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BUREAU OF MINES
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Mechanical Excavation Systems

(In Three Parts)

1. Drill-Split Narrow-Vein and Longwall Mining

By John A. Lombardi and Charles V. Jude

UNITED STATES DEPARTMENT OF THE INTERIOR

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PREFACE

The results of U.S. Bureau of Mines (USBM) research on mechanical excavation mining systems are presented in a three-part series. Part 1 deals with narrow vein and longwall mining using the USBM-developed radial-axial drill-split tool. Part 2 will present stope leaching and stope autoclave mining systems using the drill-split narrow-vein and longwall mining methods described in this report. Part 3 will review the potential environmental applications for the drill-split narrow-vein longwall methods described in this report, including the development of city-center "vertical landfills."

The USBM research presented in the series is conceptual in nature. The concepts were deemed technically feasible and costed. The costing of conceptual designs employing tools that have no industry-use track record is necessarily speculative. Wherever possible, cost estimating was guided by the USBM's Cost Estimating System Handbook* and Information Circular "Simplified Cost Models for Prefeasibility Mineral Examinations."** Where these cost sources were not applicable, the best available literature was examined and engineering judgments made and used. Costs are for comparative use only and shown in 1984 dollars. Conservative estimates of tool and tool combination productivities were sought for use in the cost-estimating exercises; however, only a further development and demonstration of the proposed tool and tool combinations can validate the cost estimates in the series. Although many components of the proposed mining systems are conceptual, a combination of all component costs that comprise a system should produce a reliable prefeasibility-type cost estimate. Prefeasibility cost estimates are best used in acceptance and rejection decisionmaking. For the mining systems proposed in the series, this level of decisionmaking makes single-component cost tracking inappropriate.

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*U.S. Bureau of Mines. Bureau of Mines Cost Estimating System Handbook (In Two Parts). 1. Surface and Underground Mining. BuMines IC 9142, 1987, 631 pp.; 2. Mineral Processing. BuMines IC 9143, 1987, 566 pp.

**Camm, T. W. Simplified Cost Models for Prefeasibility Mineral Evaluations. BuMines IC 9298, 1991, 35 pp.

CONTENTS

ILLUSTRATIONS

TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

ft	foot	mt/d	metric ton per day
h	hour	mt/h	metric ton per hour
ha	hectare	oz	ounce
in	inch	oz/d	ounce per day
kW	kilowatt	oz/mt	ounce per metric ton
m	meter	pct	percent
m^2	square meter (area)	\$/kW•h	dollar per kilowatt hour
m^3/d	cubic meter per day	\$/m	dollar per meter
m^3/min	cubic meter per minute	\$/mt	dollar per metric ton
mt	metric ton	\$/oz	dollar per ounce

MECHANICAL EXCAVATION SYSTEMS
(In Three Parts)

1. Drill-Split Narrow-Vein and Longwall Mining

By John A. Lombardi[1] and Charles V. Jude[1]

ABSTRACT

In this U.S. Bureau of Mines report, two drill-split mechanical excavation mining system concepts are described, costed, and cost compared with conventional drill-blast mining systems. The concepts for the two drill-split mechanical excavation mining systems presented are (1) a method for steeply dipping narrow veins 0.6 to 1.2 m wide and (2) a longwall method for flat-lying tabular ores.

In the proposed systems, 70 to 80 pct of the ore is disposed of underground as backfill. For sortable ores, face area crushing, sorting, and direct stowage of run-of-mine waste and low-grade ores are proposed. The underground sorting and stowing of waste reduce materials handling, processing, and waste disposal costs by reducing the quality of ore transported to the surface by 70 to 80 pct (by volume).

Because many of the tools and techniques proposed for use in these systems have little or no historical mining industry use, cost assignations are heavily influenced by engineering judgments and presented as prefeasibility-level cost estimates. These estimates, presented as discounted-cash-flow-rate-of-return (DCFROR) values, show the proposed systems to be at least as profitable as, and in some cases 50 pct more profitable than, conventional drill-blast mining.

[1]Mining engineer, U.S. Bureau of Mines, Denver Research Center, Denver, CO.

INTRODUCTION

The mission of the U.S. Bureau of Mines (USBM) is to help ensure the availability of minerals to the U.S. economy at acceptable social, environmental, and economic costs. Since many of the minerals crucial to the welfare of the Nation are domestically available only in low-grade, hard-rock resources, the USBM is engaged in the development of new hard-rock mining system technologies. Accordingly, the USBM undertook a broad review of the potential for hard-rock mechanical excavation mining. The specific goal of the research was to identify hard-rock "mining system" potentials unique to the mechanical excavation technique. An example of the kind of potential sought, taken from the soft-rock-coal industry, is the mine design revolution that followed the development of the longwall. In coal mining, safer, more productive, more economic, higher resource recovery mines resulted from this mechanical excavation innovation. This report identifies similar, revolutionary, mechanical excavator-based mine design concepts for hard-rock mining. These hard-rock mining concepts are based on the USBM-developed radial-axial drill-split tool.

The proposed mine designs are innovative and undemonstrated, and require considerable proof-of-concept research and development before technical and economic feasibilities are proved.

Technical descriptions and costs for two mechanical excavation mining methods are presented in this report: (1) drill-split narrow-vein mining, and (2) drill-split longwall mining. The mining methods were then incorporated into full, ore-body-specific mine system designs. These mine system designs were costed and evaluated using the discounted-cash-flow-rate-of-return (DCFROR) technique. The drill-split mining systems' DCFROR values were then compared with DCFROR projections for the conventional drill-blast mining of the case study ore bodies. Detailed cost estimates for the drill-split and drill-blast mining systems are shown in the appendixes.

MECHANICAL EXCAVATION OVERVIEW

The most common mechanical excavators are tunnel-boring machines (TBM's), raise borers, shaft drills, and rotating-head continuous miners. These machines penetrate the rock with picks or disks and then, through pick and disk geometry, exert sufficient local stresses to spall chips of rock from the face. The thrust forces necessary to penetrate rock are large. TBM's, raise borers, etc., are therefore energy-intensive machines that are large and heavily ballasted or stabilized with jacks.

A second kind of mechanical excavator is the hydraulic pick. These tools exploit the existence of fractures in the rock by driving a wedge into a fracture opening and breaking the rock off, in tension, toward a free face. Rock breakage in tension requires less energy than the breaking into, or compression penetration, of a rock. Hydraulic picks are therefore lighter and more versatile than the penetration machines that employ disk cutting.

A third mechanical excavator type has recently been developed: the drill-hole-breakage machine. These machines first create a drill hole and then, from deep in the drill hole, exert radial and tangential forces that spall a cone of rock (in shear and tension). The in-hole radial forces that initiate shear-tension rock breakage can be generated by high-pressure water bursts (*1*),[2] electrically generated plasma bursts (*2*), or, as is the case with the USBM-developed drill-split tool, by a mechanical wedge and expanding feather mechanism (*3*). Because drill-hole-breakage reaction forces are largely within the borehole, the tools themselves are fairly lightweight and flexible in application. The drill-hole-breakage technique, specifically the drill-split tool, was identified as the most likely mechanical excavator around to build potentially economic mining systems.

DRILL-SPLIT TOOL

The drill-split tool consists of two separate parts: the drill, a machine commonly used throughout the industry, and the splitter, a unique tool designed to apply radial and axial loads to the rock mass. The USBM has developed the drill-split mechanical excavator as a single tool—i.e., as a unit that drills a hole, indexes a splitter to the drilled hole, splits, then rotates back to the drill. The splitting tool is shown in figure 1. Extensive discussion of the drill-split tool and its operational techniques and rock excavation parameters can be found in USBM's Report of Investigations (RI) 8722, "Laboratory Testing of a Radial-Axial Loading Splitting Tool" (*4*).

