THE ECONOMICS OF BOOTSTRAPPING SPACE INDUSTRIES--
DEVELOPMENT OF AN ANALYTIC COMPUTER MODEL

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Abstract

A simple economic model of "bootstrapping" industrial growth in space and on the moon is presented. An initial space manufacturing facility (SMF) is assumed to consume lunar materials to enlarge the productive capacity in space. After reaching a predetermined throughput the enlarged SMF is devoted to products which generate revenue continuously in proportion to the accumulated output mass (such as space solar power stations). Present discounted value and physical estimates for the general factors of production (transport, capital efficiency, labor, etc.) are combined to explore optimum growth in terms of maximized discounted revenues. It is found that "bootstrapping" reduces the fractional cost of a space industry of transport off-Earth, permitting more efficient use of a given transport fleet. It is concluded that more attention should be given to structuring "bootstrapping" scenarios in which "learning while doing" can be more fully incorporated in program analysis.

Nomenclature

t	time
K(t)	capital stock (tons)
ΔKE(t)	new capital stock provided each year (tons/yr) from earth to space
ΔKS(t)	new capital stock made each year (tons/yr) in space from non-terrestrial materials (NTM's) for use in space
ΔX(t)	expendables (tons/yr) used in space
ΔXE(t)	expendables supplied from earth for use in operating capital (tons/yr)
ΔXS(t)	expendables supplied in space from NTM's for operation of capital in space (tons/yr)
ΔQ(t)	final product made each year in space (tons/yr)
ΔQE(t)	mass/yr of final product supplied from Earth (tons/yr)
ΔQS(t)	mass/yr of final product supplied from space (tons/yr)
ΔXq	mass supplied each year to maintain operation of the final products made in space (tons/yr)
ρ(t)	productivity of capital mass (tons of product per ton of capital per year)
A,B,C,D,E	dimensionless scaling factors of value unity unless specified otherwise

Time Averaged Proportions

m	tons NTM derived expendables per tons expendables
n	tons NTM derived capital per tons capital
l	tons NTM derived product per tons products (final)
mq	tons NTM derived expendables per tons expendables
Z	tons expendables per year per ton of capital mass (machinery)
Zq	tons expendables per year per ton of product
Q(t)	total tons of product at t
UP(t)	tons per year of payload transported from Earth to space
ΔXqE(t)	mass of expendables supplied each year from Earth to maintain operation of the products
$\dot{M}$	tons per year of Earth to orbit lift capability of the transport system
CF(t)	annual net cash flow ($/yr)
P	$ of revenue per ton per year of operating product
F	$ per ton of expendables purchased on Earth each year ($/ton) for mass processed in space
G	$ per ton for expendables for operation of capital each year in space
H	$ per ton for expendables used in the production of the final product in space
I	$ per ton for expendables used in the operation of the products in space
PDV	present discounted value
NDV	net discounted value
T	end of evaluation period or "time horizon" of the investment
r	discount rate
RND	research and development outlays (assume all are prior to t = 0)
INT	initialization expenditures (before t = 0)
φ	(A·e − B.Zm)/(C·n) during the bootstrapping period when e is approximately constant (effectively the inverse time constant during the bootstrapping period)
Ko	initial mass of capital in space (tons)
θ	import mass per unit of capital mass (tons/ton)
ψ	annual cost per unit mass of capital
X	tons of output product per year per ton of final operating capital

Introduction

Three basic strategies for space industrialization have been proposed. The terrestrial approach involves the exclusive use of Earth launched materials and equipment for the fabrication of useful products in space. A major detraction of the scheme is the cost of transporting material into space inside rockets. Shuttle payloads (1) will initially (1980's) be delivered into orbit for roughly 1 million \$/ton. This figure dwarfs the procurement costs of nearly all large-scale cargos. Multibillion dollar development expenses will be required to provide large lift vehicles which can reduce this cost by factors of 10 to 30 (2). There is strong incentive to employ rockets to ship only small masses of high value products into space. Recent work on electromagnetic accelerators may make it possible to eject or augment the ejection of ton-sized payloads of inert materials directly from Earth to space. Costs the order of a few times the energy costs or approximately 10's \$/kg might be achievable. However, the materials would have to withstand thousands of gravities of acceleration (3,4) and would require subsequent processing in space.

