst. Min. Metall. Bull., Vol. 67, No. 741, pp. 44-47, 1974.

12. D.M. Parkes and J. Lindsay, "Hydraulic Transportation and Dewatering of Coal," SME - AIME Transactions, pp. 6-10, Mar. 1977.
13. D. M. Parkes, "Hydraulic Mining Apparatus and Method," U.S. Patent 4,061,398, Dec. 6, 1977.
14. H.D. Dahl and E.F. Petry, "Update on Slurry Transportation from Face to Cleaning Plant," Mining Congress Journal, pp. 14-18, Dec. 1977.
15. L. L. Breitstein , "Status of Water Jet Drilling R & D," Booz, Allen and Hamilton Report to D.O.E., June 1980.
16. R.F. Dewey, "Recent Developments in American Gilsonite Company's Mining Operations," Paper at National Western Mining Conference, Denver, February 4, 1965.
17. G.S. Knoke and W.R. Archibald, "Borehole Mining: An Environmentally Compatible Method for Mining Oil Sands," Flow Industries Final Report for Bureau of Mines, Contract J0205064, February, 1980.
18. M.H. Marvin et al, "Backfilling of Cavities Produced in Borehole Mining Operations," Flow Industries Report for Bureau of Mines, May, 1979.
19. W.R. Archibald, "Field Test of Hydraulic Borehole Mining Systems in Shallow Uranium Sands," Flow Industries Report for Bureau of Mines, September, 1978.
20. Flow Industries, Inc. "Hydraulic Borehole Mining System," Form BH - 1-80, Kent, Wash. 1980.
21. P.W. Thrush, "A Dictionary of Mining, Mineral and Related Terms," U.S. Dept. of the Interior, 1968.
22. V. Rzhnevsky and G. Novik, "The Physics of Rocks," MIR Publishers, Moscow, 1971 (P. 281).
23. I. Evans and C.D. Pomeroy, "Strength, Fracture and Workability of Coal," Pergamon Press, 1966.
24. N. Brook and B. Misra, "A Critical Analysis of the Stamp Mill Method of Determining Protodyakanov Rock Strength and the Development of a Method of Determining a Rock Impact Hardness Number," Dynamic Rock Mechanics, pp. 151-165, AIME, 1971.
25. G. M. Timoshenko, et al, "A Two-Barreled Pulsed Monitor," Ugol Ukrainy, No. 12, pp. 23-24, December, 1978.

26. G. A. Savanick, personal communication to W.C. Cooley, 1980.
27. Z. Zortman, "Compressive Strength of Potash," IM & C Corp. Carlsbad, N.M.
28. U.S. Bureau of Mines, "The Bureau of Mines Minerals Availability System and Resource Classification Manual," Bureau Mines IC 8654, 1974, 199 pp.
29. J. Kanizsai, et al, "Can Bauxite be Won by a Water Jet? Ideas About the Technology of the Hydraulic Extraction of Bauxite through Deep Holes," Banyaszati es Kohaszati Lapok, Banyaszat 112, evfolyam 1979, 2 sz. (Translated from Hungarian by Terraspace, Inc. 1980, SL 2786.)
30. J.W. Stamper and H.F. Kurtz, "Aluminum" MCP - 14, U.S. Bureau of Mines, Pittsburgh, 1978.
31. E.T. Koch, Jr., "Double-Hinged, Crawler-Mounted High-Wall Slurrifier," SME-AIME Transactions, Vol. 258, pp. 229-232, September, 1975.
32. R.C. Freas, "The Impact of Flue Gas Desulphurization on Lime and Limestone Marketing," Proc. of 4th. Industrial Minerals International Congress, Atlanta, May 1980, Nassies Print & Design Ltd., Surrey, England, pp. 49-57.
33. I. Watson, "Sodium sulphate," Industrial Minerals, p. 61, May 1980.
34. G. M. Clarke, "Talc - Destiny in Diversity," Industrial Minerals, pp. 23-32, September 1979.
35. P.M. Basinski and L.T. Larson, "Uranium Potential of Zeolites in Volcanically Derived Sediments, Northern Reese River Valley, Nevada," SME Preprint 7975, AIME Annual Meeting, New Orleans, LA, February 1979.
36. R.J.M. Wyllie, "How West German Iron Ore Mines Use Continuous Miners to Tear Out Nodular Brown Ore from Flat Bed and Slurry it with Water for Pumping to Surface," World Mining, pp. 18-22, June, 1969.
37. J. Pfeufer, "Excerpt from Mining and Technology in Contemporary West German Iron Ore Mines," Gluckauf, English Translation, Vol. 114, No. 1, pp. 8-9, 5 January 1978.
38. U.S. Bureau of Mines, "Mineral Commodity Profiles," MCP-13 - Iron Ore.
39. Anon., "Limestone Slurry Transported via 17.6-mile Underground Pipeline," Rock Products, May, 1972.
40. J.W. Baxter, "Factors Favoring Expanded Underground Mining of Limestone in Illinois," Mining Engineering, pp. 1497-1504, October 1980.

