2023

SIMPLIFIED COST MODELS FOR UNDERGROUND MINE EVALUATION A Handbook for Quick Prefeasibility Cost Estimates - Revised Edition

Thomas W. Camm
Montana Tech

Scott A. Stebbins

SIMPLIFIED COST MODELS FOR UNDERGROUND MINE EVALUATION

A Handbook for Quick Prefeasibility Cost Estimates

Revised Edition

By
Thomas W. Camm & Scott A. Stebbins

2023

Montana Technological University
Mining Engineering Department

MONTANA
TECHNOLOGICAL UNIVERSITY
MINING ENGINEERING

Simplified Cost Models for Underground Mine Evaluation
A Handbook for Quick Prefeasibility Cost Estimates
2023 Revised Edition

By Thomas W. Camm & Scott A. Stebbins

Cover design for 2023 revised edition by Lisa Sullivan (Hibnes)

Keywords: cost models, prefeasibility studies, underground mine design, mineral property evaluation, mine cost estimating

Topic Area(s): Mineral property evaluation, underground mine design

Mining Engineering Department
Montana Technological University
Butte, MT

About us
In the heart of the Rocky Mountains, Montana Technological University is a place of purpose, home to uncommon thinking, research, innovation, and ideas. See our website for a sample of our numerous awards and recognition: https://www.mtech.edu/about/awards/index.html
Our ABET-accredited mining engineering degree program also boasts a 100% career outcome rate.
Visit our website: https://www.mtech.edu/mining-engineering/index.html

We hope you find this publication useful. We are strong believers in open-access teaching resources, and strive to keep the costs to our students as low as possible. For that reason, this publication is free, along with many other publications by myself and my colleagues in the Mining Engineering Department on our library Digital Commons page: https://digitalcommons.mtech.edu/mine_engr/

Suggested citation:
Camm, T. W., & Stebbins, S. A. (2023). *Simplified cost models for underground mine evaluation: A handbook for quick prefeasibility cost estimates* (2023 revised edition). Mining Engineering Department, Montana Technological University. https://digitalcommons.mtech.edu/mine_engr/

Available free as a PDF on the Montana Technological University website:
https://www.mtech.edu/
Library/Digital Commons/Faculty Scholarship/Mining Engineering
https://digitalcommons.mtech.edu/mine_engr/

CONTENTS

ABSTRACT

This handbook provides simplified cost models for evaluating underground mines. Regression analysis is used to generate capital and operating cost equations for each model in the form $Y = AX^B$, where Y is the cost estimated and X is the assumed production capacity in tonnes per day. A and B are constants determined by the regression analysis. Equations are developed for operating costs in five subcategories: equipment operation, supplies, hourly labor, administration, and sundries. Subcategories for capital costs are: equipment purchase, preproduction underground excavation, surface facilities, engineering & management, contingency, and working capital. Cost models are developed for eight underground mining methods.

This revised 2023 edition also includes a new section on cost indexes to update the models for inflation. Two appendices are also added with an example problem and an expanded discussion of cost indexes.

PREFACE TO 2023 REVISED EDITION

The first edition of this cost handbook was published in 2020, and the cost models are in 2019 US dollars. Since that time, inflation has had a significant effect on all economic aspects of mining, including costs. So, adding a section on cost indexes was necessary.

Also, to provide an example of applying cost indexes to the models, I have added an Appendix with an example cost calculation. An additional Appendix with much more detail on cost indexes (for those interested) is also included.

I have made corrections to some format inconsistencies, and a few typos that were missed in the first edition (particularly *Engineering & Management* in the tables).

The rest of the handbook remains unchanged.

What's New in the 2023 Edition?

- Cost Indexes
- Appendix A – Example Cost Calculation
- Appendix B – Cost Indexes Discussion

INTRODUCTION

Scott and I have worked on cost models off and on our entire career (Scott more consistently). This handbook is primarily intended for use in the classroom, if it is also useful to our colleagues in the industry that will be a nice bonus. [Writing in the first person usually makes for easier reading, and is my preference. So, the "I" in this handbook is Thomas; I will frequently refer to my coauthor Scott Stebbins throughout the handbook. I am providing most of the writing for this handbook. Scott provided a lot of the engineering and costing, as well as the illustrations. More on the specifics in the Methodology section].

Cost Estimating System

Scott and I first learned cost estimating from Otto Schumacher, our supervisor at Western Field Operations Center (WFOC) in Spokane, WA. This was one of the field centers for the U. S. Bureau of Mines (USBM), a federal agency that was part of the Department of the interior. The USBM no longer exists. We went to work for the USBM when we graduated from the University of Idaho's Mining Engineering program, a degree program no longer offered at Idaho (hmmm. . .). When we first arrived at WFOC, a cost handbook was being used that had been contracted by the USBM (STRAAM, 1977). It soon became apparent that a revision was needed. Remarkably, we were able to convince those up the food chain that this revision should be done in-house.

The result was the USBM Cost Estimating System (CES) Handbook, published in two volumes: part 1 for surface and underground mining (USBM, 1987a), and part 2 for mineral processing (USBM, 1987b). CES was designed for use when making prefeasibility-type cost estimates. Each unit operation was evaluated for capital and operating costs. Three regression equations for labor, supplies and equipment were developed for both capital and operating costs. Scott and I were part of the underground mining group. To perform a complete analysis using CES, a thorough design scheme for the deposit was necessary to supply all the design parameters necessary for each unit operation. Between the two of us we performed the cost analysis, developed the regression curves, and wrote 54 of the underground mining cost sections in CES (me 22 sections, Scott 32).

After CES was completed, Otto left to form his own engineering company, Western Mine Engineering, which provided consulting and developed the Mine Cost Service Handbook. This business eventually developed into CostMine [https://www.costmine.com/], which provides a wide variety of cost estimating tools to the mining industry. Scott also left and formed Aventurine Engineering, a consulting company that is still going strong (no mean feat in itself). Scott also worked with Otto and currently also works with CostMine. More on CostMine and Scott's work in the Methodology section.

Simplified Cost Models

In the 1990s, the USBM conducted studies of the economic impacts of regulations on federal lands as part of the Bureau Potential Supply Analysis (PSA) program. These studies evaluated the potential economic impacts of known and undiscovered resources on Federal lands. To meet the needs of these studies, a methodology was developed to estimate operating and capital costs for a mineral deposit given its tonnage, grade and depth (Camm, 1993). I spent a lot of this time developing a new cost model format specific to the needs of these studies. The cost models were described in USBM Information Circular 9298–*Simplified cost models for prefeasibility mineral evaluations* (Camm, 1991), and a corresponding technical article in *Mining Engineering* (Camm, 1994).

Post-USBM

After the USBM closed, I went to work for the Spokane Research Laboratory (SRL) of the National Institute for Occupational Safety and Health (NIOSH) as a research engineer specializing in cost analysis and the economic impacts of innovations in safety and health research specific to the mining industry. Part of my work included developing cost engineering models for mining health & safety research which were made available for use in SRL research projects. I have been teaching in the mining engineering department of Montana Technological University since 2011. Scott continues as President of Aventurine Engineering, Inc. He has spent his post-USBM career estimating the capital and operating costs of more than 140 mining and mineral processing projects and evaluating their economic potential. He specializes in constructing engineering-based, mathematic cost estimating models and continually updating the SHERPA cost estimating products.

METHODOLOGY

Each cost model was developed using cost estimates for five production rates. The five rates chosen vary for each method, based on the typical production rates usually found for each mining method. As stated in the title, cost models were only developed for eight (non-coal) underground mining methods:

- Block Caving
- Cut & Fill (Mechanized)
- Cut & Fill (Traditional/Jackleg)
- End Slice Mining
- Room & Pillar
- Shrinkage Stoping
- Sublevel Caving
- Sublevel Longhole

Regression analysis was used to generate capital and operating cost equations for each model in the form $Y = AX^B$, where Y is the cost estimated and X is the assumed capacity in metric tons per day (t/d). The coefficients A and B are constants determined by the regression analysis. Costs of mining and other industrial operations have been found historically to fit this equation form. This is also consistent with the format of CES cost equations and the simplified models I subsequently developed in 1991 (Camm, 1991, p. 3). The individual cost categories will be described in the capital and operating cost sections that follow.

The individual data points used to develop the cost model for each mining method were calculated using *SHERPA for underground mines* (Stebbins, 2019). SHERPA Mine Cost Estimating Software is published by CostMine, a division of InfoMine USA, Inc. and Glacier Resource Innovation Group. Scott developed this software many years ago and continues to refine and update this popular tool for providing prefeasibility cost estimates. *SHERPA* uses standard, engineering-based cost estimating techniques to estimate capital and operating costs for proposed underground mines based on specific mine design parameters.

All costs in 2019 US dollars

Categories of cost estimates are always a subject of debate among evaluators. When we worked at the Bureau of Mines, we would categorize our estimates using CES as *prefeasibility* studies. These are estimates using cost models with limited knowledge of an orebody. Accuracy of a good model at this level of detail is typically +/-30%. This type of estimate is also often called an order-of-magnitude or Level I estimate (Bulloch, 2011a). A detailed discussion of the many characteristics and categories of cost estimates is beyond the scope of this handbook. Descriptions of the many aspects of detailed cost estimating and modeling can be found in Bulloch (2011a, 2018), Camm (1993, 1994), Stebbins, (2011, 2019, 2020) and Stebbins and Schumacher (2001).

It is important to note that cost models serve a particular purpose in the discipline of cost estimating. There are typically two or more steps from a preliminary cost estimate to a bankable estimate you would use to decide on actually developing a mine (and the hundreds of millions, sometimes *billions* of dollars associated with that development). That said, cost models can be very useful for comparison of different potential deposits or for acquisition and exploration decisions. They can be useful for cut-off grade analysis, particularly for preliminary reserve estimates. The prefeasibility estimate from a cost model is also a useful starting point for decisions to progress with the more time and cost intensive aspects of more detailed evaluation (Bulloch, 2018, p. 368; Stebbins & Schumacher, 2001, p. 55).

Regression Analysis

Linear regression is probably the most common application of regression analysis, following the general equation for a straight line:

$$Y = A + B(X)$$

Where Y = dependent variable,
X = independent variable,
A, B = regression coefficients.

The following equations can be applied to solve for A and B (N = number of data points):

$$B = \frac{N\sum[(X_i)(Y_i)] - (\sum X_i)(\sum Y_i)}{N\sum(X_i)^2 - [(\sum X_i)]^2}$$

$$A = \frac{\sum(Y_i) - B\sum(X_i)}{N}$$

The challenge for an engineer evaluating the costs of a mine is that most costs do not follow a linear relationship. Usually, costs for most engineering processes, including mining and mineral processing follow the geometric regression relationship (sometimes referred to as a *power equation* or *power curve*):

$$Y = A(X^B)$$

Where Y = cost,
X = production capacity in *t/d,*
A, B = regression coefficients.

The coefficients A and B can be found using the logarithmic values of the previous linear regression:

$$lnY = lnA + B(lnX)$$

To determine A and B, use the following equations:

$$\boldsymbol{B = \frac{N\sum[(lnX_i)(lnY_i)] - (\sum lnX_i)(\sum lnY_i)}{N\sum(lnX_i)^2 - [(\sum lnX_i)]^2}}$$

$$\boldsymbol{A = \exp[\frac{\sum(lnY_i) - B\sum(lnX_i)}{N}]}$$

(Camm, 1992, p. 2; Wellmer, 1986, p. 60)

Costs Included in the Models

When using any cost model, it is important to know what is included (and not included) in the model. These models are intended to provide an estimate of the costs associated with the underground mining portion of a mining operation. These costs include:

- All labor, material, supply and equipment operation costs incurred at the mine site, including supervision, administration and onsite management
- Equipment operation costs include parts, fuel, lube, electricity, tires
- Benefits and employment taxes
- All on-site development (including pre-production development and surface facilities construction)
- Mine equipment and facilities purchase and installation or construction
- Engineering and construction management fees
- Working capital
- Contingencies

All of the models include at least two routes of access. Mines producing less than 4,000 tonnes of ore per day are accessed by one primary excavation (shaft or adit), and a secondary excavation (raise) that serves to complete the ventilation circuit and provide an alternate access route. Larger mines are accessed by two primary excavations (shafts or adits), and at least one secondary excavation (raise). For all models, additional raises are excavated as needed over the life of the operation to provide adequate ventilation pathways and routes of egress.

Cut & Fill, End Slice, Vertical Crater Retreat, and Sublevel Longhole models all assume that the stopes are backfilled to maximize recovery. Fill used in the Cut & Fill stopes contains 7.0% cement for stabilization. Fill for the other stoping methods contain 4.0% cement.

Costs Not Included in the Models

Preproduction exploration • permitting & environmental analysis • startup costs (except working capital) •access roads, power lines, pipelines, railroads to site • corporate overhead • taxes (except sales tax) • insurance • depreciation • interest expenses • townsite construction & operation • off-site transportation of products • incentive bonus premiums • overtime labor costs • sales expenses • mineral processing • smelting & refining • post-closure reclamation

Operating Costs

Operating costs are based on daily production capacity (t/d) and are expressed in dollars per metric ton ($/t). From an economic evaluation/tax standpoint, these are costs typically expensed in the year they occur. These underground mine models include labor, material, supply, and equipment operating costs at the mine site, including supervision, administration, and on-site management.