One way to minimize rocket transport from Earth is to take advantage of the resources already in space (5). Like terrestrial inputs, these materials would have to be delivered to some appropriate orbit. However, it has been estimated (6,7) that launching matter from the moon using currently known techniques will require only 1/20 to perhaps as little as 1/200 the energy needed for even advanced Earth-launch systems. The primary reasons for this difference are that lunar transport does not have to contend with the Earth's gravity or atmospheric drag. In addition, lunar cargos do not necessarily have to be inside a complex and heavy cargo vessel to protect them from the atmospheric heat and pressure, as in terrestrial launches (7).

Of course, facilities for operating with lunar soil do not currently exist. They would have to be provided from Earth. Nevertheless, since most machines are capable of processing many times their own mass each year (8), the total Earth-launched mass would still be only a fraction of that required in the terrestrial case. The extensive data base generated by ten years of lunar sample research and availability of lunar samples makes it possible to design adequate production machines to convert lunar soils into a wide range of industrial feedstocks prior to return to the moon (9, 10, 11, 12).

Earth transport requirements could be reduced even further by using lunar soil to manufacture not only the final output, but also the "production" capital (5, 13, 14). This way, only a small seed facility would be required from Earth to initiate production. Despite growing interest in this final "bootstrapping" approach, no parameterized economic model has yet been developed to analyze the potential benefits in detail.

This study begins with the derivation of some basic equations which must apply to all models of space industry, regardless of whether they involve bootstrapping or even utilization of extraterrestrial materials. The difficulties in formulating a general bootstrapping mode are then discussed. Finally, attention is focussed on a simplified model and the conclusions which can be derived from it. We hope this work will promote further analyses.

General Framework

Two types of input are required for any productive enterprise -- expendable and capital. Expendables are materials and services which contribute to productivity only during the period in which they are made or purchased. Included in this group are chemical fuels, food, and reagents lost in process cycles. These items must be supplied regularly for production to occur. According to this usage, even personnel is considered an expendable, because crews must be periodically paid and rotated back to Earth. These inputs correspond roughly to recurring and nonrecurring costs in reference (11).

In contrast, capital goods do not have to be continuously supplied. Indeed, it will be assumed that, once operating, capital remains productive throughout the life of the project, so that the capital stock never decreases. Even with this assumption, the natural wearout of equipment can be accounted for in two ways. First, replacements for worn parts can be treated as an additional type of expendable. Alternatively, if the wearout rate exceeds the repair rate, resulting in disuse of some equipment, the operating capital stock can be considered constant but with decreasing productivity. Other factors, such as expendable requirements, would also have to be adjusted accordingly.

It will be assumed that the output accumulates in a stock which continuously generates revenue according to its magnitude. Solar power satellites are one example of such an output. As in the case of capital inputs, wear can be accounted for with expendable replacement parts or reduced revenues per unit output. Again, the output and related expendables may be made from either terrestrial and/or extraterrestrial resources. Sales of manufactured goods could be accommodated by modifying the model.

A flow diagram is shown in Fig. 1. The capital stock $\underline{K}$ is supplied in annual increments $\underline{\Delta KE}$ from Earth and $\underline{\Delta KS}$ from space. To keep the capital functioning, expendables $\underline{\Delta X}$ must be imported ($\underline{\Delta XE}$) or produced locally ($\underline{\Delta XS}$) each year. The Space Manufacturing Facility (SMF) produces $\underline{\Delta QS}$ which, together with some material brought up from Earth ($\underline{\Delta QE}$), makes up the final product $\underline{\Delta Q}$. Finally, for the output to bring in revenue, it must be supplied with some expendables each year ($\underline{\Delta Xq}$). The mass flow can always be reduced to this form, no matter how many specific inputs, outputs, or process steps. However, it may sometimes be advantageous to consider some of these factors separately.

The lunar mass flow through this system is limited by the capacity of the machinery to process it. Assuming full employment of all equipment, this constraint can be expressed mathematically as follows:

$$A\cdot\rho\cdot\underline{K} = B\cdot\underline{\Delta XS} + C\cdot\underline{\Delta KS} + D\cdot\underline{\Delta QS} + E\cdot\underline{\Delta Xq} \qquad (1)$$

where all underlined terms are functions of time and $\underline{\rho}$ is the productivity of capital in mass output per (year-mass of equipment). The scaling functions A, B, C, D, and E are included for generality. They will all be unity provided that the other functions are appropriately defined. However, it is desirable to retain the scaling terms so that waste, overhead, and the like can be treated independently.

