ECONOMIC ANALYSIS TOOLS FOR MINERAL PROJECTS IN SPACE

Richard Gertsch[*] and Leslie Gertsch[†]

The charge to the workshop was to propose projects of commercial potential utilizing resources available in space. Many of the proposed projects involved resources that will have to be mined, either to supply a primary product or as raw feedstocks for products manufactured in space or for construction projects in space.

Mining engineers are accustomed to dealing with all aspects of commercial projects, from initial planning through financing to final closedown. The economic analysis tools presented here comprise an overview of the tools provided to mining engineers, and are offered here as tools that can be applied effectively to space ventures. Space and mining projects share fundamental similarities: high risk, long lead times, and high capital cost.

The analysis starts with the definition of ore, which is purely economic: ore is a geologic material that can be extracted from the ground at a profit. For profit to occur, sales must exceed costs, or:

$$\text{Sales} - \text{Costs} = \text{Profit} \qquad (1)$$

PROFIT

While commercial ventures must make a profit (and sometimes substantial ones, as we shall see), governments and their agencies may not. However, even governments usually attempt to maximize the cost-benefit ratio (or cost-sales, if you will). A classic mineral example of profit being less than or equal to zero occurred during the brutal mineral economic climate in the middle 1980's. During this period, certain South American countries mined copper at moderate loss. Their purpose was two-fold: first, it maintained an influx of hard-currency dollars from sales. Second, it allowed the mines (many state-owned) to remain open, and to be ready when better times returned.

Recognizing that initial space ventures may have some degree of government involvement, profit may not be the apparent initial motive for the venture. Allowing a commercial operation to piggyback a government operation can accomplish two things: bootstrap further space operations, and offset some of the costs incurred by the government. Both are desirable outcomes. However, the process of selecting the participating companies may have unforeseen political and economic consequences.

Government can also appeal to the profit motive with devices similar to the Air Mail Act of early this century, where it bids goods and services for fixed (perhaps even subsidized) prices,

[*] Rock Mechanics and Explosive Research Center, University of Missouri - Rolla, Rolla, MO 65401.
[†] Mining Engineering Dept. and Center for Space Mining, Colorado School of Mines, Golden, CO 80401.

and lets private companies make whatever profit they can. Similar to the old Airmail Act, this has been proposed as a mechanism to deliver oxygen to cislunar space (Davis, 1983).

SALES

Sales are generated by two complementary occurrences: 1) the existence of a product, and 2) a market for the product. Markets are based on need; there is no market if no one wants to buy the product. Therefore the product must be salable, not just produceable. Sometimes "marketeers" forget that they must produce something before they can sell it. General Motors is a well-known poster-child for this problem. During the seventies and eighties, critics charged that GM forgot they had to make not just cars, but quality cars, before they had something to sell.

In space, the problem is perhaps the opposite. Many products already have been identified, but the markets are either non-existent or government-dependent. Habitats, metals, concrete, water, air, He-3, etc., have no real demand yet except as government-sponsored activities. It becomes very difficult to calculate the true value of a product in this environment. Equation (1) becomes meaningless, and many would-be space entrepreneurs must justify their project by simply pointing out that they may be able to supply a low-demand government mission cheaper than the government can.

The basic problem is that we all believe in the promise of space, but economically there is no clear path to what we can do tomorrow. The nearest to a space-based commercial venture now is satellite communications. That market has developed over the past several decades, not in the leaps and bounds foretold by visionaries, but in fits and starts controlled by consumer perceptions and development of supporting technology. In hindsight, trying to leapfrog the erratic steps of this evolution could have been disastrous as a commercial venture. It will be just as difficult, if not more so, to forecast markets for space resources because their realization may be even farther away.

COSTS

Here lies firmer ground. Many organizations can make reasonable estimates and calculate project costs. Regardless of whether the project is commercial or governmental, costs are generally costs. But because governments are not profit-driven, they generally experience higher costs than commercial ventures. This is due to the luxury to be able to spend more on such items as enhanced safety and reliability.

It is useful to review the factors that contribute to costs. While the following discussion is general, some examples are specific to the mineral industry:

Research & Development. When a new machine or device is needed to accomplish a venture, costs are incurred during its inventing, designing, constructing and testing. Governments tend to conduct R&D over longer lead times, while commercial ventures tend to develop what is needed now. Examples would be governments providing basic research into rock fragmentation (open-ended with no clear path), and equipment manufacturers building autonomous mining machines (difficult, but with a clear pay-off).

Exploration & Delineation. In the mining industry, this means finding out with reasonable certainty what is there to be mined, and then building a mathematical model of precisely where it is and how it will be attacked. Part of the exercise is called a feasibility study, but it must be based on reliable ground truth which can only be supplied by drilling into the ground many times.

Construction & Development. After the project is a go, the physical plant must be built and the ore must be accessed by drilling, blasting, and hauling. Transportation to and from the site is needed, power must be supplied, processing plants built, and materials handling equipment provided.

Operations. The costs incurred by production: salaries, consumables, fuel, maintenance, safety, depreciation, taxes, etc.