Operating costs are subdivided into five categories:

- Equipment Operation
- Supplies
- Hourly Labor
- Administration
- Sundries

Equipment Operation

Each model includes the costs of operating all equipment required for: Drilling • Mucking • Hauling • Rock Bolting • Underground Crushing • Hoisting • Ventilation • Compressed Air • Drainage Pumping • Fresh Water Pumping • Backfilling • Support Installation • Maintenance • Exploration Drilling • Raise Boring.

Equipment purchase and operating costs used in SHERPA to develop the cost models are current costs (2019 US dollars) from *Mine and Mill Equipment Costs: An Estimator's Guide*, published by CostMine.

Supplies

Supply operating costs are based on the daily consumption of material used in the mine: Explosives • caps/boosters/detonation cord • drill bits & steel • rock bolts • electricity • electric cable • cement • steel pipe • ventilation tubing • steel liner material • timber/lagging.

A sales tax rate of 7.24% is added to all non-fuel supply prices.

Hourly Labor

Wages and salaries in *SHERPA* are based on the annual CostMine wage and salary survey for U.S. metal and industrial mineral mines. The salaries and wages include burden. Wage burden takes into account the additional cost to the employer for matching FICA/Social Security (6.2%), Medicare (1.45%), health insurance, 401(k) matching contributions, vacation & sick leave, etc. This wage burden can add 25-55% to the base wages of workers as a cost to the employer. Based on results from the survey, wages for smaller mine models are less than those for larger models. This is reflected in the burden: for the cost model, the burden for hourly labor is 37% for small operations, and 54% for large operations. This is reflected in the cost model.

Typical work categories for hourly personnel at an underground mine:

- Stope Miner
- Development Miner
- Mobile Equipment Operator
- Hoist Operator
- Motorman
- Support Miner
- Exploration Driller
- Crusher Operator
- Backfill Plant Operator
- Electrician
- Mechanic
- Maintenance Worker
- Helper
- Underground Laborer
- Surface Laborer

Administration

While the labor burden for salaried personnel is virtually the same for smaller operations, larger operations have a lower burden for their professional staff. According to the CostMine surveys, the burden for salaried personnel is 37% for small operations, and 47% for large operations.

Typical work categories for professional/salaried personnel at an underground mine:

- Mine Manager
- Superintendent
- Foreman
- Engineer
- Geologist
- Shift Boss
- Technician
- Accountant
- Clerk
- Personnel Manager
- Secretary
- Purchasing Agent

Sundries

This includes costs for miscellaneous expenses too small or numerous to list separately. The cost is 10% of the subtotal of the previous four cost categories.

Capital Costs

Capital costs are based on the costs of purchasing, installing and operating all relevant equipment and on costs associated with the development of the underground mine necessary to begin daily production. From an economic evaluation/tax standpoint, these costs are not fully expensed in the year incurred; the tax deductions for these costs are treated using depreciation/depletion/amortization (depending on the category).

Capital costs are subdivided into six categories:

- Equipment Purchase
- Preproduction Underground Excavation
- Surface Facilities
- Engineering & Management
- Contingency
- Working Capital

Equipment Purchase

Each model includes the costs of purchasing, installing and operating all equipment required for:

Drilling • Mucking • Hauling • Rock Bolting • Underground Crushing • Hoisting • Ventilation • Compressed Air • Drainage Pumping • Fresh Water Pumping • Backfilling • Support Installation • Maintenance • Exploration Drilling • Raise Boring.

Equipment purchase and operating costs used in SHERPA to develop the cost models are current costs (2019 US dollars) from *Mine and Mill Equipment Costs: An Estimator's Guide*, published by CostMine.

Preproduction Underground Excavation

Preproduction development of underground excavations includes all of the openings necessary to begin daily ore production. These openings include:

- Access adit(s) for adit entry models
- Shaft(s) for shaft entry models
- Drifts
- Crosscuts
- Access raises
- Draw points
- Ore passes
- Ventilation raises
- Underground openings (hoist stations, repair shops, lunch rooms, pump stations, etc.)

Surface Facilities

Mine facilities—including shops, offices, worker change-houses and warehouses—are included in this section.

Engineering & Management

Additional expenses associated with capital costs include project feasibility, engineering, planning, construction management, administration, accounting, and legal fees. Estimators commonly factor values for these costs from the overall capital cost subtotal. Some of the most commonly used factors include (Stebbins, 2011, p. 270):

- Feasibility, engineering, and planning (4-8%)
- Construction supervision and project management (8-10%)
- Administration, accounting, permitting and legal services (8-14%)

For the cost models, these categories are combined in Engineering & Management. The cost is a percentage of the capital cost subtotal of Equipment Purchase (CC_{EP}) + Preproduction Underground Excavation (CC_{PE}) + Surface Facilities (CC_{SF}):

$$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$$

The percentage is 13-17%, and is specified for each model. As an example, the End Slicing model specifies 15% of subtotal for Engineering & Management:

$$CC_{E\&M} = CC_{SUB}(0.15)$$

Contingency

Scott and I had a couple discussions about this category. Mining is notorious for going over budget while bringing a mine into production. Our colleague Richard Bulloch has documented this aspect of mining admirably (Bulloch, 2011a, 2018). Contingency should be an actual account set aside for any additional, unforeseen costs associated with unanticipated geologic circumstances or engineering conditions. It is not meant to cover inadequacies in the cost estimate or failings in the mine design. Scott notes the money is almost always spent (Stebbins, 2011, p.270). I think he is being a bit generous in using the term *almost*. In actual practice, the contingency account is all spent and then some.

For the cost models in this handbook, we suggest a contingency cost (CC_C) of 20% of the capital cost subtotal (CC_{SUB}). We consider this a conservative percentage.

$$CC_C = CC_{SUB}(0.20)$$

Working Capital

Working capital covers the cost of meeting operating costs in the initial stages of production, before revenue is generated from the first shipments of product (concentrates or doré). This value can vary from 2 to 6 months (Camm, 1991, p. 3). Working capital for the cost models is based on 2 months of operating costs. The number of operating days per year for each model are based on Scott's years of experience. The days used to calculate two months of operating costs are specified in each model, and will be either 52 (based on 312 d/y), 58 (based on 350 d/y), or 61(based on 365 d/y). If the operating days per year are 312 d/y, working capital is then calculated using the equation:

$$CC_{WC} = (\text{operating cost, \$/t})(\text{production capacity, t/d})(52 \text{ days})$$

Dilution & Recovery Factors

Typically a mining operation does not recover every ton of ore. The amount of ore actually extracted from a deposit over the life of the mine is referred to as the recovery factor, and is expressed as a percent. Additionally, a certain amount of waste from the wall rock in the stope is usually mixed in with the ore during mining. This waste mixed in as ore is the dilution factor (in %). Both recovery and dilution vary with each ore body, but tend to be within a similar range for each mining method. The following table summarizes the assumed dilution and recovery factors used for the mine models and reflects values commonly encountered when these mining methods are applied (Camm, 1991, p. 4).

Table 1. Mine Recovery and Dilution Factors

Mining Method	Recovery factor (%)	Dilution Factor (%)
Block Caving	95	15
Cut & Fill (Mechanized)	90	5
Cut & Fill (Jackleg)	85	5
End Slice Mining	85	15
Room & Pillar (w/pillar recovery)	80	10
Shrinkage Stoping	85	10
Sublevel Caving	80	20
Sublevel Longhole	85	15

Mine Life

The models in this handbook are designed for quick estimations of costs with a preliminary knowledge of the deposit. To use these cost models, a daily production capacity is required. One of the first decisions necessary is what tonnage will be used for this early evaluation of the deposit. Depending on the amount of sampling/mapping/drilling available, typically you will have at least preliminary estimates of reserves and resources.

After selecting a mining method, choose a recovery factor and dilution factor based on knowledge of the orebody and experience, and/or using the table. With this information, use the following equation to determine total tonnage of ore to be extracted over the life of the mine:

$$\mathrm{T} = (\mathrm{rt})(\mathrm{rf})(1+\mathrm{df})$$

Where T = total tonnage of ore to be mined,
rt = total tonnage of deposit reserve/resource,
rf = recovery factor (expressed as a decimal),
df = dilution factor (expressed as a decimal).

The life of the mine can now be calculated using Taylor's rule (Taylor, 1978):

$$\mathrm{L} = 0.2(\mathrm{T})^{0.25}$$

Where L = mine life in years.

Production capacity can now be calculated:

$$X = \frac{T}{(L)(dpy)}$$

Where X = daily production capacity of ore (t/d),
dpy = mine operating days per year.

For those interested in a more in-depth discussion of calculating mine life, see Dominski et al (2014) and Long (2009).

Cost Summary

Table 2. Cost Summary for Each Model *(2019 US dollars)*

Mining Method	Production range (t/d)	Operating Cost ($/t)	Capital Cost ($ in millions)
Block Caving – Adit	20,000 – 45,000	9.95 - 8.26	88.4 – 195.3
Block Caving – Shaft	20,000 – 45,000	10.90 – 9.23	116.8 – 237.5
Cut & Fill (Mechanized) – Adit	200 – 2,000	95.21 – 44.24	24.5 – 61.6
Cut & Fill (Mechanized) – Shaft	200 – 2,000	100.57 – 45.79	33.8 – 70.3
Cut & Fill (Jackleg) – Adit	200 – 2,000	139.33 -63.12	19.0 – 48.3
Cut & Fill (Jackleg) – Shaft	200 – 2,000	145.36 – 65.16	27.1 – 59.2
End Slice Mining – Adit	800 – 4,000	42.74 – 26.57	27.2 – 68.4
End Slice Mining – Shaft	800 – 4,000	45.60 – 28.55	35.6 – 102.1
Room & Pillar – Adit	1,200 – 14,000	45.26 – 17.15	46.2 – 156.0
Room & Pillar – Shaft	1,200 – 14,000	49.53 – 18.31	58.7 – 184.9
Shrinkage Stoping – Adit	200 – 2,000	114.74 – 54.99	17.9 – 50.6
Shrinkage Stoping – Shaft	200 – 2,000	119.61 – 57.47	26.6 – 63.5
Sublevel Caving – Adit	4,000 – 14,000	27.76 – 20.55	68.1 – 203.4
Sublevel Caving – Shaft	4,000 – 14,000	31.20 – 22.21	107.4 – 262.7
Sublevel Longhole – Adit	800 – 8,000	39.08 – 20.11	27.1 – 94.5
Sublevel Longhole – Shaft	800 – 8,000	42.90 – 21.21	37.2 – 132.0

COST INDEXES

A *cost index* is a dimensionless ratio, typically comparing the cost of something today (present time, in engineering economy terms) to the cost of something in the past (a reference year or base year; 2019 for the models in this handbook). An index is used to measure the relative change in cost over time.

I like the notation used by Blank & Tarquin (2012, p. 392):

$$C_t = C_0\left(\frac{I_t}{I_0}\right)$$

Where C_t = estimated cost at present time t,
C_0 = cost at previous time 0,
I_t = index value at time t,
I_0 = index value at time 0.

There are several sources for cost indexes, depending on the particular application and category of cost being evaluated. InfoMine includes a specific section (*Cost indexes and metal prices*) in their costmine *Mining Cost Service*, which is periodically updated. The U.S. Bureau of Labor Statistics (BLS) provides the *Consumer Price Index* (CPI) and the *Producer Price Indexes* (PPI). For all sources, the most recent indexes are usually listed as Preliminary (P), and are subject to updates up to four months after initial publication.

I go into a lot more detail (much more than most readers would care about), including tables with indexes from 2013-present, in Appendix B.

In the following sections I provide an overview of each index, and the current update index to apply to the cost models.

Mining Cost Service

As mentioned previously, *Mining Cost Service* (MCS) publishes indexes for mining cost estimation. They are found in the section *Cost indexes and metal prices,* Table 5. Mining Cost Service (MCS) Indexes - United States. Categories include surface mine, underground mine, mill; with an index for both capital cost and operating cost under each category (base year 2020=100).

This is a handbook of underground mining models, based on 2019 US dollars, so we will use the appropriate underground mine indexes.

Operating Cost (OC)

$$\boldsymbol{OC_{2022}} = OC_{2019}\left(\frac{I_{2022}}{I_{2019}}\right) = OC_{2019}\left(\frac{122.3}{100.1}\right) = \boldsymbol{OC_{2019}(1.22)}$$

Where OC_{2022} = operating cost in 2022 dollars,
OC_{2019} = operating cost in 2019 dollars (base case for cost models),
I_{2022} = 122.3 = 2022 MCS index value for underground mining operating costs,
I_{2019} = 100.1 = 2019 MCS index value for underground mining operating costs.

Capital Cost (CC)

$$\boldsymbol{CC_{2022}} = CC_{2019}\left(\frac{I_{2022}}{I_{2019}}\right) = CC_{2019}\left(\frac{123.2}{98.6}\right) = \boldsymbol{CC_{2019}(1.25)}$$

Where CC_{2022} = capital cost in 2022 dollars,
CC_{2019} = capital cost in 2019 dollars (base case for cost models),
I_{2022} = 123.2 = 2022 MCS index value for underground mining capital costs,
I_{2019} = 98.6 = 2019 MCS index value for underground mining capital costs.

An example cost calculation integrating these factors is found in Appendix A.