Define the proportions, respectively, of process expendables (m), capital (n), output (ℓ) and output-related expendables (mq) which are produced from extraterrestrial material over time and averaging these and the other related ratios over sufficient periods that their time dependencies can be ignored, we have

$$A \cdot \underline{\rho} \cdot \underline{K} = B \cdot m \cdot \underline{\Delta X} + C \cdot n \cdot \underline{\Delta K} + D \cdot \ell \cdot \underline{\Delta Q} + E \cdot mq \cdot \underline{\Delta Xq} \quad (2)$$

Defining Z as the mass of expendables required per (year-mass of machinery), and Zq as the corresponding expendable requirement for Q,

$$A \cdot \underline{\rho} \cdot \underline{K} = B \cdot m \cdot \underline{Z} \cdot \underline{K} + C \cdot n \cdot \underline{\Delta K} + D \cdot \ell \cdot \underline{\Delta Q} + E \cdot mq \cdot Zq \cdot \underline{Q} \quad (3)$$

Rearranging,

$$(A \cdot \underline{\rho} - B \cdot m \cdot \underline{Z})K - (C \cdot n)\underline{\Delta K} = (D \cdot \ell) \cdot \underline{\Delta Q} + (E \cdot mq \cdot Zq)\underline{Q} \quad (4)$$

In this way, then $\underline{Q}$ is functionally related to $\underline{K}$ once the scaling, productivity, expendable requirements, and space-manufacturing proportions are specified. There could, in more complex models, be complicated interdependences among the bracketed expressions, as well as between them and the functions $\underline{Q}$ and $\underline{K}$.

Besides being limited by the productivity of capital in space, extraterrestrial operations may also be constrained by the ability to transport support material from Earth. The mass which must be imported to space any given year is

$$\underline{UP} = B \cdot \underline{\Delta XE} + C \cdot \underline{\Delta KE} + D \cdot \underline{\Delta QE} + E \cdot \underline{\Delta XqE} \quad (5)$$

Using the definitions introduced above,

$$\underline{UP} = B(1-m)\underline{\Delta X} + C(1-n)\Delta K + D(1-\ell)\underline{\Delta Q} + E(1-mq)\underline{\Delta Xq}$$

$$= (B(1-m)Z)\underline{K} + (C(1-n))\underline{\Delta K} + (D(1-\ell))\underline{\Delta Q} + (E(1-mq)Zq)\underline{Q} \quad (6)$$

Thus, $\underline{UP}$ is a function of $\underline{Q}$ and $\underline{K}$. Since $\underline{Q}$ is a function of $\underline{K}$ in equation (4), the mass which must be supplied from Earth depends simply on how the capital stock varies over time.

The value of $\underline{UP}$ must never exceed the transport capacity, $\dot{M}$ tons/year. The converse, however, does not hold. Indeed, in the long run, even with a fixed launch fleet, $\underline{UP}$ will decrease as the space industry becomes less dependent on Earth. Since $\underline{UP}$ depends only on $\underline{K}$, the transport constraint $\dot{M}$ effectively limits the potential capital growth.

In addition to modeling the physical flows, it is important to describe the cash flows mathematically. The net cash flow $\underline{CF}$ in any given year is simply the revenue obtained during that year less expenditures. As in national income accounting, costs of goods produced and used within the manufacturing complex are internal transfers which do not contribute to the balance of payments. Consequently, the cash flow can be expressed as follows:

$$\underline{CF} = P \cdot \underline{Q} - F \cdot \underline{\Delta XE} - G \cdot \underline{\Delta KE} - H \cdot \underline{\Delta QE} - I \cdot \underline{\Delta XqE} \quad (7)$$

where the new terms are the revenue per year derived from each unit of output (P), and the costs per mass of process expendable (F), capital (G), output (H), and output-related expendable (I) brought up from Earth. The functions F, G, H, and I must be adjusted for any deviation of "A" through "E" from unity. Simplifying as before,

$$\underline{CF} = P \cdot \underline{Q} - F(1-m)\underline{\Delta X} - G(1-n)\underline{\Delta K} - H(1-\ell)\underline{\Delta Q} - I(1-mq)\underline{\Delta X}$$

$$= P \cdot \underline{Q} - F(1-m)Z \cdot \underline{K} - G(1-n)\underline{\Delta K} - H(1-\ell)\underline{\Delta Q} - I(1-mq) \cdot$$

$$Zq \cdot \underline{Q} = (P - I(1-mq)Zq)\underline{Q} - (F(1-m)Z)\underline{K}$$

$$- (G(1-n))\underline{\Delta K} - (H(1-\ell)\underline{Q} \quad (8)$$

Since $\underline{Q}$ and $\underline{K}$ are correlated as shown in equation (4), the cash flow $\underline{CF}$, like the launch requirement $\underline{UP}$, depends only on the capital growth function $\underline{K}$.