[2]Italic numbers in parentheses refer to items in the list of references preceding the appendixes.

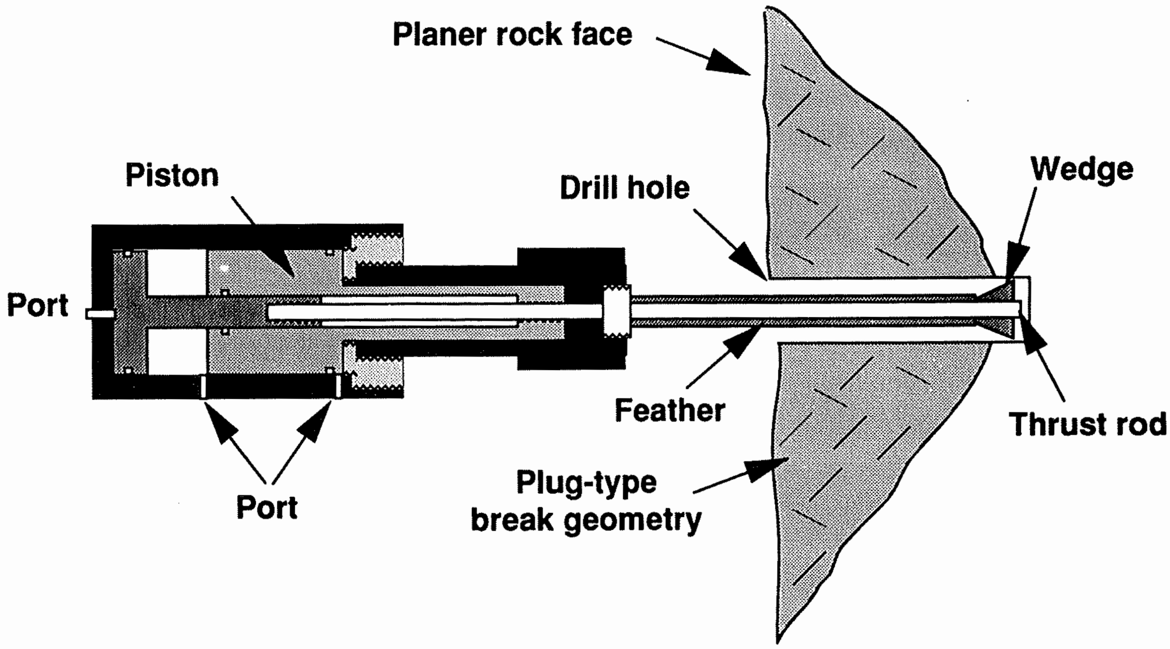

Figure 1.—Splitting tool. (Splitter is securely anchored in drill hole by radial load generated by drawing wedge into feather. Thrust rod is then extended to push against end of drill hole to create plug-type rock break.) [Adapted from Lombardi (5)]

DRILL-SPLIT MINING SYSTEMS OVERVIEW

Relative to drill-blast mining, drill-split mechanical excavation is nonviolent and creates minimal wall rock overbreak. In development headings, reduced overbreak results in a reduced need for ground support structures. In stopes, reduced overbreak means less ore dilution. In all cases, reduced overbreak results in better ground control and improved safety.

The drill-split technique, when used in shallow 0.3-m depth-of-split holes, creates a continuous flow of ore from the face, which is nominally postprimary crushed in size. This ore flow is amenable to continuous mucking and transport. A significant opportunity also exists at the nonviolent-noncyclical mechanical excavation production face for ore crushing and ore sorting prior to transport. Crushing and sorting at the face, in turn, creates the potential for the discarding of waste into mining voids adjacent to the production area. The underground discarding of sorted waste reduces the run-of-mine ore stream volume and results in reduced investments in haulage equipment, shaft-drift infrastructure, mill facilities, and waste disposal facilities (*5*).

NARROW-VEIN MINING

Many mining districts in the United States were founded on the surface outcroppings of steeply dipping narrow-vein structures. These ores were shrinkage-stope mined where the veins were 1.2 m in width and resue mined when veins were less than 1.2 m in width. Resuing is a labor-intensive, high-operating-cost technique. Only the highest grade narrow-vein structures 0.6 to 1.2 m in width were resue mined; medium-grade narrow veins were left unexploited.

The drill-split tool can be scaled down to fit and maneuver in a 0.6-m-wide vein. Since a 0.6-m stope width is too narrow for operator access, the drill-split tool would have to be independently mobile and remote controlled.

To address mobility, USBM researchers conceptually designed a number of stope "wall walking" drill-split carriages. Tracked, pad, and spiderlike "walker" designs were developed, which appeared to have the robustness and flexibility necessary to affect the required drill-split tool in-stope anchorings and repositionings. One version of a wall-walking narrow-vein mining apparatus is shown in figure 2. The proposed bar-and-arm design is telescoped to accommodate vein pinches and swells, and tool-end gear boxes are used to slew the drilling direction to accommodate vein strike and dip changes (*6*).

The mechanical aspects of remote operation were determined to be achievable using conventional remote manipulators and onboard servomechanisms tethered to power.

The "expert" aspects of remote operation—i.e., the reasoning required to position the drill-splitter based on face geology and geometry—were determined to be achievable by either of two methods: (1) face "sensing" and onboard processing or (2) manual teleoperation using state-of-the-art telepresence three-dimensional (3-D) cameras.

Geologic-geometric "sensing" and expert system processing of data to reposition and execute drill-split mining activities are available as state-of-the-art, off-the-shelf capabilities. However, these electronically based capabilities are of questionable efficacy in mining because of falling rock and environmental dust, water, and vibration.

Teleoperation using telepresence 3-D cameras would put the remote operator "in the stope space" so that geologic-geometric variables could be directly observed and interpreted. The telepresence "eyes" of the operator would, however, need to be mounted on a separately mobile telescoping bar to protect the telepresence electronics from drill platform vibration.

In drill-split narrow-vein mining, ores are blocked out by multilevel drifting and raises are driven between levels at the outby end of ore zones. Drill-split tools are then walked into the raise to dislodge rock, bottom to top, from the exposed narrow-vein face. This work proceeds for the full strike length of the stope. Lower drift mucking is protected from rock falls by either a cushioning layer of sand spread on overhead supports or as a complete backfilling of the abandoned sections of the stope. A schematic of the drill-split mining system proposed for the exploitation of steeply dipping narrow veins is shown in figure 3.

Typical capital and operating costs for three-boom drill-split narrow-vein mining are shown in table 1.