[Thanks to Jennifer Leinart, President, InfoMine USA, Inc., for permission to use these indexes in this section and the Appendix]

Consumer Price Index (CPI)

"The **Consumer Price Index (CPI)** is a measure of the average change over time in the prices paid by urban consumers for a market basket of consumer goods and services" (Bureau of Labor Statistics–Consumer Price Index https://www.bls.gov/cpi/). The CPI is the most common index used to calculate inflation numbers. To find the most current index, and historical indexes, go to CPI main page, then CPI Data/Databases/ https://www.bls.gov/cpi/data.htm:

- All Urban Consumers (Current Series), (Consumer Price Index - CPI)
- Top Picks/U.S. city average, All items - CUUR0000SA0 [Retrieve Data]

An example of the data table with monthly CPI is included in Appendix B. The user is also given the option to change the output for different dates, include annual averages, and graph results. In the data tables CPI is designated as CPI-U (for all urban consumers).

The base period for the U.S. CPI is: 1982-1984=100.

The most current CPI available at the time of this writing is April 2023 (P).

$$\boldsymbol{C_{2023\ Apr}} = C_{2019}\left(\frac{CPI_{2023\ Apr}}{CPI_{2019}}\right) = C_{2019}\left(\frac{303.4}{255.7}\right) = \boldsymbol{C_{2019}(1.19)}$$

Where $C_{2023\ Apr}$ = Cost in 2023 April dollars,

C_{2019} = Cost in 2019 dollars (base case for cost models),

$CPI_{2023\ Apr}$ = 303.4 = CPI index value for April 2023 (P),

CPI_{2019} = 255.7 = CPI index value for 2019.

Producer Price Index (PPI)

"The Producer Price Index (PPI) program measures the average change over time in the selling prices received by domestic producers for their output. The prices included in the PPI are from the first commercial transaction for many products and some services" (Bureau of Labor Statistics–Producer Price Indexes https://www.bls.gov/ppi/).

To find the most current index, and historical indexes, go to PPI main page, then PPI Data/Databases/ https://www.bls.gov/ppi/databases/:

- Industry Data, (Producer Price Index - PPI)
- Top Picks/ Total manufacturing industries - PCUOMFG--OMFG-- [Retrieve Data]

An example of the data table with monthly PPI is included in Appendix B. The user is also given the option to change the output for different dates, include annual averages, and graph results.

The base period for the U.S. PPI is: 1984 December=100.

The most current PPI available at the time of this writing is April 2023 (P).

$$\boldsymbol{C_{2023\ Apr}} = C_{2019}\left(\frac{PPI_{2023\ Apr}}{PPI_{2019}}\right) = C_{2019}\left(\frac{248.9}{196.8}\right) = \boldsymbol{C_{2019}(1.26)}$$

Where $C_{2023\ Apr}$ = Cost in 2023 April dollars,

C_{2019} = Cost in 2019 dollars (base case for cost models),

$PPI_{2023\ Apr}$ = 248.9 = PPI index value for April 2023 (P),

PPI_{2019} = 196.8 = PPI index value for 2019.

BLOCK CAVING MINING COST MODEL

Overview
Block caving is a low cost, high production mining method. This method requires a lot of preproduction development, after which caving is induced. The orebody caves by itself.

A typical development sequence includes a main lower haulage level, an intermediate extraction level, and an undercut level where the caving of the ore begins. Long hole drilling and blasting in the undercut level begins the caving process.

Characteristics
- Orebody massive both vertically and horizontally
- Ore that will easily break into manageable size
- Large, disseminated deposits too deep for open pit
- Most commonly low grade copper or molybdenum
- Ore homogeneous; sorting not possible

Advantages
- High productivity
- Low mining cost (least costly underground method)
- High production rate
- High recovery (about 90-100%)
- After development of stope, production by caving (no drilling and blasting)
- High mechanization
- Safe–operator never under unsupported back
- Low operating cost per ton
- Little exposure to hazardous conditions
- Ventilation satisfactory

Disadvantages
- Subsidence on surface common
- Complicated, extensive, & expensive development
- Inflexible mining plan
- Draw control is critical
- Dilution: can be high (10-25%)
- Hazardous dealing with hangups, risk of air blast

(Atlas Copco, 2007, p. 37; Atlas Copco, 2014, p. 106-110; Brannon et al, 2011, p. 1437-1451; Hartman & Mutmansky, 2002, p. 420-433; Stebbins, 2019)

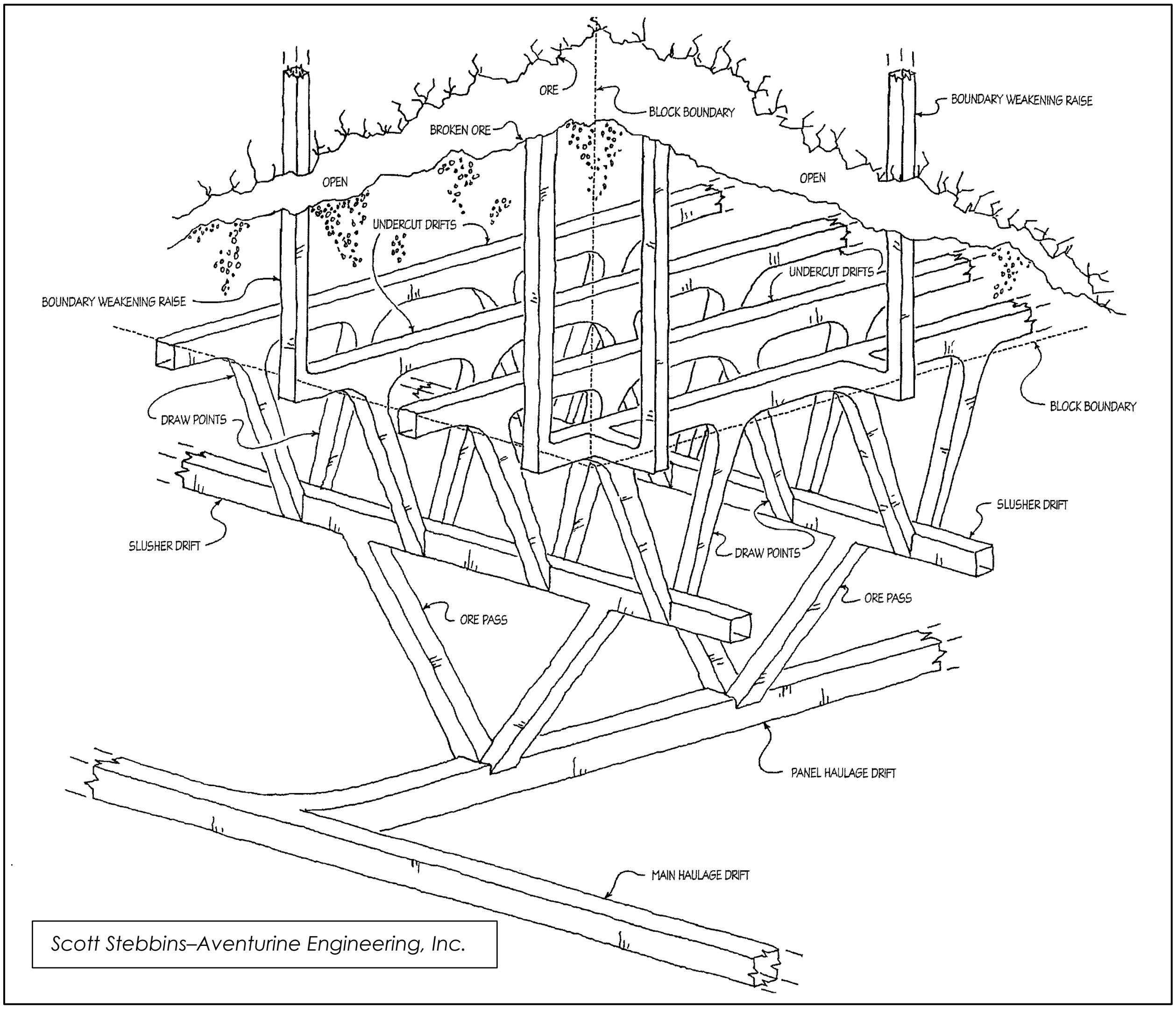


Figure 1. Block Caving Model

Block Caving Model—Adit Entry

For the adit entry model, all production is above a main adit. Haulage from the stopes is by LHD, followed by articulated trucks to the surface. Secondary access is through a ventilation raise.

Table 3. Block Caving Model—Adit Entry *(20,000-45,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 0.339(X)^{0.176}$
Supplies	$OC_S = 115(X)^{-0.479}$
Hourly Labor	$OC_L = 120(X)^{-0.351}$
Administration	$OC_A = 80.3(X)^{-0.356}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 19{,}200(X)^{0.693}$
Preproduction Underground Excavation	$CC_{PE} = 12.7(X)^{1.45}$
Surface Facilities	$CC_{SF} = 187{,}400(X)^{0.442}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (17% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.17)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(61 days)	$CC_{WC} = (OC_T)(X)(61)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

Block Caving Model—Shaft Entry

For the shaft entry model, access is by one or two shafts (depending on production capacity). Haulage from the stopes to the ore passes is by LHD. Secondary access is through a ventilation raise.

Table 4. Block Caving Model—Shaft Entry *(20,000-45,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 0.442(X)^{0.180}$
Supplies	$OC_S = 111(X)^{-0.475}$
Hourly Labor	$OC_L = 150(X)^{-0.368}$
Administration	$OC_A = 79.9(X)^{-0.355}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 31{,}600(X)^{0.700}$
Preproduction Underground Excavation	$CC_{PE} = 194(X)^{1.20}$
Surface Facilities	$CC_{SF} = 114{,}900(X)^{0.488}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (17% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.17)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(61 days)	$CC_{WC} = (OC_T)(X)(61)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

CUT & FILL (MECHANIZED) MINING COST MODEL

Variations
Drift & fill, Paste & fill

Overview
Mechanized cut & fill is a versatile mining method characterized by the use of fill to provide support in the stope. The ore is extracted in horizontal slices and replaced with fill. *Overhand* cut & fill is the most common approach, where the initial cut is at the bottom of the stope, and mining progresses up the stope with subsequent slices. The roof of the stope capable of support with rock bolts. *Underhand* cut & fill begins at the top of the stope, and progressively works down to the bottom of the stope. This requires the fill to be precisely engineered to provide a safe roof over the miners, and consequently tends to be a more expensive approach. The underhand approach is usually only used in rock with significant support issues.

The cost model is based on a steeply-dipping vein, 3.5-4.5 m wide. Stoping includes drilling and blasting using jumbo drills, ore collection and haulage by LHD, sand filling. A secondary access ramp/vent raise provides additional access to the surface.

This is a high-cost method typically used in high-grade precious metal mines. It is best suited for steeply-dipping orebodies with narrow widths and poor support characteristics.

Characteristics
- Versatile, can be used for irregularly-shaped orebodies
- Mobile equipment
- Fill provides support
- Selective
- Ore extracted in horizontal slices, opening replaced with fill
- Often used in orebodies that are steep and narrow

Advantages
- Moderate productivity
- Moderate production rate
- Good recovery (90-100%)
- Dilution: low (5-10%)
- Suitable to mechanization
- Safety–operator and machine in the stope, exposed to working face
- Same equipment can be used for development and in stope
- Use of fill reduces amount of surface waste

Disadvantages

- Fairly high mining cost
- Filling operations add cost and increase cycle time
- Stope access for mechanized equipment
- More labor-intensive than most methods; requires skilled labor

(Atlas Copco, 2007, p. 33-37; Atlas Copco, 2014, p. 40-45, 118-119; Hartman & Mutmansky, 2002, p. 365-372; Stebbins, 2019; Stephan, 2011, p. 1365-1373)

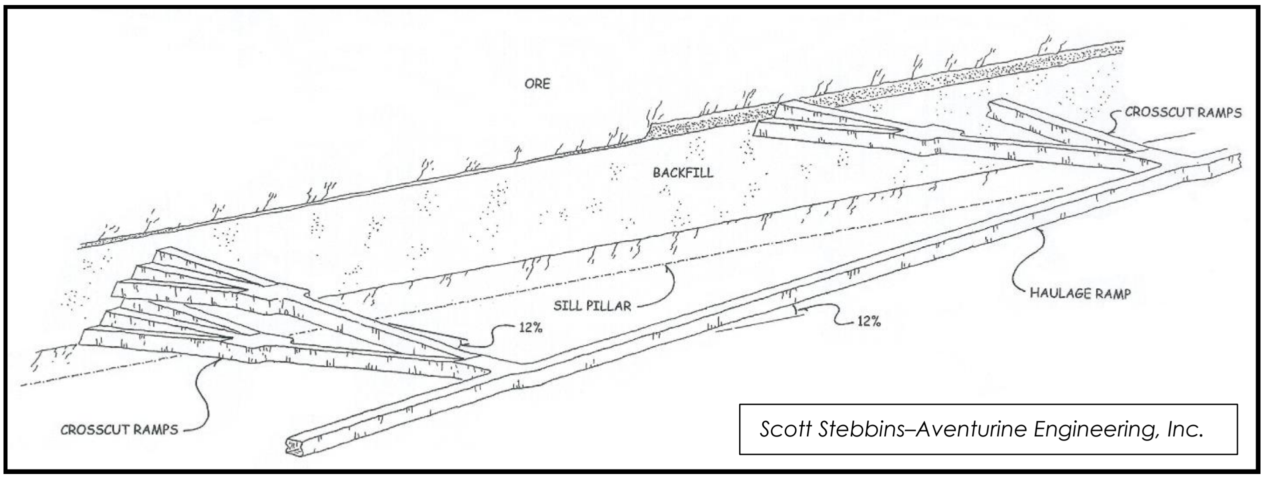


Figure 2. Cut & Fill (Mechanized) Model

Cut & Fill (Mechanized) Model—Adit Entry

For the adit entry model, all production is above a main adit. Haulage from the stopes and to the surface is by LHD. Secondary access is through a ventilation raise.