A common method for weighing the costs and benefits over the life of a project is by evaluating the present discounted value (PDV) of its net cash flow. PDV is also commonly denoted as "net present value" (NPV). Mathematically, the goal is to maximize the objective function (15)

$$PDV = \sum_{t=0}^{T} \underline{CF}\, e^{-rt} - RND - INT \quad (9)$$

where r is the discount rate, T is the "time horizon" (which may be infinite), RND is the cost of research and development, and INT is the cost associated with initializing the system.

Equation (9) is an approximation to PDV (or NPV) which is satisfactory for low discount rates. The exact form is

$$PDV = \sum_{t=0}^{T} CF\,(1+r)^{-t}$$

Future computer simulations should use the non-approximate form of PDV and should also discount both the "research and development" (RND) and "initialization" (INT) costs of the project. Both RND and INT will be spread over a period of time. They clearly begin before start of flight operations and will likely continue through a major portion of the flight operations.

When choosing between alternative production paths, PDV is one of the critical considerations. PDV must be positive for a project to be attractive. However, given two projects with positive PDV's it might be that the project with the highest PDV also has the highest capital investment requirement. If the capital investment required is greater than can be funded, then the project with the lower PDV might be pursued instead. Also, the project with the greatest PDV of two or more alternative projects might also have the greatest risk associated with it. Again, one of the alternative projects with a positive PDV might be preferred. To reiterate, our objectives are to formalize one possible approach to the PDV analysis of a bootstrapped space industry, define relevant numerical values for one example or tutorial case of a lunar-based bootstrapped industry, to explore the operation of the analytic model for that example, and finally, to encourage more analytical work on PDV and related topics such as risk analysis and specific engineering models.

Within this framework, the three approaches to space industrialization differ only quantitatively, not qualitatively. All can be analyzed with the equations above simply by varying the constituent functions (Fig. 2). In general, increases in the complexity of the forms assumed for these functions and their interrelationships lead to greater uncertainty and mathematical difficulty in evaluating the mass and cash flows.

Obstacles to the Evaluation of Bootstrapping

In order to evaluate bootstrapping, it is important to know the general form of $\underline{K}$. By definition, the capital stock in nondecreasing. Moreover, since the ability to manufacture equipment in space depends on the amount of machinery already there, the capital stock will probably increase exponentially at first. Eventually, this growth must slow down so that capacity can be diverted to production of the final output, $\underline{Q}$. Indeed, if the project horizon is finite, $\underline{K}$ will stop growing altogether since production of machinery in the last period yields no benefits.

Taken together, these arguments suggest that $\underline{K}$ is S-shaped, like a learning curve. There are many mathematical equations (i.e., logistic or the Gompertz curves) which fit this general form, all requiring at least three parameters. In general these functions are sufficiently complicated to make numerical analysis a necessity. The computations become especially burdensome since production must be optimized with respect to all three variables for every set of engineering specifications considered. (Additional complications arise from the need to specify the transport capacity function.)

Since the capital stock grows over time, the space-production proportions will not be constant. Instead, just like in underdeveloped countries, the portion of goods which are produced locally will increase as an industrial base is established. Other reasons for augmented ratios include technological improvements and increasing returns to scale, which overtake the impracticality of producing certain items in the small quantities demanded at the beginning of industrialization. The output of a fixed capital stock could be increased by changing the number or types of input. However, any large increase in production would require more machinery. Ayres et al. (16) have discussed formalisms for analyzing the growth of flexibility in production systems.

Unfortunately, the growth of the space production ratios cannot be fixed without regard to $\underline{K}$. Any substantial increase in the number of items produced in space also requires enlargement of the capital stock. Consequently, the inflection points of m, n, ℓ, and mq must occur close to that of $\underline{K}$.

"$\underline{K}$" is not the only function that links the production functions. Additionally, the final space-production ratios depend on how early the inflection point is reached. Such correlations seriously complicate the study of bootstrapping.