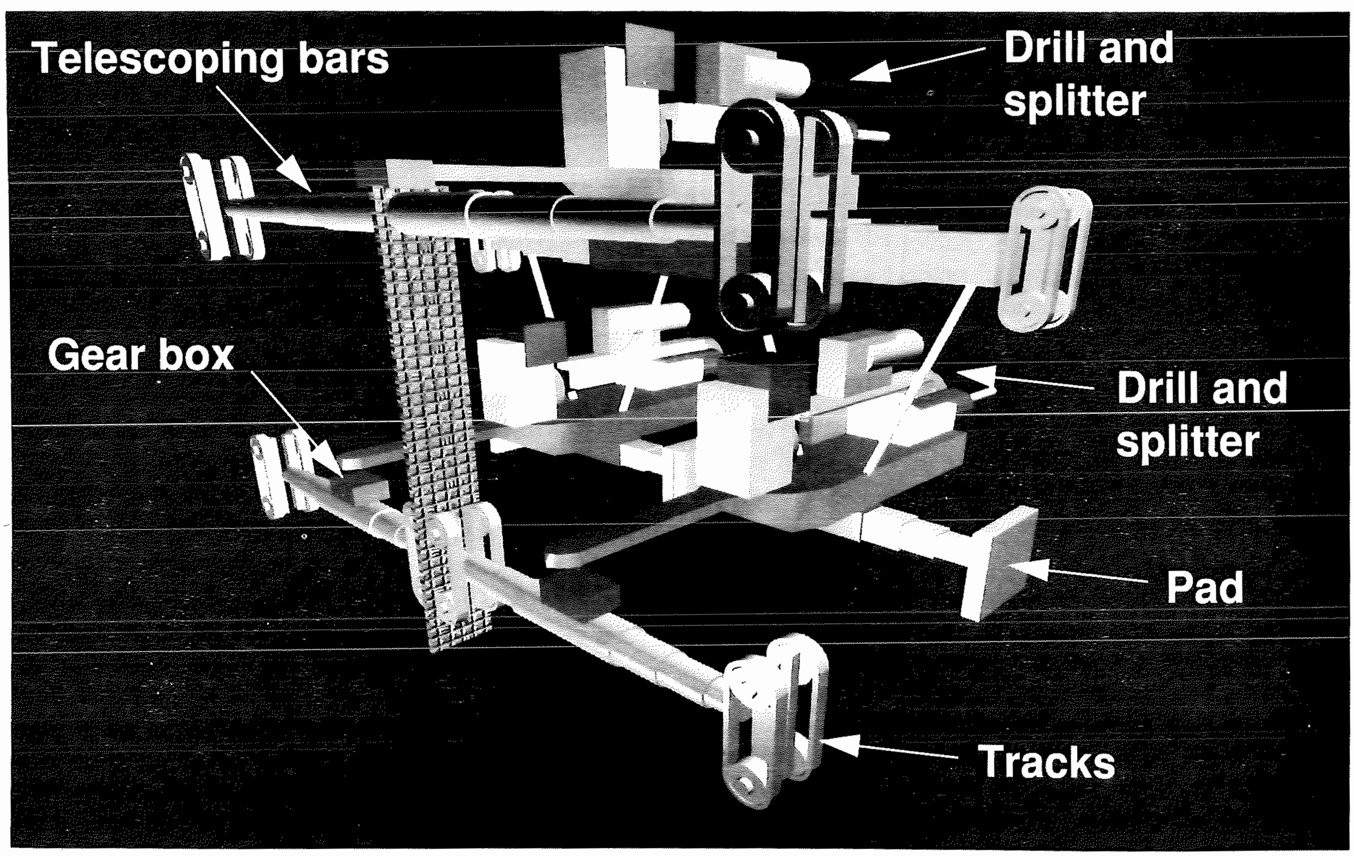

Figure 2.—Conceptual design of drill-split narrow-vein miner. [Adapted from Lombardi (*6*)]

Table 1.—Capital and operating costs for drill-split narrow-vein mining system[1]

Capital cost, $:	
Dual cameras on tracked-telescoping bar, 1 ea	30,000
Gathering arm muck, jaw, and 2-stage roll crush, sized for 15 mt/h, 1 ea	100,000
Indexing drill-split tools, 3 ea	100,000
Pneumatic feeder with 400-m horizontal, 250-m vertical pipeline, sized for 15 mt/h, 1 ea	200,000
Tracked-padded telescoping bars, 10 ea	100,000
Umbilicals and control station, 1 ea	50,000
Subtotal	580,000
Spare parts (0.33 × capital cost)[2]	190,000
Total	770,000
Operating cost, $/mt:	
Backfill	2.40
Labor (3.3 persons per shift, including maintenance and labor)	16.00
Power ($0.05/kW·h)	1.40
Supplies (bit, steel, pipeline, etc.)	5.80
Total	25.60

[1]Cost estimates for 125-mt/d capacity.
[2]Estimators "rule-of-thumb" for spare parts inventory.

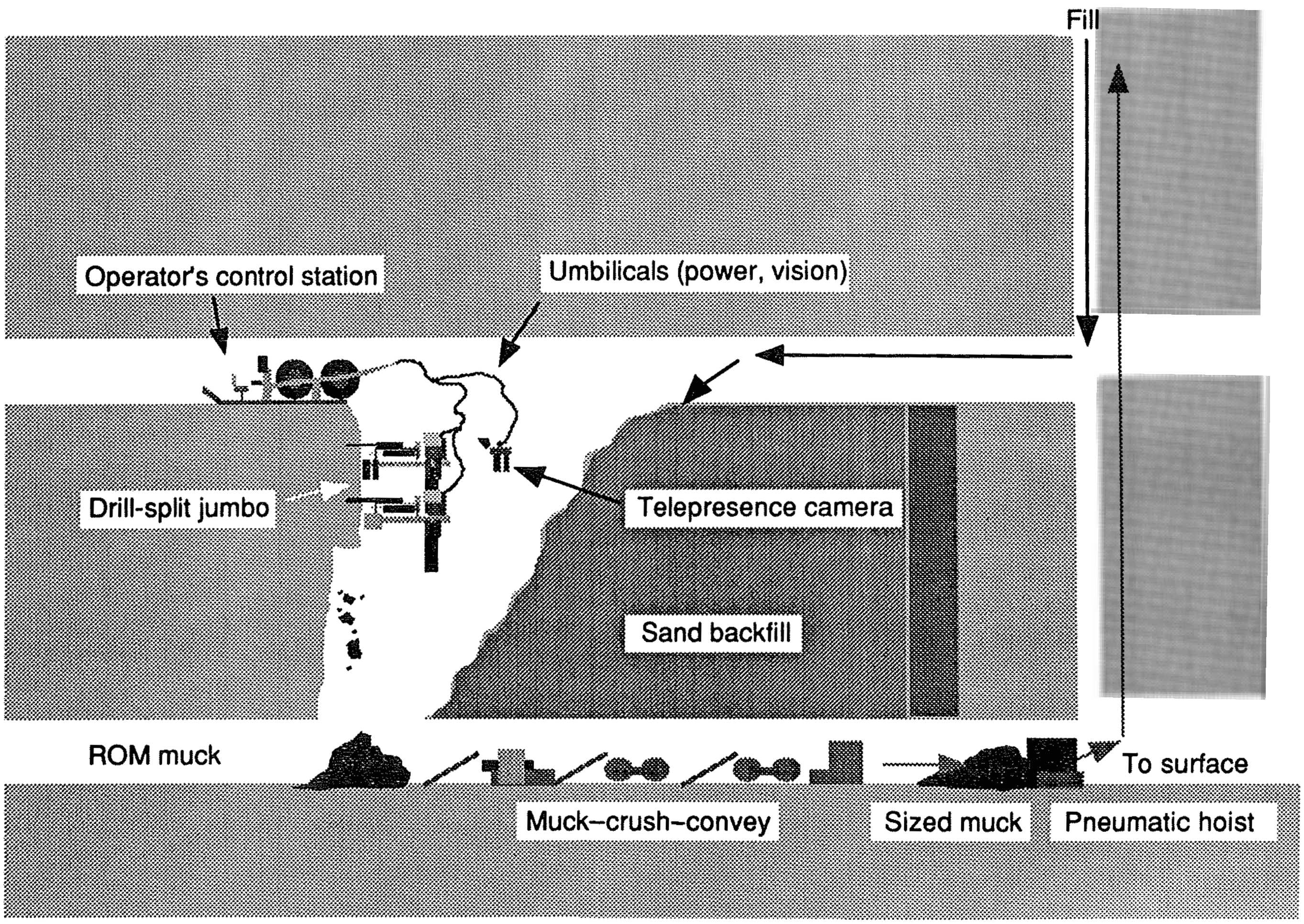

Figure 3.—Schematic of drill-split narrow-vein mining system (X section). (Narrow-vein mechanical excavation mine workings are all in the vein. Backfill retaining timbers are placed in lower drift on an as-required basis to protect crushing-conveying operation. Pneumatic hoist can operate in either shaft-located pipeline or dedicated borehole.) [Adapted from Lombardi (6)] (ROM = run-of-mine.)