Table 5. Cut & Fill (Mechanized) Model—Adit Entry *(200-2,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 1.82(X)^{0.107}$
Supplies	$OC_S = 45.5(X)^{-0.139}$
Hourly Labor	$OC_L = 399(X)^{-0.457}$
Administration	$OC_A = 408(X)^{-0.519}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 2{,}256{,}000(X)^{0.321}$
Preproduction Underground Excavation	$CC_{PE} = 88{,}800(X)^{0.612}$
Surface Facilities	$CC_{SF} = 371{,}300(X)^{0.398}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

Cut & Fill (Mechanized) Model—Shaft Entry

For the shaft entry model, access is by one or two shafts (depending on production capacity). Haulage from the stopes to the ore passes is by LHD. Secondary access is through a ventilation raise.

Table 6. Cut & Fill (Mechanized) Model—Shaft Entry *(200-2,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 17.9(X)^{-0.180}$
Supplies	$OC_S = 43.9(X)^{-0.132}$
Hourly Labor	$OC_L = 404(X)^{-0.452}$
Administration	$OC_A = 388(X)^{-0.510}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 4{,}572{,}000(X)^{0.242}$
Preproduction Underground Excavation	$CC_{PE} = 619{,}400(X)^{0.402}$
Surface Facilities	$CC_{SF} = 361{,}000(X)^{0.398}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

CUT & FILL (TRADITIONAL) MINING COST MODEL

Variations
Drift & fill, Paste & fill

Overview
Traditional cut & fill is a versatile mining method characterized by the use of fill to provide support in the stope. This method uses jackleg drills in the stope, as opposed to jumbos used in mechanized cut & fill. The ore is extracted in horizontal slices and replaced with fill. *Overhand* cut & fill is the most common approach, where the initial cut is at the bottom of the stope, and mining progresses up the stope with subsequent slices. The roof of the stope capable of support with rock bolts. *Underhand* cut & fill begins at the top of the stope, and progressively works down to the bottom of the stope. This requires the fill to be precisely engineered to provide a safe roof over the miners, and consequently tends to be a more expensive approach. The underhand approach is usually only used in rock with significant support issues.

The cost model for traditional cut & fill is based on a steeply-dipping vein, 2.5-3.5 m wide. Stoping includes drilling and blasting using jackleg drills, slushing to ore chutes, and sand filling. Ore is transported from the stope using diesel locomotives. A secondary access ramp/vent raise provides additional access to the surface.

This is a high-cost method typically used in high-grade precious metal mines. It is best suited for steeply-dipping orebodies with narrow widths and poor support characteristics.

Characteristics
- Versatile, can be used for irregularly-shaped orebodies
- Mobile equipment
- Fill provides support
- Selective
- Ore extracted in horizontal slices, opening replaced with fill
- Often used in orebodies that are steep and narrow

Advantages
- Moderate productivity
- Moderate production rate
- Good recovery (90-100%)
- Dilution: low (5-10%)
- Suitable to mechanization
- Safety–operator and machine in the stope, exposed to working face
- Use of fill reduces amount of surface waste

Disadvantages

- Fairly high mining cost
- Filling operations add cost and increase cycle time
- Stope access for mechanized equipment
- More labor-intensive than most methods; requires skilled labor

(Atlas Copco, 2007, p. 33-37; Atlas Copco, 2014, p. 40-45, 118-119; Hartman & Mutmansky, 2002, p. 365-372; Stebbins, 2019; Stephan, 2011, p. 1365-1373)

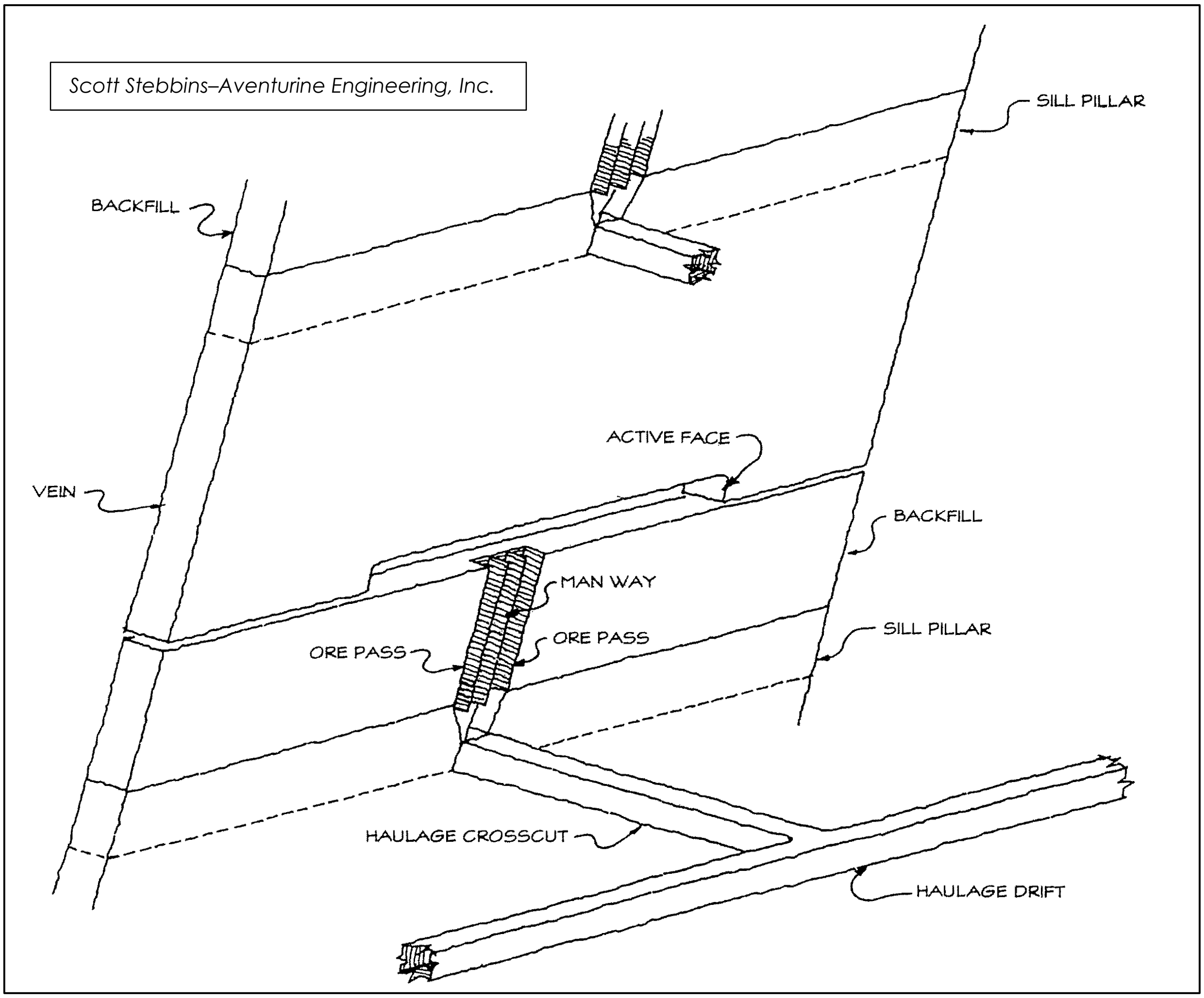


Figure 3. Cut & Fill (Traditional) Model

Cut & Fill (Traditional) Model—Adit Entry

For the adit entry model, all production is above a main rail haulage adit. Haulage from the stopes and to the surface is by diesel locomotive. Secondary access is through a ventilation raise.

Table 7. Cut & Fill (Traditional) Model—Adit Entry *(200-2,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 6.71(X)^{-0.238}$
Supplies	$OC_S = 31.0(X)^{-0.0392}$
Hourly Labor	$OC_L = 821(X)^{-0.465}$
Administration	$OC_A = 427(X)^{-0.503}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 1{,}511{,}800(X)^{0.295}$
Preproduction Underground Excavation	$CC_{PE} = 114{,}600(X)^{0.585}$
Surface Facilities	$CC_{SF} = 609{,}300(X)^{0.329}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

Cut & Fill (Traditional) Model—Shaft Entry

For the shaft entry model, access is by one or two shafts (depending on production capacity). Haulage from the stopes to the ore passes is by rail. Secondary access is through a ventilation raise.

Table 8. Cut & Fill (Traditional) Model—Shaft Entry *(200-2,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 34.3(X)^{-0.341}$
Supplies	$OC_S = 31.4(X)^{-0.0415}$
Hourly Labor	$OC_L = 851(X)^{-0.467}$
Administration	$OC_A = 427(X)^{-0.503}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 2,939,400(X)^{0.230}$
Preproduction Underground Excavation	$CC_{PE} = 671,500(X)^{0.410}$
Surface Facilities	$CC_{SF} = 590,500(X)^{0.333}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

END SLICE MINING COST MODEL

Alternative names
Long-hole/Bighole/Blasthole Stoping, End Slicing

Overview
The end slice mining method is used where the orebody is steeply dipping (exceeds 50°). Stoping includes driving a top sill, a bottom sill (mucking drift), and a slot raise. Stoping progresses by end slice drilling and blasting using large in-the-hole (ITH) blasthole drills, followed by sand filling. Haulage drifts provide access to the stope. Ore is removed using LHDs (often remotely operated).

This is a versatile and productive method used primarily for large-scale mining. By using larger drills with larger drill hole diameters, longer drill holes are feasible, eliminating the need for sublevels.

Characteristics

- Eliminates intermediate sublevel
- In-the-hole (ITH) hammer drills
- Hole dia. 75-165 mm
- Hole length typically 30-60 m (max. length 100 m)
- Blasthole burden & toe spacing typically 3 x 3 m
- Single center drive for stope width < 15 m

Advantages

- Moderately high productivity
- Moderate mining cost
- Moderate to high production rate
- Fair recovery (about 75%)
- Dilution: moderate (about 20%)
- Suitable to mechanization, not labor-intensive
- Safe–operator never under unsupported back
- Low breakage cost; fairly low handling costs
- Versatile for variety of roof conditions
- Little exposure to hazardous conditions
- Easy to ventilate

Disadvantages

- Fairly complicated & expensive development
- Inflexible in mining plan
- Long-hole drilling requires precision
- Large blasts can cause significant vibration, air blast, & structural damage

(Atlas Copco, 2007, p. 33-37; Atlas Copco, 2014, p. 113-114; Hartman & Mutmansky, 2002, p. 344-350; Pakalnis, 2011, p. 1355-1363; Stebbins, 2019)

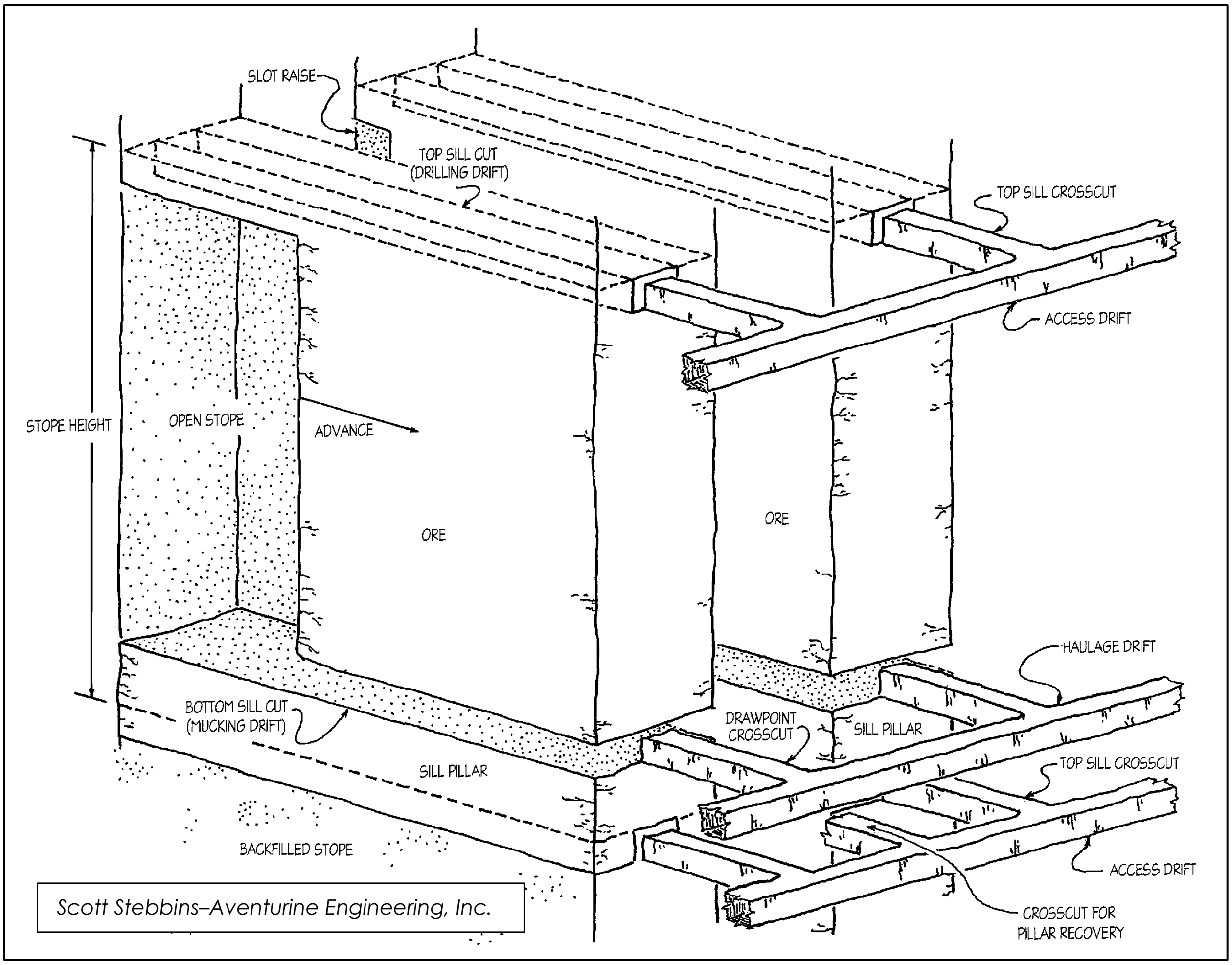


Figure 4. End Slice Model

End Slice Model—Adit Entry

For the adit entry model, all production is above a main adit. Haulage from the stopes is by LHD, followed by articulated trucks to the surface. Secondary access is through a ventilation raise.