Variation of productivity over time poses another major problem. Although $\underline{\rho}$ tends to increase, like the space-production ratios, due to technological change and returns to scale, there are other considerations which counter this influence. First, the items which are initially produced in space will be those requiring the least capital, so that the mass of output per (year-mass) of machinery should decrease. In addition, as the output from bootstrapping shifts from $\underline{K}$ to $\underline{Q}$, any equipment which is unique to the production of capital will fall into disuse, decreasing the productivity of the total capital stock. (Of course multi-purpose systems will have the opposite effect.) Finally, there is the effect of equipment wear. Without adequate information regarding the relative weight of these opposing influences, the net change in productivity is ambiguous. Similar arguments interfere with evaluation of the functions A through E, Z, and Zq as defined for equations (1) and (2).

Even with these factors constant, one would expect costs to change as the nature of the items brought up from Earth changes. Since the first goods to be produced in space will be those which require the least processing, the intrinsic value (cost per ton) of the average import will increase over time. Simultaneously, however, the proportion of imports which are less processed, but which contain lunar deficient elements, will also increase. Only the source of medium cost imports will change, so the overall effect is again unclear.

Apparently, bootstrapping permits so many degrees of freedom that modeling is extremely difficult. In addition, this strategy necessarily introduces complex interdependencies among the various physical and economic functions. In the absence of any significant experience or information to indicate the nature of the correlations, rather than attempting to formulate a general bootstrapping model, we consider a restricted case which should suffice for our exploratory purposes.

Simplified Bootstrapping Model

One way to make the analysis mathematically tractable is to assume that manufacture of the final output is delayed until all of the capital--whether produced in space or merely transported there (as in 11 and 12) is operational. This restriction has the effect of separating both the mass and cash flows into two simpler equations, corresponding to the two stages of processing.

During the capital production phase, lunar soil is used only to form expendables and machinery. Thus,

$$(A\cdot\underline{\rho} - B\cdot Z\cdot m)\underline{K} = (C\cdot n)\underline{\Delta K} \qquad (4')$$

Since no benefits can be derived until some $\underline{Q}$ is produced, this initial period will probably be quite short - a few years at the most (12). As a result, the technology, as embodied in the scaling, productivity, expendable requirements, and prices, is nearly constant. Equation (4') then reduces to

$$\underline{\Delta K} = \phi\underline{K} \qquad (10)$$

where $\phi = (A\cdot\rho - B\cdot Z\cdot m)/(C\cdot n)$ is independent of time. Integrating,

$$\underline{K} = K_o\cdot e^{\phi t} \qquad (11)$$

where K_o is the initial capital supplied from Earth. Evidently, separating the production of K and Q requires that the capital stock grow exponentially (13). Implicit in the integration is the assumption that the capital stock is infinitely divisible and compounds continuously. This approximation might be approached in practice since most space equipment is expected to be relatively small. Increased production can be achieved in many cases by building additional similar sized parallel units.

The Earth launch requirement can be reduced similarly to

$$\underline{UP} = (B\cdot Z(1-m) + C\cdot\phi(1-n))\underline{K} = \underline{K}\cdot\theta \qquad (6')$$

where θ is the annual import mass per unit mass of capital. Assuming a fixed fleet during capital production, $\underline{UP}$ may never exceed the transport capacity, $\dot{M}$ tons/year.

$$\underline{UP} = \theta\cdot\underline{K}<\dot{M} \qquad (12)$$

Rearranging,

$$\underline{K}<\dot{M}/\theta \qquad (13)$$

Therefore $\dot{M}/\theta$ is an upper bound on the capital operating during its formation period. More machinery may be accumulated, but the additional capital cannot function until manufacturing of the final product has begun.

The transport fleet also affects the onset of exponential growth. If the vehicles are used to capacity, installation of the initial equipment will take $K_o/\dot{M}$ years. In this way, the entire production path for a given technology can be specified by just two parameters,- K_o and $\dot{M}$.

These same factors also uniquely determine the cost of developing a given capital mass. The initial capital nominally costs G\$/ton, with the payment schedule fixed by $\dot{M}$. Once all of this equipment is in place, the cash flows required to finance production of machinery in space is

$$\underline{CF} = -(F(1-m)Z)\underline{K} - (G(1-n))\underline{\Delta K}$$

$$= -(F(1-m)Z)\underline{K} - (G(1-n)\phi\cdot\underline{K} = \psi\cdot\underline{K} \qquad (14)$$

where ψ is the annual cost per unit mass of capital. If $\underline{K}$ is defined as the equipment in actual operation at any given time, equation (8) holds whether the capital grows linearly, as when constrained by fleet size, or exponentially. The costs at all points during SMF formation (and consequently the PDV costs), are therefore fixed by the same two variables which determine K(t).