41. P. Harben, "The Clamour for Cement," Industrial Minerals, p. 52, August, 1979.
42. J. Hrbek and E. Gibian, "Hydraulic Transport of Pb-Zn Ore from 450m Depth to Surface," Proc. of Hydrotransport 3 Conference, BHRA Fluid Engineering, Paper A4, May, 1974.
43. K. Noyan et al, "The KBI Parallel Pipelines for Sulfide Concentrates," Hydrotransport 3, BHRA Fluid Engineering, Paper B2, May, 1974.
44. E.J. McNamara, "Operational Problems with a 69-Mile Copper Concentrate Slurry Pipeline," Hydrotransport 4, BHRA, Paper F3, 1976.
45. E. J. Wasp, et. al., "Solid-Liquid Flow, Slurry Pipeline Transportation," Trans Tech Publications, 1977.
46. Anon, "Butte Has Large Manganese Deposit," The Mining Record, Feb. 4, 1981.
47. S. Groff, Personal communication to W.C. Cooley, July 1981.
48. F. Q. Barnes, "Uranium - Where are the Reserves," Mining Congress Journal, pp. 28-33, February 1976.
49. T.M. Li and J.D. Wiebmer, "Uranium Mining in the U.S.," Mining Engineering, pp. 1405-13, October 1978.
50. D. Jackson, "Hydromining Comes of Age at Kaiser," Coal Age, pp. 54-63, November 1980.
51. J.J. Scott and D. Jackson, "Continuous Miner and Friction Bolts Play Big Roles in Highland's Move Underground," E/MJ Operating Handbook of Underground Mining, pp. 135-141.
52. T.L. Neff and H.D. Jacoby, "World Uranium: Softening Markets and Rising Security," Technology Review, pp. 19-30, January 1981.
53. G. White, Jr., "Uranium - Supply-Demand Unbalance Leads to Sharp Price Break and Intense Seller Competition," Engg. & Mining Journal, pp. 139-145, March 1981.
54. D. K. Walker, "U.S. Uranium Mines and Mills," Mining Engineering, pp. 1424-26, October 1978.
55. R. Hoppe, " A Stretch of Desert Along Route 66 - The Grants Belt - is Chief Locale for U.S. Uranium," Engg. & Mining Journal, pp. 73-84, Nov. 1978.

56. Geology and Technology of the Grants Uranium Region, New Mexico Bureau of Mines and Mineral Resources.
57. Anon., "Mineralization and Geology of the Uranium Capital of the World," Mining Engg., pp. 20-22, August 1974.
58. R.J. Borendson, "Mt. Taylor Project - Overview," The Mines Magazine, pp. 14-15, May 1980.
59. Anon., "Mount Taylor Uranium Mine," Gulf Minerals Co., San Mateo, N.M. 1980.
60. D. Jackson, "Gulf Digs in to Tap a Major Uranium Orebody," Engg. & Mining Journal, pp. 73-79, August 1977.
61. J.A. Heron, "Mt. Taylor Project - Mine," The Mines Magazine, p. 16, May 1980.
62. M.C. Head, Personal communication, December 1980.
63. W.C. Cooley, Personal communications from visits to Gulf, Conoco and Phillips in Grants, N.M., December 1980.
64. W.C. Larson, U.S. Bureau of Mines, TCMRC, Personal communication to W. C. Cooley based on group visit to Grants, N.M. in 1977.
65. UNITAR, "The Future of Heavy Crude Oils and Tar Sands," McGraw-Hill, Mining Info. Services, NYC, 1981.
66. Edey, A., Kennedy, B.A. and Readdy, L.A., "Oil Mining. A Technical and Economic Feasibility Study of Oil Production by Mining Methods," Golder Associates, Report for U.S. Bureau of Mines, October, 1978 (NTIS-PB 297,134).
67. E.C. Heikenhoff, "When Are We Going to Mine Oil?" Engg. & Mining Journal, pp. 132-138, June 1972.
68. R.A. Dick and S.P. Wimpfen, "Oil Mining," Scientific American, p. 182, September 1980.
69. G.S. Rice, "Mining for Petroleum by Underground Methods," U.S. Bureau of Mines Bulletin 351, U.S. Dept. of Commerce, 1932.
70. B. A. Kennedy, O. Nair and L.A. Readdy, "The Mining of Oil," Mining Magazine pp. 26-37, July 1980.
71. J. S. Hutchins, E. Bond and D.M. Bass, "Mining for Petroleum: Feasibility Study," Report by Energy Development Consultants, Inc., Denver, CO for U.S. Bureau of Mines on Contract.