Engineering. The cost to monitor, model, control, and thereby improve the economy of operations: surveying, analyzing, inventorying, record keeping, computing, etc.

Environmental. The cost of mitigating environmental impacts.

General and Administrative. The cost of management and sales. Costs of air, stowage, housekeeping, health and safety, and extra training would be added for space projects.

Time Value of Money. Mineral projects tend to have long lead times, because exploration & delineation and construction & development are simply time consuming. Recently, environmental permitting has added to the required lead times. This is a real cost. Space projects by necessity also will have long lead times. When a $100M mining machine spends two years in orbit to reach an asteroid, it has consumed a large amount of money before operations even start.

PROFIT REDUX

Money management is driven by two simple ideas: more money is better than less, and money now is better than money later. This leads to the basic analysis tools:

DCF/ROI. The Discounted Cash Flow / Return On Investment analysis lays out the projected costs and revenues for the proposed project over time. It also accounts for the time value of money (the discount) and the required income as a percentage of the investment (the ROI).

NPV. The Net Present Value tool takes the many revenues and costs over time in the DCF/ROI and calculates the present value of the entire project.

In addition to ROI, payback period plays an important role. Most commercial projects pay back the investment within 3 to 5 years. The reason is simple: while many companies will consider high risk ventures, shorter payback periods limit their exposure to the risk (Gentry and

O'Neil, 1984). The gamble is settled quickly, whether win or lose. Generally, the higher the risk the shorter the desired payback period and the higher the desired ROI (Table 1).

Project Risk	**ROI**	**Notes**
Low	< 15 %	Small projects, mom & pop, passbook savings
Moderate to High	20-50 %	Industrial projects, large projects, Mature Industries
Risky	50-200 %	Novel products / ventures
Wildcatting	200+ %	A very novel product, area, and/or customer

Table 1. Typical Expected Return on Investment as a Function of Risk

PLATINUM FROM AN ASTEROID, AN EXAMPLE

For illustration (Tables 2 and 3), consider a very simplistic NPV analysis of a mission to mine an asteroid for platinum. The total estimated cost of $5 billion is almost certainly low, however a time of 12 years to completion is not unreasonable and probably represents the shortest possible time. The asteroid would have an average ore grade of approximately 150 ppm of platinum group metals, which is a 90^{th} percentile object as defined by Kargill (1994).

The goal of the analysis is to calculate the amount of platinum as well as the total amount of mined rock required to pay for the cost of the mining and processing, while also accounting for the time value of money. The time required to explore, mine, and transport material are reasonable estimates. The platinum project would consist of seven major activities (Table 2), each with an estimated cost or revenue (Table 3).

Activity	**Year**	**Notes**
R&D	1 to 5	Develop and test the mining and processing equipment.
Explore Asteroid	1 to 4	Determine mining needs. (For approximately 2 year one way trip.)
Construct Miner & Processing Plant	2 to 5	Start as early as possible, but the final capabilities required will not be known until the exploration mission is complete.
Fly to Asteroid	6 to 7	2 year flight as miner is completed. Includes launch costs.
Mine and Process Asteroid	8	Assume one year for all mining activities. Processing will probably start during mining phase.
Fly & Process	9 to 11	Return to Earth. Continue processing in-flight if required.
Sell Product	11 to 12	Should be accomplished as soon as possible for highest return.

Table 2. Platinum Mining Project for a Near Earth 90^{th} Percentile Asteroid. Outline of project milestones and estimated completion times.

The project has similarities to large-scale terrestrial world-class mining and construction projects, which tend to be characterized by large capital investments and long life (not to be confused with payback period). Analogous projects include the Henderson molybdenum mine in Colorado or the English Channel Tunnel Project. The Henderson Mine cost approximately $1.0 billion to develop in the 1970's, possessed an in-situ mineral value of approximately $10 billion, and had a projected life of about 30 years. Risk for the Henderson Mine was considered low, and the payback period relatively short, on the order of 4 years. The Channel Tunnel cost over $12 billion and has not turned a profit 10 years later, and will not for several more years. While significant expenses for the tunnel were incurred early, most expenses, such as the trains, were incurred late in the project life. (Surprisingly, tunnel construction only cost about $1 billion, the trains and infrastructure consumed the rest.) The Channel Tunnel was considered a relatively risky venture, and has already seen major refinancing.

While the order of magnitude of cost for these two large terrestrial projects might be approximately correct, the platinum asteroid risk is higher and the pay back period is longer than most large terrestrial projects. Although both example terrestrial projects were expensive, they were not subject to as high a risk of failure as in space. Even moderate failures in the flight of an asteroid mining mission could halt the operation and result in no return on investment. However, both of the terrestrial ventures could suffer even several catastrophic failures (such as the collapse of a mine shaft) and still proceed profitably, although with a lessened ROI. (Or even greatly lessened, the recent Chunnel fire may have very costly effects.)

Table 4 shows that an asteroid containing 150 ppm platinum group metals, requires 4.6M tonnes to be mined for 10% ROI, or 45M tonnes for 50% ROI.