Table 9. End Slice Model—Adit Entry *(800-4,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 0.261(X)^{0.241}$
Supplies	$OC_S = 6.77(X)^{0.0232}$
Hourly Labor	$OC_L = 350(X)^{-0.452}$
Administration	$OC_A = 320(X)^{-0.485}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 899{,}700(X)^{0.388}$
Preproduction Underground Excavation	$CC_{PE} = 1{,}110(X)^{1.154}$
Surface Facilities	$CC_{SF} = 306{,}300(X)^{0.398}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (15% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.15)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

End Slice Model—Shaft Entry

For the shaft entry model, access is by one or two shafts (depending on production capacity). Haulage from the stopes to the ore passes is by LHD. Secondary access is through a ventilation raise.

Table 10. End Slice Model—Shaft Entry *(800-4,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 2.62(X)^{0.0202}$
Supplies	$OC_S = 6.77(X)^{0.0232}$
Hourly Labor	$OC_L = 354(X)^{-0.445}$
Administration	$OC_A = 298(X)^{-0.475}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 932{,}200(X)^{0.418}$
Preproduction Underground Excavation	$CC_{PE} = 2{,}890(X)^{1.127}$
Surface Facilities	$CC_{SF} = 314{,}900(X)^{0.392}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (15% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.15)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

ROOM & PILLAR MINING COST MODEL

Variations
Stope & pillar, Post pillar, Step room & pillar

Overview
The room & pillar method is commonly used for mining deposits that are flat, bedded, and of limited thickness. The ore is recovered in open stopes, supported by pillars of ore arranged in regular patterns.

The cost model is based on a flat-lying bedded deposit with extensive areal dimensions, 2.5-10 m thick. Stoping follows a conventional room-and-pillar pattern using horizontal drill jumbos. Ore is collected at the face using LHDs and loaded into articulated haul trucks. A secondary access ramp/vent raise provides additional access to the surface.

Characteristics
- Tabular, flat, lens-shaped orebodies
- Mobile equipment
- Pillar support, supplemented with rock bolts
- Ore grade typically low to moderate

Advantages
- Moderate to high productivity
- Moderate mining cost
- Fair recovery (60-80%), depending on amount of pillar recovery
- Dilution: low (10-20%)
- Suitable to mechanization
- Same equipment can be used for development and in stope
- Multiple working faces possible
- Relatively little preproduction development

Disadvantages
- Ground control requires constant maintenance
- Ore left in pillars reduces recovery factor
- Large capital investment for mechanized equipment
- Multiple openings complicate ventilation
- Recovery of pillars (if feasible) difficult, present safety challenges

(Atlas Copco, 2007, p. 39-41; Atlas Copco, 2014, p. 120-123; Bullock, 2011b, p. 1327-1338; Hartman & Mutmansky, 2002, p. 323-338; Stebbins, 2019)

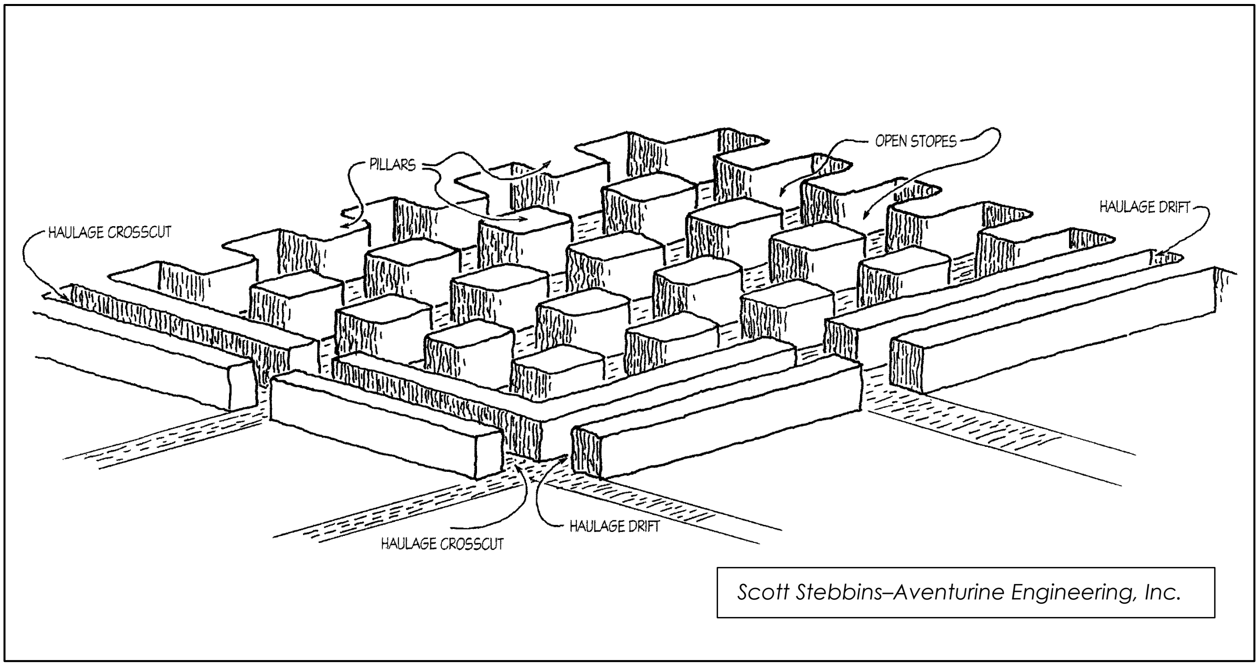


Figure 5. Room & Pillar Model

Room & Pillar Model—Adit Entry

For the adit entry model, access is by two adits. Ore is collected at the face using LHDs and loaded into articulated haul trucks. Up to 10,000 t/d capacity, the trucks haul the ore to the surface. For production capacity greater than 10,000 t/d, the ore is hauled to a centralized crushing station, then to the surface on a belt conveyor. Secondary access is through a ventilation raise.

Table 11. Room & Pillar—Adit Entry *(1,200-14,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 0.720(X)^{0.0919}$
Supplies	$OC_S = 94.4(X)^{-0.327}$
Hourly Labor	$OC_L = 442(X)^{-0.443}$
Administration	$OC_A = 417(X)^{-0.508}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 584{,}500(X)^{0.497}$
Preproduction Underground Excavation	$CC_{PE} = 193{,}600(X)^{0.504}$
Surface Facilities	$CC_{SF} = 281{,}700(X)^{0.423}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(58 days)	$CC_{WC} = (OC_T)(X)(58)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

Room & Pillar Model—Shaft Entry

For the shaft entry model, access is by two shafts and a secondary access/ventilation raise. Ore is collected at the face using LHDs and loaded into articulated haul trucks for transport to a shaft.

Table 12. Room & Pillar Model—Shaft Entry *(1,200-14,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 5.84(X)^{-0.0766}$
Supplies	$OC_S = 94.2(X)^{-0.326}$
Hourly Labor	$OC_L = 606(X)^{-0.475}$
Administration	$OC_A = 469(X)^{-0.524}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 1{,}432{,}700(X)^{0.417}$
Preproduction Underground Excavation	$CC_{PE} = 135{,}000(X)^{0.584}$
Surface Facilities	$CC_{SF} = 271{,}800(X)^{0.423}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(58 days)	$CC_{WC} = (OC_T)(X)(58)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

SHRINKAGE STOPE MINING COST MODEL

Variations
Inclined shrinkage, Rill shrinkage, Long-hole shrinkage

Overview
Shrinkage stoping is a vertical overhand mining method used in steeply-dipping narrow ore bodies with regular boundaries. As mining progresses, most of the broken ore remains in the stope to provide a working floor for the miners and wall support. Once the stope is completed the remaining ore is drawn down.

This cost model is based on a steeply-dipping vein, 2.5-3.5 m wide. Stoping includes drilling and blasting using stoper and jackleg drills, drawing ore to the level below, with no sand filling. Ore is transported from the stope using diesel locomotives. A secondary access ramp/vent raise provides additional access to the surface.

This is a labor-intensive, relatively high-cost method typically used in high-grade precious metal mines. It is best suited for steeply-dipping orebodies with narrow widths.

Characteristics
- Ore strong and non-oxidizing, should not pack or stick together
- Host rock moderately strong
- Ore extracted in horizontal slices, overhand from the bottom and advancing up
- Broken ore provides a working floor and wall support until stope mining completed
- 60-70% of ore remains in stope until completion
- Often used in orebodies that are steep and narrow

Advantages
- Adaptable to small veins
- Ore drawn down by gravity
- Minimal ground support required
- Does not require backfill
- Relatively low capital investment
- Simple method
- Stope development uncomplicated and minimal
- Fairly good recovery (75-95%)
- Dilution: low (5-20%)

Disadvantages

- Labor intensive
- Rarely amenable to mechanization
- Low to moderate productivity
- Fairly high mining cost
- Only 30-40% of ore available for extraction until stope complete
- Uneven footing—miners work on broken ore floor
- Possible ore oxidation, packing, and spontaneous combustion
- Ore hang-ups in stope serious safety concern
- Risk of losing stope during ore drawdown

(Atlas Copco, 2007, p. 33-37; Atlas Copco, 2014, p. 112-116; Haptonstall, 2011, p. 1347-1353; Hartman & Mutmansky, 2002, p. 338-344; Stebbins, 2019)

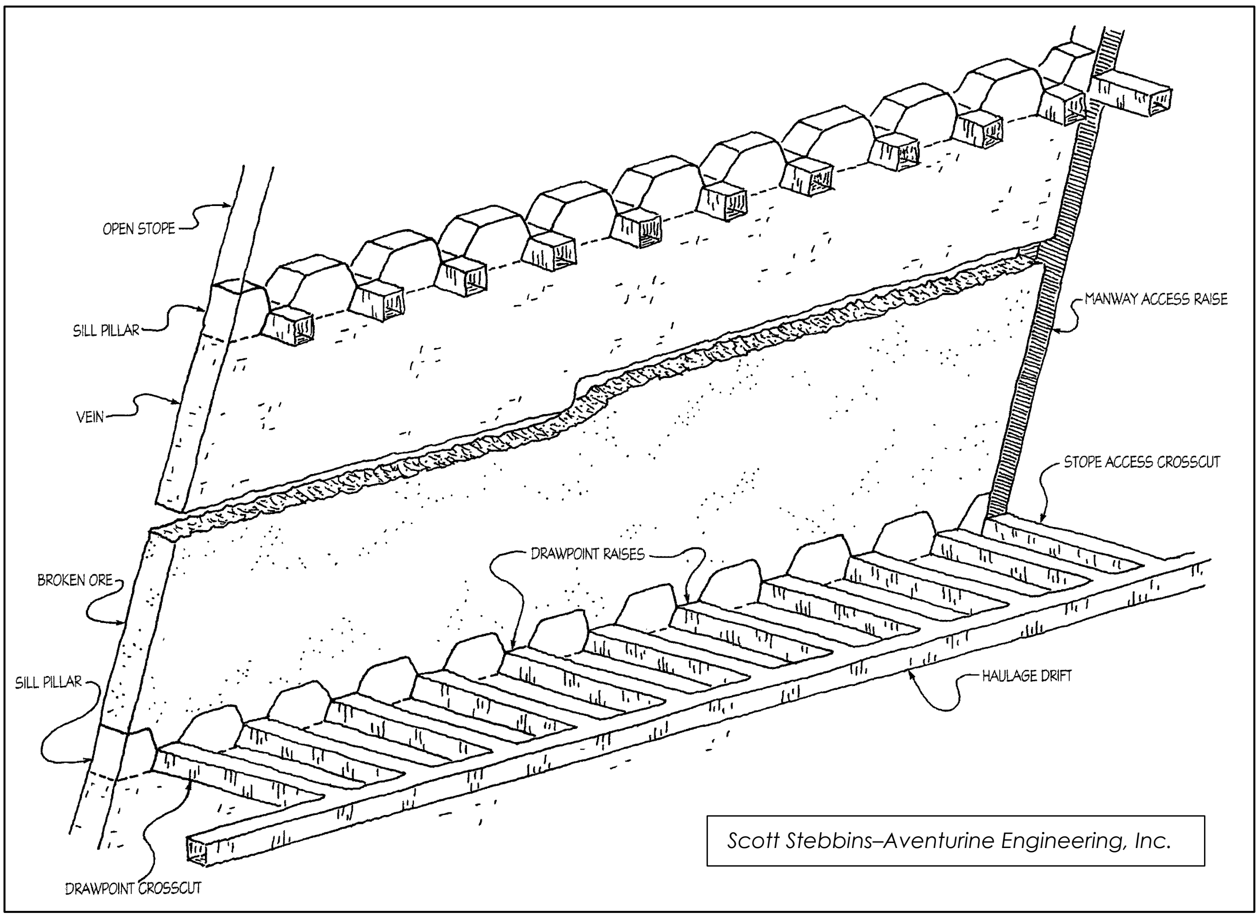


Figure 6. Shrinkage Stope Model

Shrinkage Stope Model—Adit Entry

For the adit entry model, all production is above a main rail haulage adit. Haulage from the stopes and to the surface is by diesel locomotive. Secondary access is through a ventilation raise.