The cost estimate for the narrow-vein mining method was incorporated into a mine system design for a narrow-vein ore body, and system costs were developed. Similarly, costs were developed for drill-blast shrinkage stope, narrow-vein mining systems. The system's cost studies, reported as DCFROR values, were then compared.

The hypothesized narrow-vein case study ore body was 0.6 m wide, steeply dipping, and at a depth of 150 m. The ore block is 500 m deep and 400 m long. The ore grade was assumed to be 0.70 oz/mt Au and 90 pct recoverable in a gravity milling facility. The results of the mining system cost studies are shown in table 2. The mechanical excavation mining operation's 0.6-m-wide stope required the extraction of 125 mt/d for the production of 78.8 oz Au, while the conventional drill-blast mining stope width of 1.2 m, mandated by person access into the stope, required 250 mt/d production to achieve the same 78.8 oz Au output.

The drill-split narrow-vein DCFROR value is projected to be no less than 50 pct better than conventional mining. The bulk of the mechanical excavation return-on-investment improvement is related to reduced mining dilution—i.e., better selectivity in mining vein ores only. For 1.2-m-wide ores (nominally 4 ft wide), the drill-blast and drill-split narrow-vein mining systems were determined to be approximately equal in return-on-investment.

Further descriptions and costing details for the narrow-vein mining systems comparators are shown in appendix A.

Table 2.—DCFROR comparison of drill-split narrow-vein and conventional drill-blast shrinkage stope mining systems

	Mechanical excavation (narrow-vein jumbo)	Drill-blast excavation (shrinkage stope)
Capital cost: Equipment, $:		
Mill	1,025,000	1,825,000
Mine	1,725,000	1,950,000
Operating cost, $/oz:		
Mill	19	38
Mine	112	165
Preproduction cost: Mine, $	1,650,000	1,850,000
Production:		
Au . . . . oz/d	78.8	78.8
Total . . . . mt/d	125	250
Recovery, pct:		
Mill	90	90
Mine	93	93
DCFROR value[1] . . . . pct	60-65	35-40

[1]Return on investment.

LONGWALL MINING

The concept of hard-rock longwalling using drill-blast methods has been tested previously by the mining industry (*7*). Although unsuccessful, the effort is instructive because failure was principally due to blast cycle effects. Blasting both damaged the travelling longwall shields and overloaded the chain conveyor (the thrown muck would pile 2 m high on the chain). Other elements in the test cycle, like drill jumbo movement along the face and stowage of fill behind the shields, performed satisfactorily.

In the proposed drill-split hard-rock longwall system, a multiboom drill jumbo travels along the face and drills short holes, nominally 0.3-m depth. A splitting jumbo follows the drill jumbo and sequentially splits the predrilled holes. An independently mobile mucker follows the splitting jumbo to plow feed the face conveyor. The broken ore is conveyed to a hard-rock-capable feeder-breaker (designed as a series of mobile jaw and roll crushers). The crushed ores are transported via a conveyor belt to a shaft for pipeline hoisting to the surface. Mill tails are brought from the surface and stowed behind the advancing shield line to support the mine roof, and fill walls are constructed at each end of the shield line to maintain two-entry access. The proposed drill-split longwall mining system is shown graphically in figure 4 (*6*).

Typical capital and operating costs for drill-split longwall mining are shown in table 3.

Table 3.—Capital and operating costs for drill-split longwall mining system[1]

Capital cost, $:	
Conveyor (400 m), pneumatic backfill (160 mt/h), pneumatic hoist (200 mt/h, 275 m vertical)	2,250,000
Drills (hydraulic, 18-in stroke), 18 ea	315,000
Jaw crush, 2-stage rolls crush (200 mt/h), 1 ea	750,000
Lattice jumbos (vertically telescoping, horizontally skewing), 2 ea	250,000
Longwall shield and chain conveyor, 200 m ($10,000/m)	2,000,000
Muckers, 2 ea	50,000
Splitters, 12 ea	120,000
Splitter hole-finding computer-assistance assembly, 1 ea	50,000
Subtotal	5,785,000
Spare parts (0.33 × capital cost)[2]	1,910,000
Total	7,695,000
Operating cost, $/mt:	
Backfill	.60
Labor (8 persons per shift, including maintenance and labor)	1.40
Power ($0.05/kW·h)	.60
Supplies (bits, steel, pipeline, etc.)	2.20
Total	4.80

[1]Cost estimates for 3,500-mt/d capacity.
[2]Estimators "rule-of-thumb" for spare parts inventory.

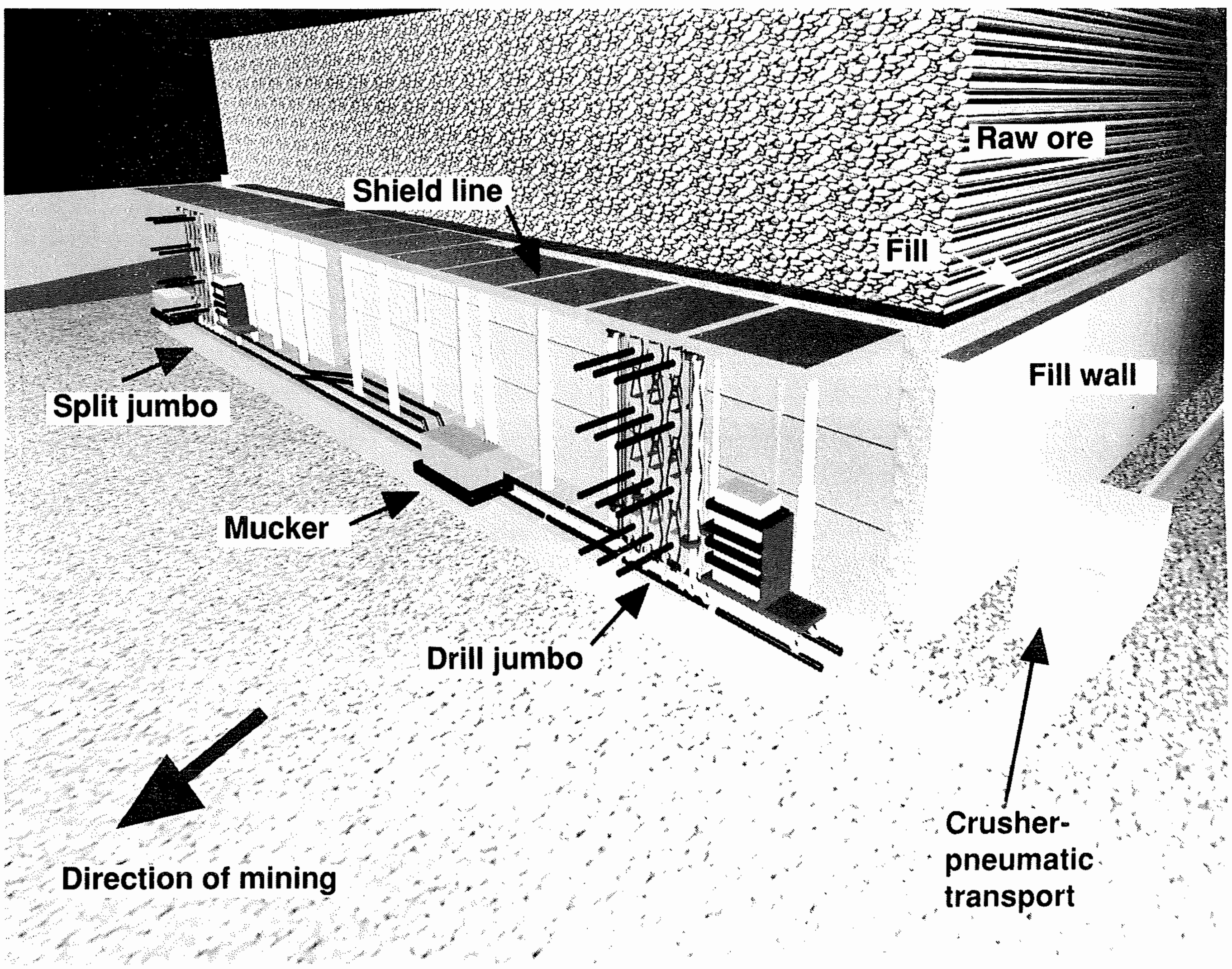

Figure 4.—Conceptual design of drill-split longwall mining system. [Adapted from Lombardi (*6*)]