ROI	ounces Platinum	grams Platinum	Asteroid tonnes Mined
10%	22,300,000	694,000,000	4,620,000
50%	219,000,000	6,813,000,000	45,400,000
100%	2,407,000,000	74,873,000,000	499,000,000

Table 4. Tonnes of Ore, Ounces and Grams of Platinum (and PGMs) Required to give Specific Returns on Investment (ROI), given $400 per ounce platinum and platinum group metals.

CONCLUSIONS

The risk involved in exploiting space resources is very high, from risky to wildcatting (Table 2). Terrestrial investors would like a very high ROI and a very short payback period for this level of risk. However, high ROIs makes the project technologically more difficult. In the example project, 100% ROI is basically prohibited by the very high ore tonnage needed, 500 million tonnes. However, lesser ROIs are feasible (Tables3 and 4).

The payback period for the example project also is very long for a commercial venture. However, 11 years before any income is long even for a low risk venture. Perhaps it is in the nature of space projects to have long payback periods. Asteroids, in particular, have a long trip time.

The very high cost of space transportation alone (both for Earth to LEO and in space itself) is a significant barrier to commercial success. Lowering transportation costs is one key to furthering successful commercial space ventures.

When planning long space missions, costs should be delayed as long as possible, and revenues captured as soon as possible. For example, an asteroid mining project could delay building processing plants and miners until the exploration phase is complete. Sellable material from the asteroid should be returned with minimum delay.

R&D increases the cost of space projects compared to terrestrial projects. Most large scale terrestrial mining and manufacturing uses essentially off the shelf equipment, making R&D relatively inexpensive. Further, R&D increases the risk of the project: new designs are less reliable than tested designs, and testing takes time and money.

Environmental concerns may play a role in driving extraterrestrial mining. The amount of environmental mitigation required is increasing, and this pressure may make extraterrestrial mining an economical alternative. Precious metals are particularly vulnerable, since a large fraction goes to jewelry, a perceived waste of resources. The money spent in terrestrial mitigation may switch one day to space resource recovery.

What can mitigate these drawbacks of commercial utilization of space resources? One possibility, with a long history in science missions, is to combine projects. Platinum recovery, for example, would be a good add-on for another project, such as defraying part of the cost for a water retrieval mission. Water is useful in space for life support and propellant, and water mining scenarios have been proposed (ISU 1990). With the continued interest in a manned Mars Mission, an asteroid mine to supply materials to this long mission could also supply high value materials to Earth at the same time.

The realities of business make investment in space resource utilization unlikely without extraordinarily good preparation on the part of the entrepreneurs.

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Table 3. Projected Costs, Sales, and Completion Times for a Platinum Group Metal Asteroid Mining Project. Project duration lasts 11 years, and has a total expenditure of $6 billion, and an average asteroid re grade of 150 ppm platinum group metals. All costs are in millions of dollars. Years are the average time assumed in Table 2. See Table 4 for production as a function of NPV.

Activity:	**R&D**	**Explore**	**Construction**	**Launch**	**Fly**	**Mine**	**Fly & Process**	**Sales**
Mean Project Year:	2	2	3	6	6	8	10	11
(Cost)/Sales	($500M)	($800M)	($1,000M)	($500M)	($500M)	($1000M)	($700M)	
NPV @ 10%	($413M)	($661M)	($751M)	($282M)	($282M)	($467M)	($270M)	$8,920M
NPV @ 50 %	($125M)	($200M)	($125M)	($8M)	($8M)	($4M)	($1M)	$963,000M
NPV factor @ 10%	0.8264	0.8264	0.7513	0.5645	0.5645	0.4665	0.3855	0.3505
NPV factor @ 50%	0.4444	0.4444	0.2963	0.0878	0.0878	0.0390	0.0173	0.0116

Assumptions:

1. Conservative 1996 platinum group metal prices ($400 per ounce). The effect on the market from a large influx of new metal is not considered.

2. Asteroid grade is 150 ppm platinum group metals. Recovery is 100% (not possible, but the reader can easily substitute the recovery for any candidate process. Most terrestrial PGM metal recoveries are > 80%, with many > 95%.)

3. Mission profile is a two year trip out; one year mining; and processing during two year return. While arbitrary and optimistic, this is a reasonable start (2 to 3 out, 2 for mining and processing, and 2 to 3 for return is probably more realistic).

4. NPV is calculated by

$$\frac{P}{F_{n,i}} = \frac{1}{(1+i)^n} \quad \text{(Stermole and Stermole, 1996)} \qquad (2)$$

where: n = number of periods in years; i = discount rate; and P = present value for a F = future value n years away and at a rate of i%; and

$$\text{Revenue - Costs} = 0 \qquad (3)$$

n is taken at the middle of the expense period. Since the ROI is already contained in the factor $P/F_{n,i}$ and the discount rate equals 10% or 50%, the result is a break-even return on investment; most ventures hope to do better.

5. The costs associated with each phase of the project are an educated guess. However, $5 billion, even over 10 years, would be considered a very large mining project. Readers are encouraged to substitute their own figures.