The dependence of PDV costs on K_o and $\dot{M}$ for the base case technology described in Appendix 2 is illustrated in Fig. 3. The lowest isocost contours are at the origin, indicating a preference for the maximum amount of bootstrapping (smallest K_o) and the smallest transport fleet. The reason for this bias is readily explained. By starting with a minimum of capital from Earth, capital costs are deferred to the discounted future. Similarly, a small transport capability forces expenses to be spread out over a long period so that costs are discounted heavily. However, even though this strategy minimizes the cost of establishing an SMF, it also delays receipt of revenues from the final product.

Evaluation of the resulting tradeoff between the time and cost of capital development first requires that the effect of K_o and $\dot{M}$ on the length of the capital production period be determined. For any given launch fleet, the time required to achieve a certain capital mass is minimized by delaying lunar soil processing until capital can be increased at a faster rate by producing it in space than by transporting it from Earth. Mathematically, K_o must be chosen so that

$$\left.\frac{dk}{dt}\right|_{K = K_o} = \dot{M}$$

Evaluation of the derivative for the exponential portion of K gives

$$\left.\frac{dK}{dt}\right|_{K = K_o} = \left.\phi\underline{K}\right|_{K = K_o} = \phi K_o = \dot{M} \qquad (15)$$

Thus, the time can be minimized for every fleet size by starting with a seed facility of $(\dot{M}/\phi)$ tons. Indeed, this fact is displayed by the isotime curves of Fig. 4.

The rapid increase in time near the K_o-axis can be explained in a similar manner. As noted above, it takes $K_o/\dot{M}$ years to transport the initial capital into space. The effect of an incremental change in the transport fleet on the length of this period is

$$\left(\frac{dK}{d\dot{M}}\right)\frac{K_o}{\dot{M}} = \frac{-K_o}{(\dot{M})^2} \qquad (16)$$

suggesting that changes in the fleet size have the greatest effect on the time needed to install K_o when $\dot{M}$ is small. (This influence is accentuated in later periods of lunar soil processing.)

In order to see how detrimental deferral of the revenues can be, it is also important to estimate the magnitude of the benefits. Once production of the final output has started, no more capital is manufactured. Consequently, the lunar mass flow reduces to

$$(A'\cdot\underline{\rho}' - B'\cdot m'\cdot Z')K_f = (D\cdot\ell)\underline{\Delta Q} + (Em_q\cdot Z_q)\underline{Q} \qquad (4'')$$

where K_f is the total capital mass and the primes serve to distinguish certain functions from their previous values during the capital production phase. Since the equipment does not change, the production method is essentially fixed, thereby freezing the physical and economic parameters (9). It will further be assumed that the amount of output related expendables produced in space ($\Delta X_q S$) is negligible. Therefore, equation (4") becomes

$$\underline{\Delta Q} = (A'\cdot\underline{\rho}' - B'\cdot m'\cdot Z')\ K_f/(D\cdot\ell) = X\cdot K_f \qquad (17)$$

which satisfies the condition of steady state production.

This relationship can be incorporated into the cash flow equation as follows:

$$\underline{CF} = (P-I(1-m_q)Z_q)\underline{\Delta Q} - (F'(1-m')Z')\underline{K} - (H(1-\ell))\underline{\Delta Q}$$

$$= (P-I(1-m_q)Z_q)\underline{\Delta Q}\cdot t - (F'(1-m')Z')\underline{K} - (H(1-\ell))\underline{\Delta Q}$$

$$= (X\cdot P - X\cdot I(1-m_q)Z)K_f\cdot t - (F'(1-m')Z' - X\cdot H(1-\ell))K_f$$

The PDV can be evaluated by applying the discount factor e^{-rt}, and integrating over the period in question. For a 100,000 T SMF using the base case technology, the PDV of 50 years of net revenues is approximately $1 trillion, discounted at 10% per year to the time at which production of Q begins.

These benefits are introduced to the total project value at the times specified in Fig. 4. The result of adding the appropriately discounted revenues to the isocost curves of assembling the SMF is shown in Fig. 5. The length of time required to develop the capital obviously exerts the dominant influence. However, the cost of establishing the SMF (Fig. 3) adds a slight bias toward the origin.