Drill-split longwall mining costs were incorporated into a mine system design for a flat-lying tabular ore body. The mechanical excavation mining system cost, expressed as a DCFROR value, was then compared with the return-on-investment projected for a conventional drill-blast room-and-pillar mining of the tabular ore body.

The hypothesized tabular ore body was 5 m thick, horizontal, 800 m long, 800 m wide, and 250 m below the surface. The ore grade was assumed to be 0.06 oz/mt Au and 90 pct recoverable in a gravity milling facility.

The results of the mining system cost studies are shown in table 4. The full extraction of the ore body using the drill-split longwall technique is easily cost competitive with 72 pct recovery room-and-pillar drill-blast mining.

A separate systems case study was developed for the drill-split longwall mining of the tabular ore body in combination with underground ore sorting. Underground sorting by jigging was presumed to segregate 90 pct of the ore values into 30 pct of the run-of-mine ore stream. In the scenario, the low-grade jig overflow was directly disposed of behind the advancing shield line, and the high-grade hutch product was sent to the surface. The 70 pct reduction in materials handled and processed, accruing to the sort separation and discarding of low-grade ores and waste underground, resulted in a DCFROR value 30 to 50 pct better than the drill-blast room-and-pillar and drill-split longwall mining (without sorting) approaches.

By sorting underground and hoisting only enriched ores, the proposed drill-split longwall mining system approaches the mining industry ideal of a "values only" extraction. In values-only mining, earth disturbances due to mine development and nondilution mining are combined to effect, essentially, values-only materials handling and processing. Values-only mining is environmentally advantageous because it minimally disrupts the land and economically advantageous because precise, selective mining and processing exhibit high labor and energy use systems efficiencies.

Further descriptions and costing details for the case study tabular ore body mining systems are shown in appendix B.

Table 4.—DCFROR comparison of drill-split longwall and conventional drill-blast room-and-pillar mining systems

	Mechanical excavation (longwall)	Drill-blast excavation (room-and-pillar)
Capital cost: Equipment, $:		
Mill	9,800,000	8,500,000
Mine	10,050,000	7,500,000
Operating cost, $/mt:		
Mill	3.10	3.80
Mine	5.20	6.00
Preproduction cost: Mine, $	3,150,000	4,750,000
Production: Total . . . mt/d	3,500	2,500
Recovery, pct:		
Mill	90	90
Mine	97	72
DCFROR value[1] . . . pct	25-30	15-20

[1]Return on investment.

CONCLUSIONS

The drill-split mining of narrow 0.6- to 1.2-m-wide veins is proposed as technically and economically feasible. Drill-split narrow-vein mining would be a vein-selective, remote-control operation, with ongoing backfilling of all production mining voids. The backfill material was presumed to be mill tailing. This complete backfilling of the production mining voids with mill tailing has the beneficial effect of reducing surface-disposed mineral to the muck swell volume only. Validation of the technical and economic feasibilities of the drill-split narrow-vein mining system would significantly increase the domestic reserves base for a large number of metals.

The drill-split longwall mining of tabular ores 2 to 5 m in thickness is proposed as technically and economically feasible. The drill-split longwall mining system requires the backfilling of all production mining voids for roof-control purposes. If the backfill is mill tailing, the backfilling requirement has the beneficial effect of reducing surface-disposed mineral to the muck swell volume only. Because the drill-split longwall mining method extracts 100 pct of the ore body versus nominally 75 pct by conventional drill-blast techniques, domestic tabular ore reserves will increase accordingly.

The drill-split mechanical excavation longwall mining of tabular ores that are sortable was examined and described to be clearly economically superior to mining systems that do not sort underground. A new class of low-grade sortable ore reserves may result from the further development of the mechanical excavation-sorting technology combination. The winning of metals from sortable ores by the proposed techniques results in greatly reduced surface disturbances and makes domestic metals mining more environmentally acceptable.

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APPENDIX A.—NARROW-VEIN CASE STUDY—COST ESTIMATE DETAILS

The hypothesized ore body is a 0.61-m-wide, steeply dipping vein, under 150 m of overburden. The ore block is 500 m deep and 400 m long. The ore grade was assumed to be 0.70 oz/mt Au and 90 pct recoverable in a gravity milling facility.

The drill-split mechanical excavation mining of the above-described ore body was costed and compared with the drill-blast, shrinkage stope mining costs for the same ore body. Mechanical excavation and drill-blast system costs were developed for comparability—i.e., both scenarios begin with land clearing and include parallel shaft accessing, level development, stoping, hoisting, and processing efforts that end with tails disposal. The major citable differences between the systems are (1) the 0.6-m mechanical excavation stoping width versus the 1.2-m stope width for drill-blast shrinkage stoping, (2) the use of backfill in the mechanical excavation technique to fill all production mining voids, (3) the pneumatic hoisting of "pea-gravel" size ore in the mechanical excavation scenario versus the skip hoisting of randomly sized muck in the drill-blast scenario, and (4) the 125 mt/d ore stream of the mechanical excavation mine versus the 250 mt/d ore stream for drill-blast mining and the half-size mill accordingly required for an equal metals recovery. Cost estimate details for the drill-split mechanical excavation mining system are shown in table A-1; cost estimate details for the conventional drill-blast shrinkage stoping cost system are shown in table A-2.

The major operating assumption behind the drill-split mining scenario is the productivity of the telepresence-operated, three-boom, wall-walking drill-split jumbo. Shallow 0.36-m deep holes are assumed to be drilled and broken at a one-per-minute-per-boom rate when the jumbo operates. In an 18-h operating day, at 75 pct machine availability, this splitting rate produces about 375 mt/d. However, given the exigencies of the narrow-vein face geology-geometry evaluations and the lesser productivities of sidewall (trim hole) excavations, a conservative estimate of 125 mt/d narrow-vein jumbo productivity is used in the mechanical excavation scenario.