72. P. Chronis, "Mining for Oil," Denver Post, September 21, 1980.
73. C.R. Nelson et. al., "Hydraulic Transportation and Solids Separation of Excavated Material in Tunnels," (DOT - HTT - 75-1) Dept. of Transportation, Washington, D.C., 1975.
74. S.M. Miller, C. R. Nelson, G.L. Christensen and D.M. Yardley, "Hydraulic Transportation and Solids Separation of Excavated Materials in Tunnels," Minnesota Univ. Report to U.S. Dept. of Transportation, Jan. 1977, 307 pp. (DOT - TST - 77-75) (PB - 273, 274)
75. R. Huftel, Martin-Marietta Corp., Personal communications to W.C.Cooley, 1981.
76. G.A. Savanick, Personal communications to W.C. Cooley, 1981.
77. R. H. Singleton, "Potash," MCP-11, U.S. Bureau of Mines, Pittsburgh, PA, February 1978.
78. K. Schriek, et al, "Some Experimental Results of a Long Distance Pipeline Feasibility Study to Carry Potash," Hydrotransport 2, Paper K3, BHRA, Bedford, England, September, 1972.
79. R. V. Sondermeyer, "The Mineral Industry of New Mexico," BuMines Mineral Yearbook 1972, V. 2, p. 488, 1974.
80. Dames and Moore, "Inventory and Market Analysis of the Potash Resources of the Paradox Basin in Utah," Contract Report for Bureau of Land Management, Dames & Moore, Salt Lake City, June 13, 1978.
81. G. A. Burghardt, "Hydraulic Vertical Transport of Potash," Paper at Transrohr 80, Baden-Baden, W. Germany, May 1980, VDI - Berichte 371, pp. 139-147, 1980. Translated from German by Terraspace Inc., 1981.
82. J. P. Aman and J.R. Dewey, " Longwall Mining of Trona," Presented at AMC Convention, Denver, September 26-29, 1976.
83. I. Watson, "U.S. Soda Ash," Industrial Minerals pp. 37-38, March 1981.
84. D. Jackson, "Trona," Engg. & Mining Journal, p. 99, March 1981.
85. D. Jackson, Jr., "Wyoming Trona: Unbroken and Orderly Growth," Engg. & Mining Journal, pp. 67-76, April 1976.
86. W. H. Engelmann, G. A. Savanick, and P.J. Watson, " Phosphate Mining and Processing Bibliography," U.S. Bureau of Mines, Pittsburgh, PA 15213.

87. M.E. Zellars and J.M. Williams, " Evaluation of the Phosphate Deposits of Florida Using the Minerals Availability System," Report by Zellars - Williams, Inc. Lakeland, Fla. for U.S. Bureau of Mines, Contract J0377000, June 1978.
88. J. A. Beck, "Phosphate," Engg. and Mining Journal, pp. 93-95, March 1981.
89. USGS, "Draft E.I.S. - Development of Phosphate Resources in Southeastern Idaho," Vol. I and II, July 1976.
90. W. F. Stowasser, "Phosphate Rock," U.S. Bureau of Mines Reprint from Mineral Facts and Problems, Bulletin 671, 1980.
91. W. F. Stowasser, "Phosphate," U.S. Bureau of Mines, Pittsburgh, PA January 1979.
92. W.S. Anderson, "Test Operation of a Pneumatic Vibrating - Blade Planer," U.S. Bureau of Mines RI 6863, 1966.
93. C.V. Winter, "Ground Water Flow Systems in the Phosphate Sequence Caribou County, Idaho, Idaho Univ., Mar. 1980, NTIS No. PB81-113078.
94. A.R. Role et.al., "Recent Advances in Beneficiation of Western Phosphates," Mining Engg. pp. 37-40, Jan. 1978.
95. W. F. Stowasser, Personal communication, 1980.
96. T.M. Li, "Southeastern Idaho Phosphate Mining: How an Environmental Impact Statement Distorts Growth Plans," Mining Engg., pp. 25-28, Jan. 1978.
97. R. A. Carter, "An Integrated Industry - Phosphate Mining and Milling in Idaho," Mining Engg., pp. 29-36, January 1978.
98. S.T. Absalon, "Boron," U.S. Bureau of Mines, Pittsburgh, PA, May 1979.
99. W. B. Hall, " Bureau of Mines Forcasts of Supply and Demand for Major Industrial Minerals," Proc. of 4th. Ind. Min. Interstate Congress, Atlanta, 1980, pp. 211-219.
100. J. W. Blakely, "American Borate's Billie Mine in Death Valley," World Mining, pp. 57-60, April 1980.
101. Wirth, "Pumps for Hydraulic Transport of Solids," Wirth, GMBH, Erkelenz, W. Germany, 1980.