Table 13. Shrinkage Stope Model—Adit Entry *(200-2,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 4.86(X)^{-0.204}$
Supplies	$OC_S = 28.1(X)^{-0.0679}$
Hourly Labor	$OC_L = 393(X)^{-0.371}$
Administration	$OC_A = 405(X)^{-0.504}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 916{,}600(X)^{0.378}$
Preproduction Underground Excavation	$CC_{PE} = 110{,}100(X)^{0.598}$
Surface Facilities	$CC_{SF} = 476{,}300(X)^{0.357}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

Shrinkage Stope Model—Shaft Entry

For the shaft entry model, access is by one or two shafts (depending on production capacity). Haulage from the stopes to the ore passes is by rail. Secondary access is through a ventilation raise.

Table 14. Shrinkage Stope Model—Shaft Entry *(200-2,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 11.1(X)^{-0.179}$
Supplies	$OC_S = 28.3(X)^{-0.0692}$
Hourly Labor	$OC_L = 417(X)^{-0.376}$
Administration	$OC_A = 405(X)^{-0.504}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 1{,}924{,}800(X)^{0.304}$
Preproduction Underground Excavation	$CC_{PE} = 672{,}600(X)^{0.422}$
Surface Facilities	$CC_{SF} = 472{,}600(X)^{0.358}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

SUBLEVEL CAVING MINING COST MODEL

Overview

Sublevel caving is a low cost, high production mining method. All of the ore is drilled and blasted in sublevels. Mining progresses downward. As the ore is extracted, the hanging wall is allowed to cave by itself.

A typical development sequence includes ore passes, access raises, haulage drifts, and ventilation raises. Stoping includes driving production drifts and access crosscuts. Long hole drilling is done in a fan pattern upwards, with blasting the undercut retreating toward the footwall.

Characteristics

- Large orebody with steep dip and continuity at depth
- Ore is drilled and blasted, usually with fan pattern
- Hanging wall needs to fracture and collapse by gravity, caving into stope opening
- Sublevel footwall drifts/ramps need to be stable, may require rockbolting
- Ore homogeneous; sorting not possible

Advantages

- Fairly high productivity
- Moderate mining cost
- High production rate
- After development of stope, production by caving (no drilling and blasting)
- High mechanization
- Somewhat flexible and selective; no pillars required
- Safety and health conditions considered good

Disadvantages

- Subsidence on surface common
- Extensive development, multiple headings to prepare sublevels
- Draw control is critical
- Moderate recovery (75-85%)
- Dilution: can be high (10-40%)
- High development cost

(Atlas Copco, 2007, p. 36-37, 129-131; Atlas Copco, 2014, p. 106-110; Dunstan & Power, 2011, p. 1417-1436; Hartman & Mutmansky, 2002, p. 413-420; Stebbins, 2019)

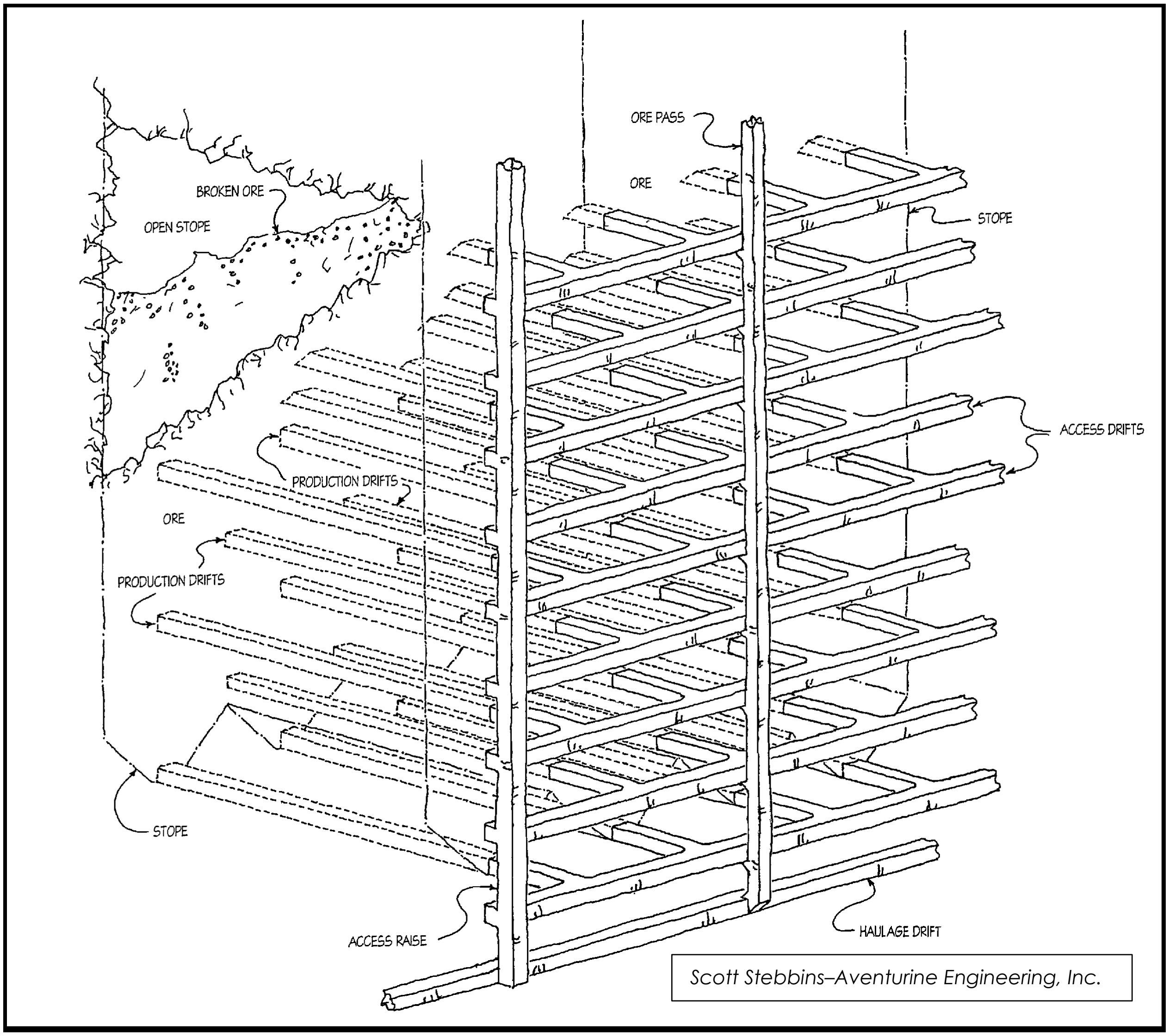


Figure 7. Sublevel Caving Model

Sublevel Caving Model—Adit Entry

For the adit entry model, access is through two to four adits, depending on production capacity. Haulage from the stopes is by LHD, followed by rear-dump trucks to the surface. Secondary access is through a ventilation raise.

Table 15. Sublevel Caving Model—Adit Entry *(4,000-14,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 0.0359(X)^{0.426}$
Supplies	$OC_S = 20.4(X)^{-0.0982}$
Hourly Labor	$OC_L = 320(X)^{-0.426}$
Administration	$OC_A = 284(X)^{-0.472}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 58{,}600(X)^{0.734}$
Preproduction Underground Excavation	$CC_{PE} = 183(X)^{1.32}$
Surface Facilities	$CC_{SF} = 110{,}200(X)^{0.526}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (17% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.17)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(58 days)	$CC_{WC} = (OC_T)(X)(58)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

Sublevel Caving Model—Shaft Entry

For the shaft entry model, access is by two to four shafts (depending on production capacity). Haulage from the stopes to the ore passes is by LHD. Secondary access is through a ventilation raise.

Table 16. Sublevel Caving Model—Shaft Entry *(4,000-14,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 3.36(X)^{0.00305}$
Supplies	$OC_S = 20.4(X)^{-0.0982}$
Hourly Labor	$OC_L = 508(X)^{-0.472}$
Administration	$OC_A = 326(X)^{-0.486}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 209{,}000(X)^{0.626}$
Preproduction Underground Excavation	$CC_{PE} = 18{,}200(X)^{0.880}$
Surface Facilities	$CC_{SF} = 202{,}800(X)^{0.453}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (17% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.17)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(58 days)	$CC_{WC} = (OC_T)(X)(58)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

SUBLEVEL LONGHOLE MINING COST MODEL

Alternative names
Sublevel stoping, Sublevel open stoping

Variations
Transverse stoping, Vertical Crater Retreat (VCR), Vein/Alimak mining, Rill/Longitudinal/Avoca mining

Overview
Sublevel stoping is used where the orebody is steeply dipping (exceeds 50°). Stoping includes driving a top sill, a bottom sill (mucking drift), and a slot raise. Stoping includes excavating haulage cross cuts and draw points at the base of the stope and drill access crosscuts into the stope, followed by ring drilling using longhole drill jumbos, blasting, and sand filling. Haulage drifts provide access to the stope. Ore is removed using LHDs followed by articulated rear-dump trucks.

This is a versatile and productive method used primarily for large-scale mining. This method is distinguished from the end slicing model by the presence of one or more sublevels, smaller diameter drill holes, and shorter hole depths that typically provide more precise drill patterns.

Characteristics
- Moderate to thick orebody width, fairly uniform and large extent
- Sublevels typically 20-30 m apart
- Top hammer drills
- Hole dia. 50-75 mm
- Blasthole burden & toe spacing typically 1.2 x 1.2 m (50-mm blasthole)
- Minimum stope width generally 3-6 m

Advantages
- Moderately high productivity
- Moderate mining cost
- Moderate to high production rate
- Fair recovery (about 75%)
- Dilution: moderate (about 20%)
- Suitable to mechanization, not labor-intensive
- Safe–operator never under unsupported back
- Low breakage cost; fairly low handling costs
- Versatile for variety of roof conditions
- Easy to ventilate

Disadvantages
- Fairly complicated & expensive development
- Inflexible in mining plan
- Long-hole drilling requires precision

(Atlas Copco, 2007, p. 33-37; Atlas Copco, 2014, p. 112-114; Hartman & Mutmansky, 2002, p. 344-350; Pakalnis, 2011, p. 1355-1363; Stebbins, 2019)

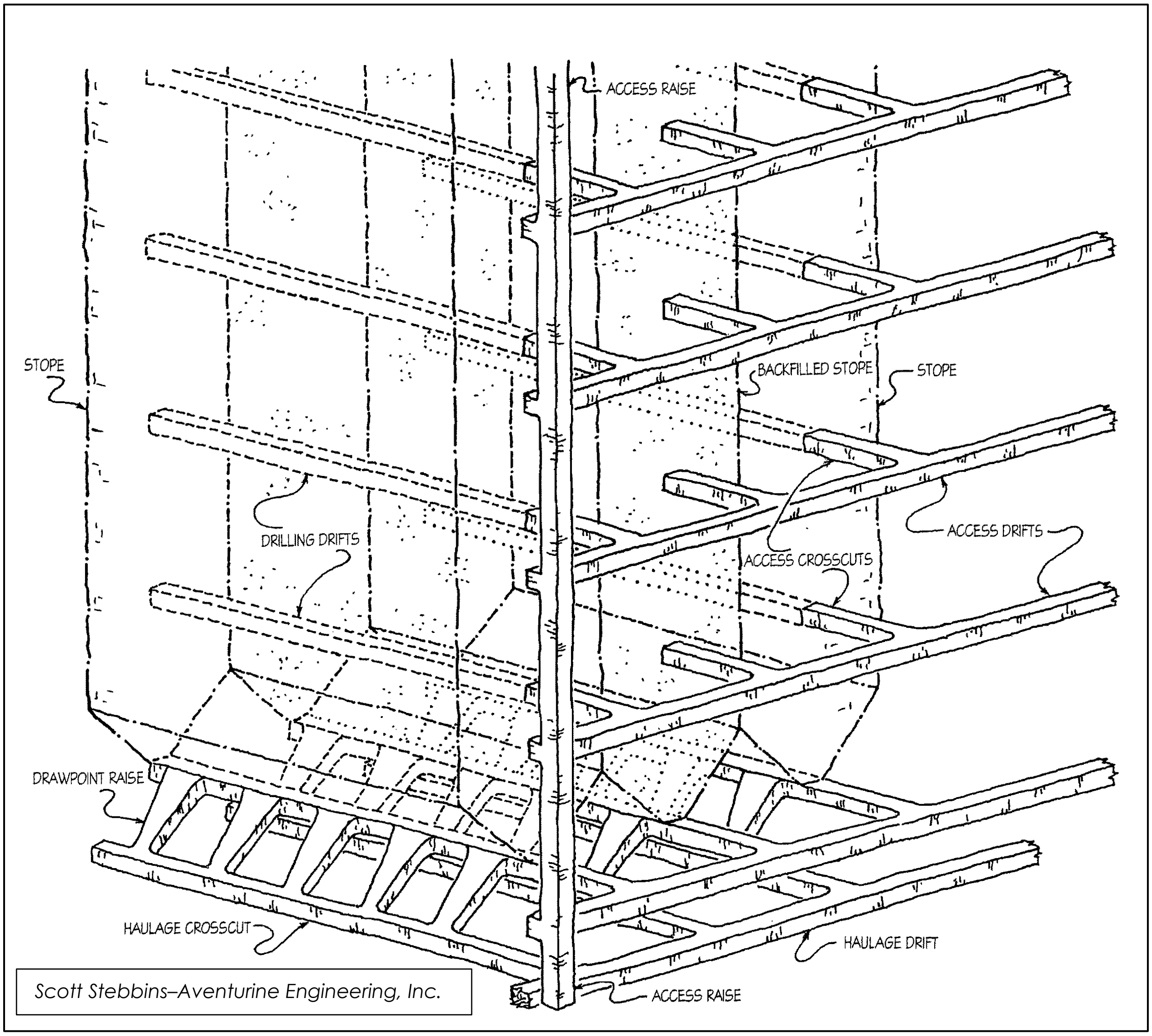


Figure 8. Sublevel Longhole Model

Sublevel Longhole Model—Adit Entry

For the adit entry model, all production is above a main adit. Haulage from the stopes is by LHD, followed by articulated trucks to the surface. Secondary access is through a ventilation raise.