Table A-1.—Cost estimate details for drill-split narrow-vein mining system

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
MINE										
Clearing: 5 ha	$13,226	0	0	0	0	0	0	0	0	0
Sinking shaft: 8 m^2, 175 m deep	715,464	0	$872	$872	$872	$872	$872	$872	$872	0
Driving raises: 6 m^2, 164 m long	95,954	0	125	125	125	125	125	125	125	0
Small drifts: 6 m^2, 800 m long	328,156	0	544	544	544	544	544	544	544	0
Small raises: 2 m^2, 61 m (year 0)	20,949	0	70	70	70	70	70	70	70	0
Ore pockets: 100-mt capacity	8,764	0	29	29	29	29	29	29	29	0
Ventilation: 1,000 m^3/min	291,880	$111	111	111	111	111	111	111	111	$111
Water drainage: 650 m^3/d, 650 m deep	103,857	69	83	94	105	116	127	142	149	149
Drill-split mining: 125 mt/d[1]	0	0	4,666	4,666	4,666	4,666	4,666	4,666	4,666	4,666
Drill splitters: 175 mt/d[1]	450,000	0	0	0	0	0	0	0	0	0
Roof shields: 3.75 m^2 per section[1]	20,000	0	100	100	100	100	100	100	100	100
Backfilling: 44 m^3/d[1]	30,000	0	283	283	283	283	283	283	283	283
Second- and third-stage crushing: 150 mt/d[1]	125,000	0	1,500	1,500	1,500	1,500	1,500	1,500	1,500	1,500
Hoisting:										
Service: Double drum	21,690	863	864	865	866	867	869	870	871	0
Production: Pneumatic[1]	200,000	0	167	167	167	167	167	167	167	167
Electric: 827 kW	118,999	0	0	0	0	0	0	0	0	0
LHD haulage: 50 mt/d, 200-m hauls	228,607	31	27	27	27	27	27	27	27	0
Fueling system: 100 mt/d	11,637	0	0	0	0	0	0	0	0	0
Office and laboratories: 100 m^2 total	148,765	0	0	0	0	0	0	0	0	0
Repair shop-warehouse: 100 m^2	56,587	0	0	0	0	0	0	0	0	0
Compressed air: 15 m^3/min	65,431	21	21	21	21	21	21	21	21	21
Administrative expenses:										
125 mt/d (year 0), 150 mt/d (year 1)	0	788	863	863	863	863	863	863	863	863
Engineering fee	222,771	0	0	0	0	0	0	0	0	0
Working capital	30,625	0	0	0	0	0	0	0	0	0
Total capital	3,308,362	0	0	0	0	0	0	0	0	0
Average daily operating cost	NAp	1,883	10,325	10,337	10,349	10,361	10,374	10,390	10,398	7,860
Average yearly operating cost	NAp	564,900	3,097,500	3,101,100	3,104,700	3,108,300	3,112,200	3,117,000	3,119,400	2,358,000

See footnotes at end of table.

Table A-1.—Cost estimate details for drill-split narrow-vein mining system—Continued

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
MILL										
Grinding: 125 mt/d[2]	$220,196	0	$737	$737	$737	$737	$737	$737	$737	$737
Reichert cones: 125 mt/d[2]	21,280	0	19	19	19	19	19	19	19	19
Gravity tables: 12.5 mt/d	8,953	0	25	25	25	25	25	25	25	25
Tails thickener: 125 mt/d	112,731	0	68	68	68	68	68	68	68	68
Tails placement: 125 mt/d	12,652	0	26	26	26	26	26	26	26	26
Electric: 90 kW	15,365	0	0	0	0	0	0	0	0	0
Mill buildings: 250 m^2	488,253	0	0	0	0	0	0	0	0	0
Miscellaneous equipment: 125 mt/d	14,001	0	0	0	0	0	0	0	0	0
Administrative expenses: 125 mt/d	0	$609	609	609	609	609	609	609	609	609
Engineering fee	91,315	0	0	0	0	0	0	0	0	0
Working capital	18,270	0	0	0	0	0	0	0	0	0
Total capital	1,003,016	0	0	0	0	0	0	0	0	0
Average daily operating cost	NAp	609	1,484	1,484	1,484	1,484	1,484	1,484	1,484	1,484
Average yearly operating cost	NAp	182,700	445,200	445,200	445,200	445,200	445,200	445,200	445,200	445,200

LHD Load-haul-dump machine.
NAp Not applicable.
[1]Author estimate.
[2]Out of cost-estimating-system range.

Table A-2.—Cost estimate details for narrow-vein shrinkage stope mining system

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
MINE										
Clearing: 10 ha	$24,697	0	0	0	0	0	0	0	0	0
Sinking shaft: 16 m^2, 175 m deep	1,006,995	0	$1,225	$1,225	$1,225	$1,225	$1,225	$1,225	$1,225	0
Raise development: 6 m^2, 164 m long	95,954	0	124	124	124	124	124	124	124	0
Ore pocket: 200-mt capacity	10,447	0	34	34	34	34	34	34	34	0
Ventilation: 1,500 m^3/min	297,776	$166	166	166	166	166	166	166	166	$166
Water drainage: 600 m^3/d, 623 m deep	98,276	69	71	80	90	100	110	120	131	138
Stope preparation: 105 m^2, 4 stopes	336,171	0	1,120	1,120	1,120	1,120	1,120	1,120	1,120	0
Stope mining: 250 mt/d	0	0	7,791	7,791	7,791	7,791	7,791	7,791	7,791	7,791
Hoisting: 27 mt/h, double drum[1]	315,916	860	889	899	909	920	929	939	951	928
Drills-jacklegs: 350 mt/d	305,964	0	0	0	0	0	0	0	0	0
LHD haulage: 350 mt/d, 200-m hauls	358,349	112	226	226	226	226	226	226	226	171
Compressed air: 30 m^3/min	105,925	21	49	49	49	49	49	49	49	49
Electric: 2,000 kW	224,741	0	0	0	0	0	0	0	0	0
Fueling system: 350 mt/d	11,636	0	0	0	0	0	0	0	0	0
Office and laboratories: 75 m^2	183,286	0	0	0	0	0	0	0	0	0
Repair shop-warehouse: 100 m^2	56,586	0	0	0	0	0	0	0	0	0
Administrative expenses: 250 mt/d	0	1,142	1,142	1,142	1,142	1,142	1,142	1,142	1,142	1,142
Engineering fee	347,800	0	0	0	0	0	0	0	0	0
Working capital	45,359	0	0	0	0	0	0	0	0	0
Total capital	3,825,878	0	0	0	0	0	0	0	0	0
Average daily operating cost	NAp	2,370	12,837	12,856	12,876	12,897	12,916	12,936	12,959	10,385
Average yearly operating cost	NAp	711,000	3,851,100	3,856,800	3,862,800	3,869,100	3,874,800	3,880,800	3,887,700	3,115,500
MILL										
Crushing: 250 mt/d[1]	$174,091	0	$987	$987	$987	$987	$987	$987	$987	$987
Grinding: 250 mt/d[1]	384,981	0	997	997	997	997	997	997	997	997
Reichert cones: 25 mt/d	40,628	0	33	33	33	33	33	33	33	33
Gravity tables: 250 mt/d	15,707	0	41	41	41	41	41	41	41	41
Tails thickener: 250 mt/d	92,231	0	84	84	84	84	84	84	84	84
Tails placement: 250 mt/d	19,578	0	42	42	42	42	42	42	42	42
Electric: 120 kW	19,560	0	0	0	0	0	0	0	0	0

See footnotes at end of table.

Table A-2.—Cost estimate details for narrow-vein shrinkage stope mining system—Continued

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
MILL—Continued										
Mill buildings: 500 m^2	$891,744	0	0	0	0	0	0	0	0	0
Miscellaneous equipment: 250 mt/d	22,572	0	0	0	0	0	0	0	0	0
Administrative expenses: 250 mt/d	0	$834	$834	$834	$834	$834	$834	$834	$834	$834
Engineering fee	167,812	0	0	0	0	0	0	0	0	0
Working capital	25,040	0	0	0	0	0	0	0	0	0
Total capital	1,853,944	0	0	0	0	0	0	0	0	0
Average daily operating cost	NAp	834	3,018	3,018	3,018	3,018	3,018	3,018	3,018	3,018
Average yearly operating cost	NAp	250,200	905,400	905,400	905,400	905,400	905,400	905,400	905,400	905,400

LHD Load-haul-dump machine.
NAp Not applicable.
[1]Out of cost-estimating-system range.