Figure 5 still does not tell the whole story. It demonstrates the PDV from the first launch of terrestrial materials, but ignores the costs incurred prior to space operations. Perhaps the most important of these factors is the cost of the transport fleet. Indeed, it is the neglect of this expense which allows the peak PDV to stay at the maximum $\dot{M}$.

It has been previously suggested that the optimal fleet for bootstrapping would consist of numerous small vehicles (11). In this case, the fleet cost is roughly proportional to the transport capacity and can be viewed on a relief diagram as a plane inclined upwards from the initial-capital axis. When the cost plane for a shuttle derived fleet is subtracted, the PDV contours of Fig. 5 close up (Fig. 6). This effect is simply a graphical representation of the fact that, past a certain point, additional vehicles increase fleet costs without substantially affecting the time or the costs of SMF development.

The other costs that must precede space operations are associated with research and development. In order to analyze the effect of these expenses on the optimal production point, it is important to know just how they vary with K_o and $\dot{M}$. Qualitatively, the degree of bootstrapping is related to the number of manufacturing processes employed in space. Although most tools and techniques can be used in a variety of processes (12), decreases in K_o are still expected to raise research costs. At the same time, however, bootstrapping reduces the need for developing optimal equipment at the outset by permitting changes in early project designs. In essence, starting with a small amount of capital enables some of the RND to be integrated with the space operations. The economic effect on PDV of this type of "learning by doing" is diminished by the brevity of the capital growth period.

Since the correlation between RND and K_o is difficult to assess, it will be assumed negligible. This assumption is reinforced by estimates which show that material processing represents a rather small proportion of the total research costs (12). Development costs should be even more insensitive to changes in $\dot{M}$, since the transport capacity is enlarged by increasing the number, rather than the size, of the launch vehicles. To the extent that more advanced vehicles might be used at high transport rates, there would be a slight bias in favor of large $\dot{M}$. (Even though development costs for such a system would be greater, the incremental costs would not be incurred unless some savings could be realized. Since RND costs are assumed constant over the entire plane, they change only the absolute magnitudes, and not the relative positions, of the contours in Fig. 6.

Conclusions

Although there is great uncertainty in the input parameters for the graphs above, the general behavior of the curves remains the same over a wide range of values. The optimal combination of K_o and $\dot{M}$ always lies close to a line through the origin with slope ϕ. Since ϕ is dominated by the productivity, the peak PDV must be quite sensitive to $\underline{\rho}$.

Just where along the line one should operate is determined by three considerations. First is the importance of time as indicated by the discount rate and the revenues. Second is the extent to which ϕ enables the utilization of lunar resources to shorten the period prior to steady state operation. Finally, the optimum is influenced by the cost of the transport fleet.

The costs during capital development, in contrast, play only a minor role in determining the optimal production path. They introduce only a slight bias toward the origin. Indeed, Fig. 6 can be approximated quite closely by ignoring these costs altogether (Fig. 7). As transport costs decrease with more advanced launch systems, the difference becomes negligible.

This particular model shows, as expected, that producing capital with lunar resources does reduce the cost of transporting materials into space. More importantly it shows that "bootstrapping" can reduce the time needed to assemble a space manufacturing facility using a given fleet. Bootstrapping utilizes a given fleet more efficiently. True bootstrapping would be even more attractive than this simplified strategy since it would postpone many of the costs and start delivering benefits much sooner. Furthermore, bootstrapping would decrease research time and risk by transferring more development to the productive phase of operations. This computer model should be useful in exploring the effect of bootstrapping the development of a space economy with a variety of products. It can yield insight into the results of incorporating research and development into the growth phase. The specific model (SPS) analyzed in this work required very fast deployment rates which precluded "learning while doing." In addition, the computer program used in this analysis should be expanded to handle the time value of investments in research and development (RND) and initialization costs (INT) in a more realistic manner.