Table 17. Sublevel Longhole Model—Adit Entry *(800-8000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 0.252(X)^{0.235}$
Supplies	$OC_S = 7.15(X)^{0.00254}$
Hourly Labor	$OC_L = 365(X)^{-0.472}$
Administration	$OC_A = 320(X)^{-0.498}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 922{,}600(X)^{0.386}$
Preproduction Underground Excavation	$CC_{PE} = 3{,}600(X)^{0.977}$
Surface Facilities	$CC_{SF} = 249{,}600(X)^{0.413}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (17% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.17)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

Sublevel Longhole Model—Shaft Entry

For the shaft entry model, access is by one or two shafts (depending on production capacity). Haulage from the stopes to the ore passes is by LHD. Secondary access is through a ventilation raise.

Table 18. Sublevel Longhole Model—Shaft Entry *(800-8,000 t/d)*

Category	Cost Equation (2019 US dollars)
Operating Costs (OC)	
Equipment Operation	$OC_E = 2.81(X)^{0.00303}$
Supplies	$OC_S = 7.14(X)^{0.00246}$
Hourly Labor	$OC_L = 505(X)^{-0.504}$
Administration	$OC_A = 320(X)^{-0.498}$
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A$
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10)$
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D$
Capital Costs (CC)	
Equipment Purchase	$CC_{EP} = 1{,}463{,}700(X)^{0.363}$
Preproduction Underground Excavation	$CC_{PE} = 13{,}100(X)^{0.898}$
Surface Facilities	$CC_{SF} = 302{,}100(X)^{0.384}$
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF}$
Engineering & Management (17% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.17)$
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20)$
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52)$
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC}$

X = production capacity of mine in tonnes per day.

Acknowledgements

I would like to thank my employer, Montana Tech, for allowing me to take a sabbatical year to work on this handbook. Thanks also to Al & Nancy for the barn so I had a place to stay in Spokane. Scott and I would both like to thank Jennifer Leinart (President, CostMine) for her encouragement and support.

And we both would like to acknowledge Otto Schumacher, founder of Western Mine Engineering, Inc., and developer of *Mining Cost Service* (which eventually grew into the current CostMine) for his unmatched contributions to the art of mine cost estimating. Otto was also a great mentor to Scott and me, teaching us both about cost estimating and how to be engineers.

About the Authors

Thomas W. Camm, Ph.D., P.E.

Thomas W. Camm is a Professor of Mining Engineering at Montana Technological University. He is an active member in SME, frequently serving as a session chair and presenter at annual meetings. He has been Chair of the Coal & Energy Division; and received the M&E Distinguished Service Award and AIME Mineral Economics Award. Dr. Camm earned a B.S. and a Ph.D. in Mining Engineering from the University of Idaho, and a Master of Engineering Management degree from Washington State University. He studied leadership in the Gonzaga University doctoral program, and is a licensed professional mining engineer in the state of Washington.
Email: tcamm@mtech.edu
Faculty page: https://www.mtech.edu/mining-engineering/faculty/thomas-camm/index.html
LinkedIn: https://www.linkedin.com/in/thomaswcamm

Scott A. Stebbins, P.E.

Scott, now retired, is the former President of Aventurine Engineering, Inc. He has spent the majority of his 35-year career estimating the capital and operating costs of more than 140 mining and mineral processing projects, and then evaluating their economic potential. He specialized in constructing engineering-based, mathematic cost estimating models that can be used to evaluate a multitude of development scenarios for exploration stage projects. Scott is a licensed professional mining engineer based in Spokane, Washington, USA, and authored the chapters on both surface and underground mine cost estimating for the 2011 edition of the *SME Mining Engineering Handbook*.
Email: aventsherp@aol.com
LinkedIn: https://www.linkedin.com/in/scott-stebbins-2a874080/

REFERENCES

Atlas Copco. (2007). *Mining methods in underground mining* (2nd ed.). Atlas Copco [now Epiroc].

Atlas Copco. (2014). *Underground mining: a global review of methods and practices* (1st ed.). Atlas Copco [now Epiroc].

Blank, L. & Tarquin, A. (2012). *Engineering economy* (7th ed.). McGraw-Hill.

Brannon, C. A., Carlson, G. K., & Casten, T. P. (2011). Block caving [Ch. 13.10]. In P. Darling (Ed.), *SME mining engineering handbook* (3rd ed., Vol. 2, pp. 1437-1451). Society for Mining, Metallurgy, and Exploration.

Bullock, R. L. (2011a, April). Accuracy of feasibility study evaluations would improve accountability. *Mining Engineering, 63*(4), 78-85.

Bullock, R. L. (2011b). Room-and-pillar mining in hard rock [Ch. 13.1]. In P. Darling (Ed.), *SME mining engineering handbook* (3rd ed., Vol. 2, pp. 1327-1338). Society for Mining, Metallurgy, and Exploration.

Bullock, R. L., & Mernitz, S. (Eds.) (2018). *Mineral property evaluation: Handbook for feasibility studies and due diligence*. Society for Mining, Metallurgy, and Exploration.

Bureau of Labor Statistics. (2023, May). *Consumer Price Index*. U.S. Bureau of Labor Statistics. https://www.bls.gov/cpi/

Bureau of Labor Statistics. (2023, May). *Producer Price Indexes*. U.S. Bureau of Labor Statistics. https://www.bls.gov/ppi/

Camm, T. W. (1991). *Simplified cost models for prefeasibility mineral evaluations.* USBM IC 9298. https://digitalcommons.mtech.edu/mine_engr/

Camm, T. W. (1992). *The development of cost models using regression analysis.* Preprint no. 92-48, SME Annual Meeting, Phoenix, AZ.

Camm, T. W. (1993). Engineering analysis methodology for regional economic studies of mineral deposits on federal lands. In J. Elbrond & X. Tang (Eds.), *Proceedings: APCOM XXIV international symposium on the application of computers and operations research in the mineral industries* (Vol. 2, pp. 479-485). CIM: Montreal, Quebec, Canada.

Camm, T. W. (1994, June). Simplified cost models for prefeasibility mineral evaluations. *Mining Engineering, 46*(6), 559-562. [Also published as SME preprint 93-85]

Dominski, T., Kolankowski, B., Marck, A., Pasternak, M., & Shamba, S. (2009). *Estimation of the potential production rate.* Quenn's College Mine Design Wiki. https://minewiki.engineering.queensu.ca/mediawiki/index.php/Estimation_of_the_potential_production_rate

Dunstan, G., & Power, G. (2011). Sublevel Caving [Ch. 13.9]. In P. Darling (Ed.), *SME mining engineering handbook* (3rd ed., Vol. 2, pp. 1417-1436). Society for Mining, Metallurgy, and Exploration.

Haptonstall, J. (2011). Shrinkage stoping [Ch. 13.3]. In P. Darling (Ed.), *SME mining engineering handbook* (3rd ed., Vol. 2, pp. 1347-1353). Society for Mining, Metallurgy, and Exploration.

Hartman, H. L., & Mutmansky, J. M. (2002). *Introductory mining engineering* (2nd ed.). John Wiley & Sons.

InfoMine. (2023, January). *Cost Indexes and metal prices* [section in costmine: Mining Cost Service, periodically updated]. InfoMine USA. https://www.costmine.com/mining-cost-service/

Long, K.R. (2009, March). A test and re-estimation of Taylor's empirical capacity–reserve relationship. *Natural Resources Research, 18*(1), 57-63. https://link.springer.com/article/10.1007/s11053-009-9088-y

Pakalnis, R. T., & Hughes, P. B. (2011). Sublevel stoping [Ch. 13.4]. In P. Darling (Ed.), *SME mining engineering handbook* (3rd ed., Vol. 2, pp. 1355-1363). Society for Mining, Metallurgy, and Exploration.

Stebbins, S. A. (2011). Cost estimating for underground mines [Ch. 4.8]. In P. Darling (Ed.), *SME mining engineering handbook* (3rd ed., Vol. 1, pp. 263-279). Society for Mining, Metallurgy, and Exploration.

Stebbins, S. A. (2019). *SHERPA for underground mines* (version 3.19). Spokane, WA: CostMine USA. https://www.costmine.com/software/sherpa-underground/

Stebbins, S. A. (2020). *Underground mine models* [Section CM–Cost models, Mine Costing Service]. Spokane, WA: CostMine USA. https://www.costmine.com/mining-cost-service/

Stebbins, S. A., & Schumacher, O. L. (2001). Cost estimating for underground mines [Ch. 4]. In W. Hustrulid & R. Bullock (Eds.), *Underground mining methods: Engineering fundamentals and international case studies* (pp. 49-72). Society for Mining, Metallurgy, and Exploration.

Stephan, G. (2011). Cut-and-fill mining [Ch. 13.5]. In P. Darling (Ed.), *SME mining engineering handbook* (3rd ed., Vol. 2, pp. 1365-1373). Society for Mining, Metallurgy, and Exploration.

STRAAM. (1977). *Capital and operating cost estimating system handbook* [USBM OFR 10-78]. STRAAM Engineers, Inc.

Taylor, H. K. (1978). Mine valuation and feasibility studies. In J. Hoskins & W. Green (Eds.), *Mineral Industry Costs* (2nd ed., pp. 1-17). Northwest Mining Association.

U.S. Bureau of Mines. (1987a). *Bureau of Mines cost estimating system handbook, (in two parts), 1. Surface and underground mining* [USBM IC 9142].

U.S. Bureau of Mines. (1987b). *Bureau of Mines cost estimating system handbook, (in two parts), 2. Mineral processing* [USBM IC 9143].

Wellmer, F.-W. (1986). *Economic evaluations in exploration.* Springer-Verlag.

APPENDIX A – Example Cost Calculation

This example problem is based on a mechanized cut-and-fill mine, shaft entry, with 3,000,000 tonnes of reserves.

Mine Life

$$T = (rt)(rf)(1+df) = (3{,}000{,}000)(0.90)(1.05) = \mathbf{2{,}835{,}000}$$

Where T = total tonnage of ore to be mined,
rt = total tonnage of deposit reserve/resource (3,000,000),
rf = recovery factor (0.90, from Table 1),
df = dilution factor (0.05, from Table 1).

The life of the mine can now be calculated using Taylor's rule (Taylor, 1978):

$$L = 0.2(T)^{0.25} = 0.2(2{,}835{,}000)^{0.25} = \mathbf{8.2\ years}$$

Where L = mine life in years.

Production capacity can now be calculated:

$$X = \frac{T}{(L)(dpy)} = \frac{2{,}835{,}000}{(8.2)(312)} = \mathbf{1{,}107\ t/d}$$

Where X = daily production capacity of ore (t/d),
dpy = mine operating days per year (312).

For the cost calculations, round the production capacity to **1,100 t/d**.