APPENDIX B.—TABULAR ORE BODY CASE STUDY—COST ESTIMATE DETAILS

The hypothesized ore body is 5 m thick, horizontal, 800 m long, 800 m wide, and 250 m below the surface. The ore grade was assumed to be 0.06 oz/mt Au and 90 pct recoverable in a gravity milling facility.

The mechanical excavation and drill-blast mining systems costed for the extraction of this ore body were developed to facilitate comparability. In both mining scenarios, the extraction programs are set at 8 years, the number of shaft accesses is equal, and the mill recovery is the same. In the 100 pct recovery drill-split longwall mechanical excavation mine, the ore body is mined at a 3,500-mt/d rate. In the 72 pct recovery room-and-pillar drill-blast mine, the ore body is mined at a 2,500-mt/d rate. Including the economies-of-scale costing bias inherent to the cost estimating literature, the drill-split longwall system has a 50 pct better DCFROR value than room-and-pillar mining. The drill-split longwall cost estimate details are shown in table B-1; the room-and-pillar cost estimate details are shown in table B-2.

The higher resource recovery of the drill-split longwall method makes the mechanical excavation approach the preferred technique from a conservation of resources perspective.

The drill-split technique also lessens the surface environmental impact of mining because it requires that all the excavated rock, less swell, be returned back underground for use as backfill.

The economic rate of return of the drill-split longwall mining method is dramatically improved when the ore is sortable. In the sorting scenario, 90 pct of the deposit values was assumed to be concentrated into 30 pct of the mined volume (30 pct by volume is nominally that quantity of ore that must be sent to the surface to accommodate muck swell). The low grade and/or waste (70 pct of the excavated rock) was disposed of underground behind the advancing shields in the mining area. Sort separation greatly reduces the volume of ore hauled and hoisted from the mine and surface processed. The materials handling and processing efficiencies accruing to sorting improve the DCFROR value for the drill-split longwall mining system by 30 to 50 pct. The sorting scenario is detailed in table B-3.

Table B-1.—Cost estimate details for tabular ore body drill-split longwall mining system

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
MINE										
Clearing: 75 ha	$152,158	0	0	0	0	0	0	0	0	0
Sinking shaft: 20 m^2, 265 m long	1,703,035	0	0	0	0	0	0	0	0	0
Medium drifts: 15 m^2, 1,000 m long	533,902	0	0	$356	0	$356	0	$356	0	0
Small drifts: 15 m^2	0	0	0	927	$620	0	0	927	$620	0
Raise development: 9.5 m^2, 500 m long	365,708	0	0	0	0	0	0	0	0	0
Ore pocket: 2,500-mt capacity	43,905	0	0	0	0	0	0	0	0	0
Ventilation: 1,750 m^3/min	300,769	$11	$77	77	77	77	$77	77	77	$77
Water drainage: 1,750 m^3/d, 265 m deep	151,167	83	194	194	194	194	194	194	194	194
Longwall mining: 3,500 mt/d, 200-m face[1]	2,750,000	0	8,333	8,333	8,333	8,333	8,333	8,333	8,333	8,333
Drill-blast jumbos: 100 mt/d[2]	25,000	0	0	0	0	0	0	0	0	0
Conveyor haulage: 3,500 mt/d, 500-m belt	407,205	0	549	549	549	549	549	549	549	549
Hoisting:										
Service: 60 mt/h, 275 m deep	3,028,389	873	966	966	966	966	966	966	966	966
Production: 3,500 mt/d[1]	0	0	1,666	1,666	1,666	1,666	1,666	1,666	1,666	1,666
Backfilling: 2,500 mt/d[1]	450,000	0	1,666	1,666	1,666	1,666	1,666	1,666	1,666	1,666
Second- and third-stage crushing: 3,500 mt/d[1]	1,100,000	0	2,250	2,250	2,250	2,250	2,250	2,250	2,250	2,250
Electric: 7,250 kW[1]	900,000	0	0	0	0	0	0	0	0	0
Fueling system: 200 mt/d	11,636	0	0	0	0	0	0	0	0	0
Office and laboratories: 250 m^2 ea	554,822	0	0	0	0	0	0	0	0	0
Repair shop-warehouse: 1,250 m^2	491,665	0	0	0	0	0	0	0	0	0
Administrative expenses: 3,500 mt/d	0	4,880	4,880	4,880	4,880	4,880	4,880	4,880	4,880	4,880
Engineering fee	481,009	0	0	0	0	0	0	0	0	0
Working capital	175,410	0	0	0	0	0	0	0	0	0
Total capital	13,625,780	0	0	0	0	0	0	0	0	0
Average daily operating cost	NAp	5,847	20,581	21,864	21,201	20,937	20,581	21,864	21,201	20,581
Average yearly operating cost	NAp	1,754,100	6,174,300	6,559,200	6,360,300	6,281,100	6,174,300	6,559,200	6,360,300	6,174,300
MILL										
Grinding: 3,500 mt/d	$3,230,123	0	$4,854	$4,854	$4,854	$4,854	$4,854	$4,854	$4,854	$4,854
Reichert cones: 3,500 mt/d	476,619	0	298	298	298	298	298	298	298	298
Gravity tables: 350 mt/d	133,542	0	253	253	253	253	253	253	253	253

See footnotes at end of table.

Table B-1.—Cost estimate details for tabular ore body drill-split longwall mining system—Continued

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
				MILL—Continued						
Tails thickener: 3,500 mt/d	$904,727	0	$254	$254	$254	$254	$254	$254	$254	$254
Tails placement: 3,500 mt/d	74,338	0	284	284	284	284	284	284	284	284
Electric: 2,000 kW	207,255	0	0	0	0	0	0	0	0	0
Mill buildings: 3,500 mt/d	3,611,149	0	0	0	0	0	0	0	0	0
Miscellaneous equipment: 3,500 mt/d	139,484	0	0	0	0	0	0	0	0	0
Administrative expenses: 3,500 mt/d	0	$2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870	2,870
Engineering fee	892,605	0	0	0	0	0	0	0	0	0
Working capital	86,107	0	0	0	0	0	0	0	0	0
Total capital	9,755,959	0	0	0	0	0	0	0	0	0
Average daily operating cost	NAp	2,870	8,813	8,813	8,813	8,813	8,813	8,813	8,813	8,813
Average yearly operating cost	NAp	861,000	2,643,900	2,643,900	2,643,900	2,643,900	2,643,900	2,643,900	2,643,900	2,643,900

NAp Not applicable.
[1]Author estimate.
[2]Out of cost-estimating-system range.

Table B-2.—Cost estimate details for tabular ore body room-and-pillar mining system