102. K. Funaki, "Hydrohoist," Data from Hitachi Ltd., Tokyo, Jan. 1974.
103. T. Yamaguchi, "Investigation of Hydrohoist for Pumping Bauxite Slurry," Hitachi Review, Vol. 19, No. 5 pp. 185-190, 1970.
104. M. Sakamoto et al, "Vertical Type Hydrohoist for Hydraulic Transportation of Fine Slurry," Hydrotransport 6, Paper F1, BHRA, Bedford, England, 1979.
105. H. Siebert, W. Kortensbusch and H. Harzer, "Further Experience with Horizontal and Vertical Hydraulic Hoisting of Coarse Run-of-Mine Coal at Hansa Hydromine," Hydrotransport 7, Paper B2, BHRA Fluid Engineering, Bedford, England, November 1980.
106. Zimpro, Inc. "High Pressure Hydraulic Exchange Pumps," Zimpro, Inc. Rothschild, Wisconsin, 1981.
107. M.E. Zoborowski, "Cylindrical Diaphragm Pumps," Plant Engineering, September 1, 1978.
108. Anon, "Bringing Rutile Out of the Jungle," The Reactor Magazine, No. 42, August 1979.
109. M. Surratt, Personal communication, December 1980.
110. A.C. Horn and M.E. Zoborowski, "Operating Experience of High Pressure Hydraulic Exchange Pumps in Pumping Ores and Industrial Minerals," Hydrotransport 7, BHRA Fluid Engineering, Bedford, England, 1980.
111. Mitsubishi, "Data on Mars Pumps," Mitsubishi Ltd., 1980.
112. Anon., "Hydrotransport for Coal," Kamyrc Inc., Bulletin WOC 1777, Glens Falls, N.Y.
113. M. Burnett, A.C. Harvey and L.S. Rubin, "Design and Development of a Hydrotransport Face Haulage System Using a Self-Regulating Dry Feed Injector and Ventilated Boost Pumps," Proc. 5th. Int. Tech. Conf. on Slurry Transport, pp. 144-150, Mar. 26-28, 1980.
114. G. K. Clement, et. al., "Capital and Operating Cost Estimating System Manual for Mining and Beneficiation of Metallic and Nonmetallic Minerals Except Fossil Fuels in the United States and Canada," Superintendent of Documents, U.S. Government Printing Office, Washington, D.C., 1981.
115. G. Christiansen, U.S. Bureau of Mines, Denver, Personal communication to W.C. Cooley, August 20, 1981.
116. J.C. Green, "A Water Rights Strategy for Mining Operations in the Western U.S.," Mining Engineering, pp. 1220-22, August 1981.

117. C.F. Cook, "Enacting Laws Regulating Environmental Aspects of Noncoal Mining," 1980 Mining Yearbook, pp. 32-39, Colo. Mining Assn., 1980.
118. I.A.E.A., "Radiation Protection in the Mining and Milling of Radioactive Ores," International Atomic Energy Agency, Safety Series No. 26, I.L.O., Geneva, 1968.
119. S.G. Vandevender, "State Policies and Requirements for Management of Uranium Mining and Milling in New Mexico," Five volumes, Sandia Labs Report for Dept. of Energy, April 1980.
120. Bu Mines, "Minerals Health and Safety in-House Research, Development and Demonstration in Fiscal Year 1980, Bu Mines IC-8817, 1980.
121. R.M. Fry, "Radiation Hazards in Uranium Mining and Milling," Atomic Energy, pp. 12-31, October 1975.
122. NTIS, "Uranium Mining and Milling Environmental Studies," Nat'l. Tech. Info. Service, PB81-805517, Springfield, VA, April 1981.
123. I.A.E.A., "Management of Wastes from the Mining and Milling of Uranium and Thorium Ores," Int. Atomic Energy Agency, Safety Series No. 44, Vienna, 1976.
124. J.V. Rouse, "Environmental Considerations of Uranium Mining and Milling," Mining Engineering, pp. 1433-36, October 1978.
125. D.R. Dressen, "Uranium Mill Tailings - Environmental Implications," Los Alamos Sci. Lab., LASL 77-37, February 1978.
126. D.R. Kasper, et. al., "Environmental Assessment of In Situ Mining," PRC Toups Report to Bureau of Mines on Contract J0265022, December 1979. (NTIS PB81-106783)