Cut & Fill (Mechanized) Model—Shaft Entry

Table 19. Cut & Fill (Mechanized) Model—Shaft Entry *(1,100 t/d)*

Category	Cost Equation (2019 US dollars)	
Operating Costs (OC)		
Equipment Operation	$OC_E = 17.9(1,100)^{-0.180} =$	5.07
Supplies	$OC_S = 43.9(1,100)^{-0.132} =$	17.42
Hourly Labor	$OC_L = 404(1,100)^{-0.452} =$	17.05
Administration	$OC_A = 388(1,100)^{-0.510} =$	10.91
Subtotal	$OC_{SUB} = OC_E + OC_S + OC_L + OC_A =$	50.45
Sundries (10% of subtotal)	$OC_D = OC_{SUB}(0.10) = (50.45)(0.10) =$	5.04
TOTAL OPERATING COST ($/t)	$OC_T = OC_{SUB} + OC_D = 50.45 + 5.04 =$	**55.49**
Capital Costs (CC)		
Equipment Purchase	$CC_{EP} = 4,572,000(1,100)^{0.242} =$	24,895,637
Preproduction Underground Excavation	$CC_{PE} = 619,400(1,100)^{0.402} =$	10,342,155
Surface Facilities	$CC_{SF} = 361,000(1,100)^{0.398} =$	5,861,132
Subtotal	$CC_{SUB} = CC_{EP} + CC_{PE} + CC_{SF} =$	41,098,925
Engineering & Management (13% of subtotal)	$CC_{E\&M} = CC_{SUB}(0.13) = (41,098,925)(0.13) =$	5,342,860
Contingency (20% of subtotal)	$CC_C = CC_{SUB}(0.20) = (41,098,925)(0.20) =$	8,219,785
Working Capital ($/t)(t/d)(52 days)	$CC_{WC} = (OC_T)(X)(52) = (55.49)(1,100)(52) =$	3,174,191
TOTAL CAPITAL COST ($)	$CC_T = CC_{SUB} + CC_{E\&M} + CC_C + CC_{WC} =$	**57,835,761**

X = production capacity of mine = 1,100 tonnes per day.

Cost Indexes

For the example problem, we will use *Mining Cost Service* (MCS) indexes. CPI or PPI may also be used if MCS indexes are unavailable.

This is a handbook of underground mining models, based on 2019 US dollars, so we will use the appropriate underground mine indexes.

Operating Cost (OC)

$$\boldsymbol{OC_{2022}} = OC_{2019}\left(\frac{I_{2022}}{I_{2019}}\right) = OC_{2019}\left(\frac{122.3}{100.1}\right) = \mathbf{55.49(1.22) = 67.80}$$

Where OC_{2022} = operating cost in 2022 dollars,

OC_{2019} = operating cost in 2019 dollars (base case for cost models),

I_{2022} = 122.3 = 2022 MCS index value for underground mining operating costs,

I_{2019} = 100.1 = 2019 MCS index value for underground mining operating costs.

Capital Cost (CC)

$$\boldsymbol{CC_{2022}} = CC_{2019}\left(\frac{I_{2022}}{I_{2019}}\right) = CC_{2019}\left(\frac{123.2}{98.6}\right) = \mathbf{57,835,761(1.25) = 72,177,401}$$

Where CC_{2022} = capital cost in 2022 dollars,

CC_{2019} = capital cost in 2019 dollars (base case for cost models),

I_{2022} = 123.2 = 2022 MCS index value for underground mining capital costs,

I_{2019} = 98.6 = 2019 MCS index value for underground mining capital costs.

APPENDIX B – Cost Indexes Discussion

There are several sources for cost indexes. InfoMine has a specific section (*Cost indexes and metal prices*) in the subscription costmine *Mining Cost Service* (MCS). The U.S. Bureau of Labor Statistics (BLS) provides the *Consumer Price Index* (CPI) and the *Producer Price Indexes* (PPI) open access to the public on their websites. For all sources, the most recent indexes are usually listed as Preliminary (P), and are subject to updates up to four months after initial publication.

As mentioned previously, *Mining Cost Service* (MCS) publishes indexes for mining cost estimation in the section *Cost indexes and metal prices,* Table 5. Mining Cost Service (MCS) Indexes - United States. The categories appropriate for this handbook are capital cost and operating cost – underground mine (base year 2020=100).

"The **Consumer Price Index (CPI)** is a measure of the average change over time in the prices paid by urban consumers for a market basket of consumer goods and services" (Bureau of Labor Statistics–Consumer Price Index https://www.bls.gov/cpi/). The CPI is the most common index used to calculate inflation numbers. To find the most current index, and historical indexes, go to CPI main page, then CPI Data/Databases/ https://www.bls.gov/cpi/data.htm:

- All Urban Consumers (Current Series), (Consumer Price Index - CPI)
- Top Picks/U.S. city average, All items - CUUR0000SA0 [Retrieve Data]

An example of the data table with monthly CPI is in the following CPI discussion. CPI is designated as CPI-U (for all urban consumers).

The base period for the U.S. CPI is: 1982-1984=100.

"The Producer Price Index (PPI) program measures the average change over time in the selling prices received by domestic producers for their output. The prices included in the PPI are from the first commercial transaction for many products and some services" (Bureau of Labor Statistics–Producer Price Indexes https://www.bls.gov/ppi/).

To find the most current index, and historical indexes, go to PPI main page, then PPI Data/Databases/ https://www.bls.gov/ppi/databases/:

- Industry Data, (Producer Price Index - PPI)
- Top Picks/ Total manufacturing industries - PCUOMFG--OMFG-- [Retrieve Data]

An example of the data table with monthly PPI is included in the following PPI section.

The base period for the U.S. PPI is: 1984 December=100.

The following table compares the yearly change for MCS underground mine indexes with CPI and PPI for 2019-2022. In both 2021 and 2022, the resulting CPI factor is a little less than the MCS factors, and the PPI is a little larger. The MCS factors reflect changes specific to underground mining operating and capital costs, and are the preferred factors to use if available. However, for situations where the MCS factors are not available, CPI and PPI are reasonable substitutes, and are available anytime online.

Cost Indexes					**Index Factor, yearly change I_t / I_{t-1}**			
	MCS Underground Mine				MCS Underground Mine			
Year	Capital Cost Index	Operating Cost Index	PPI (US)	CPI (US)	Capital Cost Index	Operating Cost Index	PPI (US)	CPI (US)
2019	98.6	100.1	199.8	255.7	1.00	1.00	1.00	1.00
2020	100.0	100.0	194.4	258.8	1.01	1.00	0.97	1.01
2021	107.6	107.0	227.4	271.0	1.08	1.07	1.17	1.05
2022	123.2 (P)	122.3 (P)	264.5	292.7	1.14	1.14	1.16	1.08

(P) Preliminary

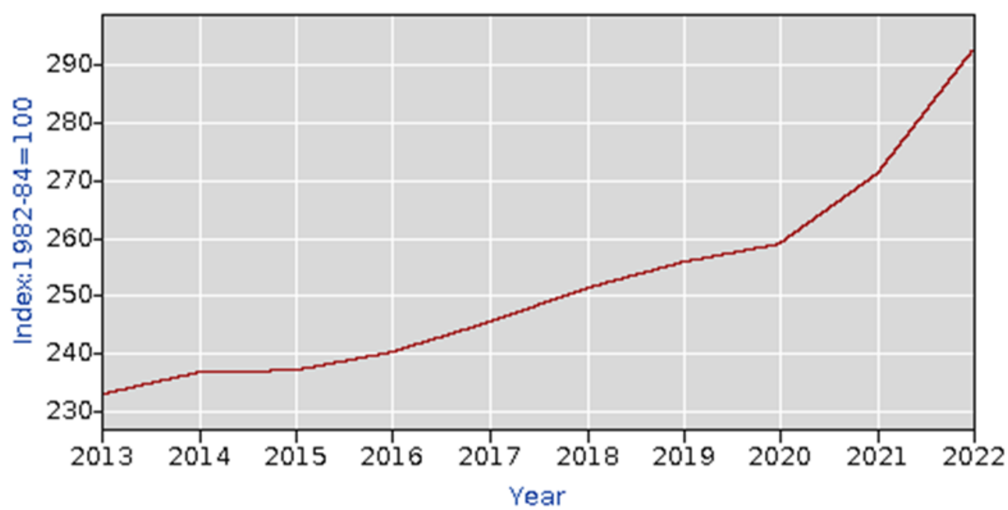
CPI discussion

Below is a table of the annual CPI for 2013-2022, followed by a graph highlighting the steep rise in inflation for the years 2020-2022 (which continued into 2023).
[Data extracted on: May 15, 2023; include graphs, annual averages; CPI for All Urban Consumers (CPI-U), https://data.bls.gov/pdq/SurveyOutputServlet]

Year	Annual CPI
2013	233.0
2014	236.7
2015	237.0
2016	240.0
2017	245.1
2018	251.1
2019	**255.7**
2020	258.8
2021	271.0
2022	**292.7**

CPI for All Urban Consumers (CPI-U)

Series Id: CUUR0000SA0
Not Seasonally Adjusted
Series Title: All items in U.S. city average, all urban consumers, not seasonally adjusted
Area: U.S. city average
Item: All items
Base Period: 1982-84=100



CPI for All Urban Consumers (CPI-U)

Original Data Value

Below is an example of the data available from the BLS website, providing the CPI on a monthly basis, as well as half-yearly and yearly numbers.

Series Id: CUUR0000SA0
Not Seasonally Adjusted
Series Title: All items in U.S. city average, all urban consumers, not seasonally adjusted
Area: U.S. city average
Item: All items
Base Period: 1982-84=100
Years: 2013 to 2023

Data extracted on: May 17, 2023
https://data.bls.gov/cgi-bin/surveymost

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Annual**	HALF1	HALF2
2013	230.3	232.2	232.8	232.5	232.9	233.5	233.6	233.9	234.1	233.5	233.1	233.0	**233.0**	232.4	233.5
2014	233.9	234.8	236.3	237.1	237.9	238.3	238.3	237.9	238.0	237.4	236.2	234.8	**236.7**	236.4	237.1
2015	233.7	234.7	236.1	236.6	237.8	238.6	238.7	238.3	237.9	237.8	237.3	236.5	**237.0**	236.3	237.8
2016	236.9	237.1	238.1	239.3	240.2	241.0	240.6	240.8	241.4	241.7	241.4	241.4	**240.0**	238.8	241.2
2017	242.8	243.6	243.8	244.5	244.7	245.0	244.8	245.5	246.8	246.7	246.7	246.5	**245.1**	244.1	246.2
2018	247.9	249.0	249.6	250.5	251.6	252.0	252.0	252.1	252.4	252.9	252.0	251.2	**251.1**	250.1	252.1
2019	251.7	252.8	254.2	255.5	256.1	256.1	256.6	256.6	256.8	257.3	257.2	257.0	**255.7**	254.4	256.9
2020	258.0	258.7	258.1	256.4	256.4	257.8	259.1	259.9	260.3	260.4	260.2	260.5	**258.8**	257.6	260.1
2021	261.6	263.0	264.9	267.1	269.2	271.7	273.0	273.6	274.3	276.6	277.9	278.8	**271.0**	266.2	275.7
2022	281.1	283.7	287.5	289.1	292.3	296.3	296.3	296.2	296.8	298.0	297.7	296.8	**292.7**	288.3	297.0
2023	299.2 (P)	300.8 (P)	301.8 (P)	**303.4** (P)											

(P) Preliminary

Cost Model Factor

2023 Apr	/ 2019	=	303.4	/	255.7	=	**1.19**

PPI Industry Data

Original Data Value

Below is an example of the data available from the BLS website, providing the PPI (Producer Price Index) on a monthly basis, as well as yearly numbers.

Series Id:	PCUOMFG--OMFG--
Series Title:	PPI industry group data for Total manufacturing industries, not seasonally adjusted
Industry:	Total manufacturing industries
Product:	Total manufacturing industries
Base Date:	198412 (December, 1984)
Years:	2013 to 2023

Data extracted on: May 15, 2023
https://www.bls.gov/ppi/databases/

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
2013	192.6	195.2	194.5	194.0	194.0	193.9	194.0	194.6	194.3	193.7	192.7	193.2	193.9
2014	194.2	195.2	196.2	197.5	197.2	197.2	197.4	197.4	196.8	194.8	192.7	189.1	195.5
2015	185.0	185.4	186.2	185.7	188.2	188.9	188.5	187.0	184.3	183.7	182.9	180.8	185.5
2016	179.7	178.7	179.3	180.5	181.9	183.6	183.4	182.5	183.0	183.7	183.2	183.9	181.9
2017	185.6	186.2	186.7	187.6	187.3	187.6	187.3	188.4	189.6	190.2	191.2	191.3	188.3
2018	192.6	193.5	194.0	195.3	197.7	198.4	198.5	198.6	198.9	200.4	198.4	195.2	196.8
2019	194.3	195.4	197.4	199.2	199.1	197.0	197.5	196.4	195.9	196.6	196.5	196.4	**196.8**
2020	196.6	195.1	192.3	186.1	188.9	190.2	192.3	193.0	192.9	193.7	194.5	196.7	192.7
2021	199.6	203.1	207.9	210.1	215.1	217.9	219.5	220.1	221.9	225.5	227.1	226.5	216.2
2022	231.5	237.2	245.4	249.6	256.4	262.4	256.5	251.5	251.9	254.0	252.9	245.1	249.5
2023	249.2 (P)	249.2 (P)	249.0 (P)	**248.9** (P)									

Cost Model Factor

2023 Apr	/ 2019	=	248.9	/	196.8	=	**1.26**

Data extracted on: May 15, 2023 (4:42:28 PM)

PPI Industry Data

Series Id: PCUOMFG--OMFG--
Series Title: PPI industry group data for Total manufacturing industries, not seasonally adjusted
Industry: Total manufacturing industries
Product: Total manufacturing industries
Base Date: 198412

PPI Databases
https://www.bls.gov/ppi/databases/
Data extracted on: May 15, 2023

MONTANA
TECHNOLOGICAL UNIVERSITY
MINING ENGINEERING
Mining for our future