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
MINE										
Clearing: 100 ha	$197,327	0	0	0	0	0	0	0	0	0
Sinking shaft: 40 m^2, 275 m deep	2,494,536	0	0	0	0	0	0	0	0	0
Large rubber tired drifts: 25 m^2, 1,600 m long	1,127,879	0	0	$1,875	0	$1,875	0	$1,875	$1,875	0
Raise development: 9.5 m^2, 500 m long	365,708	0	0	0	0	0	0	0	0	0
Ore pocket: 2,000-mt capacity	36,947	0	0	0	0	0	0	0	0	0
Ventilation: 5,500 m^3/min	349,443	$609	$609	609	$609	609	$609	609	609	$609
Water drainage: 600 m^3/d, 275 m deep	72,804	85	85	85	85	85	85	85	85	85
Room-and-pillar mining: 2,500 mt/d	0	0	6,223	5,822	6,223	5,822	6,223	5,822	5,822	6,223
Drill-blast jumbos: 2,750 mt/d	1,585,464	0	0	0	0	0	0	0	0	0
Truck haulage: 2,750 mt/d	2,119,856	184	1,115	1,135	1,452	1,437	1,452	1,466	1,575	1,588
Hoisting: 150 mt/h, 265 m deep	1,346,566	898	1,048	1,048	1,048	1,048	1,048	1,048	1,048	1,048
Compressed air: 180 m^3/min	367,974	67	433	433	433	433	433	433	433	433
Electric: 7,250 kW	568,046	0	0	0	0	0	0	0	0	0
Fueling system: 2,750 mt/d	18,406	0	0	0	0	0	0	0	0	0
Office and laboratories: 250 m^2 ea	554,822	0	0	0	0	0	0	0	0	0
Repair shop-warehouse: 1,000 m^2 total	406,176	0	0	0	0	0	0	0	0	0
Administrative expenses: 2,500 mt/d	0	4,043	4,043	4,043	4,043	4,043	4,043	4,043	4,043	4,043
Engineering fee	1,182,261	0	0	0	0	0	0	0	0	0
Working capital	149,753	0	0	0	0	0	0	0	0	0
Total capital	12,943,968	0	0	0	0	0	0	0	0	0
Average daily operating cost	NAp	5,886	13,556	15,050	13,893	15,352	13,893	15,381	15,490	14,029
Average yearly operating cost	NAp	1,765,800	4,066,800	4,515,000	4,167,900	4,605,600	4,167,900	4,614,300	4,647,000	4,208,700
MILL										
Crushing: 2,500 mt/d	$1,036,996	0	$2,360	$2,360	$2,360	$2,360	$2,360	$2,360	$2,360	$2,360
Grinding: 2,500 mt/d	2,462,861	0	3,798	3,798	3,798	3,798	3,798	3,798	3,798	3,798
Reichert cones: 2,500 mt/d	348,204	0	223	223	223	223	223	223	223	223

See footnotes at end of table.

Table B-2.—Cost estimate details for tabular ore body room-and-pillar mining system—Continued

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
		MILL—Continued								
Gravity tables: 250 mt/d	$101,650	0	$200	$200	$200	$200	$200	$200	$200	$200
Tails thickener: 2,500 mt/d	733,141	0	215	215	215	215	215	215	215	215
Tails placement: 2,500 mt/d	83,517	0	222	222	222	222	222	222	222	222
Electric: 1,200 kW	135,012	0	0	0	0	0	0	0	0	0
Mill buildings: 2,500 mt/d	3,231,475	0	0	0	0	0	0	0	0	0
Miscellaneous equipment: 2,500 mt/d	110,301	0	0	0	0	0	0	0	0	0
Administrative expenses: 2,500 mt/d	0	$2,446	2,446	2,446	2,446	2,446	2,446	2,446	2,446	2,446
Engineering fee	838,120	0	0	0	0	0	0	0	0	0
Working capital	73,380	0	0	0	0	0	0	0	0	0
Total capital	9,154,657	0	0	0	0	0	0	0	0	0
Average daily operating cost	NAp	2,446	9,464	9,464	9,464	9,464	9,464	9,464	9,464	9,464
Average yearly operating cost	NAp	733,800	2,839,200	2,839,200	2,839,200	2,839,200	2,839,200	2,839,200	2,839,200	2,839,200

NAp Not applicable.

Table B-3.—Cost estimate details for tabular ore body drill-split longwall, sorting, mining system

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
MINE										
Clearing: 40 ha	$86,000	0	0	0	0	0	0	0	0	0
Shaft sinking: 20 m^2, 265 m long	1,700,000	0	0	0	0	0	0	0	0	0
Medium drifts: 15 m^2, 1,000 m long	530,000	0	0	$356	0	$356	0	$356	0	0
Small drifts: 15 m^2	0	0	0	927	$620	0	0	927	$620	0
Raise development: 9.5 m^2, 500 m long	370,000	0	0	0	0	0	0	0	0	0
Ore-pocket: 600-mt capacity	11,000	0	0	0	0	0	0	0	0	0
Ventilation: 1,750 m^3/min, 265 m deep	301,000	$11	$77	77	77	77	$77	77	77	$77
Water drainage: 3,750 mt/d w/hoist and recirculating	302,000	83	388	388	388	388	388	388	388	388
Shortwall mining: 3,500 mt/d, 200-m face[1]	2,750,000	0	8,333	8,333	8,333	8,333	8,333	8,333	8,333	8,333
Drill-blast jumbo: 100 mt/d[1]	25,000	0	0	0	0	0	0	0	0	0
Underground backfilling: 2,450 mt/d[1]	200,000	0	300	300	300	300	300	300	300	300
Hoisting:										
Service: 60 mt/h, 275 m deep	525,000	873	966	966	966	966	966	966	966	966
Production: 1,050 mt/d to surface	1,000,000	0	500	500	500	500	500	500	500	500
Underground jigging: 3,500 mt/d, 70:30 split	800,000	0	1,622	1,622	1,622	1,622	1,622	1,622	1,622	1,622
Backfilling (other): 350 mt/d from surface	65,000	0	250	250	250	250	250	250	250	250
Second- and third-stage crushing: 3,500 mt/d	902,000	0	2,060	2,060	2,060	2,060	2,060	2,060	2,060	2,060
Electric: 5,000 kW[1]	650,000	0	0	0	0	0	0	0	0	0
Fueling system: 3,500 mt/d	21,000	0	0	0	0	0	0	0	0	0
Office and laboratories: 250 m^2 ea	555,000	0	0	0	0	0	0	0	0	0
Repair shop-warehouse: 1,250 m^2	492,000	0	0	0	0	0	0	0	0	0
Administrative expenses: 3,500 mt/d	0	4,880	4,880	4,880	4,880	4,880	4,880	4,880	4,880	4,880
Working capital: 30 days	175,000	0	0	0	0	0	0	0	0	0
Mine capital	12,710,000	5,847	19,376	20,659	19,996	19,732	19,376	20,659	19,996	19,376
Average yearly operating cost	NAp	1,754,100	5,812,800	6,197,700	5,998,800	5,919,600	5,812,800	6,197,700	5,998,800	5,812,800
MILL										
Grinding: 1,050 mt/d, partial to complete grind	$700,000	0	$630	$630	$630	$630	$630	$630	$630	$630
Reichert cones: 1,050 mt/d	143,000	0	89	89	89	89	89	89	89	89
Gravity tables: 1,050 mt/d	40,000	0	76	76	76	76	76	76	76	76

See footnotes at end of table.

Table B-3.—Cost estimate details for tabular ore body drill-split longwall, sorting, mining system—Continued

Unit processes and parameter values	Capital cost, year 0	Daily operating costs								
		Year 0	Year 1	Year 2	Year 3	Year 4	Year 5	Year 6	Year 7	Year 8
MILL—Continued										
Tails thickener: 1,050 mt/d	$270,000	0	$76	$76	$76	$76	$76	$76	$76	$76
Tails placement: 700 mt/d	74,000	0	284	284	284	284	284	284	284	284
Electric: 1,200 kW	62,000	0	0	0	0	0	0	0	0	0
Mill buildings: 3,000 m^2	1,083,000	0	0	0	0	0	0	0	0	0
Miscellaneous equipment: 1,050 mt/d	100,000	0	0	0	0	0	0	0	0	0
Administrative expenses: 1,050 mt/d	0	$1,550	1,550	1,550	1,550	1,550	1,550	1,550	1,550	1,550
Engineering fee	250,000	0	0	0	0	0	0	0	0	0
Working capital	46,500	0	0	0	0	0	0	0	0	0
Average daily operating costs	NAp	1,550	2,705	2,705	2,705	2,705	2,705	2,705	2,705	2,705
Average yearly operating costs	NAp	465,000	811,500	811,500	811,500	811,500	811,500	811,500	811,500	811,500
Mill capital	2,768,500	0	0	0	0	0	0	0	0	0

NAp Not applicable.
[1]Author estimate.

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