APPENDIX A

DATA ON MINERAL DEPOSITS AND MINES

Relevant data on deposits of minerals and associated mines which passed the initial screening tests are included in Table 15-1. Data on three uranium deposits in New Mexico were included in Table 7-3.

TABLE 15-1 DATA ON MINERAL DEPOSITS AND MINES

	STATE 1	DEPOSITION AREA 2	COMPANY 3	UNDERGROUND MINE 4	PRODUCTION 5	DEPTH (feet) 6	THICKNESS (feet) 7	DIP 8	RESERVES 9	ORE 10	STRENGTH OF ORE (psi) 11	COMMENTS 12
1					PHOSPHATE							
2												
3	Idaho	Phosphoria	ComInco	WarmSpring	200,000 TPY	300-400	4	30° - 60°	6x10 <sup>6</sup> T	Phosphate Rock	15-20,000	
4			American									
5												
6	Montana	Phosphoria	Stauffer	Maiden	Closed					Phosphate Rock	Soft	Closed for economic reasons.
7												
8												
9												
10					POTASH							
11												
12	New Mexico	Carlsbad	Kerr-McGee	Hobbs	10,000 TPD			Level		Sylvinitite	AVE = 4100	
13												
14		Carlsbad	Potash Co. of America	PCA	9,000 TPD			Level		"		
15												
16												
17		Carlsbad	AMAX	AMAX	7,600 TPD			Level		"		
18												
19		Carlsbad	Miss. Chem.	MCC	3x10 <sup>5</sup> TFY		4 - 7	Level	30x10 <sup>6</sup> T	"		
20												
21		Carlsbad	Int. Mineral & Chemical	IMC	14,000 TPD			Level		"		
22												
23												
24					TRONA							
25												
26	Wyoming	Green River	FMC Corp.	FMC Mine	2x10 <sup>6</sup> TPY	1470	11.6	Level		Trona		
27												
28			Stauffer Chem.	Big Island	1.6x10 <sup>6</sup> TPY	890	18	Level		"	6435	
29												
30												
31			Allied Chem.	Alchem	1.6x10 <sup>6</sup> TPY	1520	12	Level		"	8000	

TABLE 15-1 DATA ON MINERAL DEPOSITS AND MINES (CONT'D.)

	STATE 1	DEPOSITION AREA 2	COMPANY 3	UNDERGROUND MINE 4	PRODUCTION 5	Depth (feet) 6	THICKNESS (feet) 7	DIP 8	RESERVES 9	ORE 10	STRENGTH OF ORE (psi) 11	COMMENTS 12
1					TRONA							
2												
3	Wyoming	Green River	Texasgulf	Soda ash	0.6x10 <sup>6</sup> TPY	1100	10	Level		Trona		
4												
5					IRON ORE	(HEMATITE)						
6												
7	Michigan	Marquette	Cleveland-Cliffs	Mather	7000 TPD	<3500			Large	Hematite	Friable Granules	High % hematite
8												
9												
10				Tracy		<1500						
11												
12					BORATES							
13												
14	Calif.	Death Valley	Amer. Borate	Billie	600,000 TPY (Planned)	400-1200	<300		10x10 <sup>6</sup> T	Ulexite Colemanite Probertite	Soft(2000) Hard(5000) Hardest (20,000)	Two products produced.
15												
16												
17												
18												
19					OIL BEARING	ROCKS						
20												
21	Calif.	Wheeler Ridge		Study only	6660 bbl/d	1000-1310	170	Level	93x10 <sup>6</sup> bbl of oil	Sands	Friable Sandstone	Ore strength Unknown
22		Field			(Gravity drainage)							
23												
24												
25												
26												
27												
28												
29												
30												
31												