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```
C***************************************************************************
C                          Appendix 1.  Computer Programs
C
C                                   MODEL.FTN
C
C     THIS PROGRAM COMPUTES THE PRESENT DISCOUNTED VALUE (PDV) AND THE
C     TIME NEEDED TO ESTABLISH THE SMF FOR AN ARRAY OF KO AND M-DOT VALUES.
C     THE SMF PRODUCTION COSTS ARE COMPUTED IN THREE STEPS:
C
C            1) COST OF "EMPLANTING" THE KO SEED FACILITY
C
C            2) COST OF EXPONENTIAL GROWTH (IF ANY OCCURS)
C
C            3) COST OF LINEAR, TRANSPORT-LIMITED GROWTH (IF ANY OCCURS)
C
C     FINALLY REVENUES, FLEET COSTS, AND RESEARCH COSTS ARE ADDED TO GET THE
C     TOTAL PDV.  THE POINT WITH THE HIGHEST PDV IS ALSO LOCATED.
C
C     INPUTS
C        FILE 3 : TECHNOLOGICAL PARAMETERS
C
C     OUTPUTS
C        FILE 1 : KO AND M-DOT FOR HIGHEST PDV
C        FILE 2 : PDV AND TIME VALUES FOR THE ENTIRE ARRAY
C
C
C***************************************************************************
      REAL KOOO, MNM, K, JFL
      CALL ASSIGN (1, 'DD:')
      CALL ASSIGN (2, 'DD:')
C
C
C*****INPUT TECHNOLOGICAL PARAMETERS
C
C
      READ (3,150) A,B,C,F,G,P1,P2,P3,P4,RATE,RHO,RM,RN,WANT,Z
150   FORMAT (16(6X,F15.5/))
      R=ALOG(RATE)
      PEAK=0.
      TOPK=0.
      TOPM=0.
C
C
C*****COMPUTES PHI, PSI, AND THETA FOR INPUT TECHNOLOGY
C
C
      PHI=(A*RHO-B*RM*Z)/(C*RN)
      THETA=B*Z*(1.-RM)+C*PHI*(1.-RN)
      PSI=F*Z*(1.-RM)+G*PHI*(1.-RN)
C
C
C*****CHOOSES POINT IN THE MATRIX
C
C
      DO 5678 INT1=1,50
      KOOO=1990.*FLOAT(INT1)+500.
      DO 5678 INT2=1,50
      MNM=1990.*FLOAT(INT2)+500.
      VALUE=0.
      VONE=0.
      VTWO=0.
      VTHRE=0.
C
C
C*****COMPUTES COST OF "EMPLANTING" THE SEED FACILITY
C
C
      YTTI=KOOO/MNM
      VONE=G*MNM*(1.-EXP(-R*YTTI))/R
      TSTK=KOOO
      JFL=YTTI
      IF (KOOO.GE.WANT) GO TO 4321
      STOPK=MNM/THETA
      STOPK=AMIN1(STOPK,WANT)
      IF (STOPK.LE.KOOO) GO TO 1111
C
C
C*****COMPUTES COSTS DURING EXPONENTIAL GROWTH
C
C
      TINT=YTTI+ALOG(STOPK/KOOO)/PHI
      VTWO=PSI*KOOO*EXP(-PHI*YTTI)/(PHI-R)
      VTWO=VTWO*(EXP(TINT*(PHI-R))-EXP(YTTI*(PHI-R)))
      TSTK=KOOO*EXP(PHI*(TINT-YTTI))
      JFL=TINT
      IF (TSTK.GE.WANT) GO TO 4321
      GO TO 2222
```

```
C
C
C*****COMPUTES COSTS DURING LINEAR, TRANSPORT-LIMITED GROWTH
C         WHEN THERE IS NO EXPONENTIAL GROWTH
C
C
1111  TINT=YTTI
      VTWO=0.
      TFIN=YTTI+(WANT-KOOO)/(PHI*STOPK)
      JFL=TFIN
      VTHRE=PSI*STOPK*(EXP(-R*TINT)-EXP(-R*TFIN))/R
      TSTK=KOOO+PHI*STOPK*(TFIN-TINT)
      GO TO 4321
C
C
C*****COMPUTES COSTS DURING LINEAR, TRANSPORT-LIMITED GROWTH
C         IF THERE WAS PREVIOUS EXPONENTIAL GROWTH
C
C
2222  TFIN=TINT+(WANT-STOPK)/(PHI*STOPK)
      VTHRE=PSI*STOPK*(EXP(-R*TINT)-EXP(-R*TFIN))/R
      JFL=TFIN
      TSTK=STOPK+PHI*STOPK*(TFIN-TINT)
C
C
C*****COST OF ESTABLISHING THE SPACE MANUFACTURING FACILITY
C
C
4321  VALUE=VONE+VTWO+VTHRE
C
C
C*****PRESENT DISCOUNTED VALUE (PDV)
C
C
1999  GRAND=P2*EXP(-R*JFL)-VALUE-P1*MNM-P4-P3*(WANT-KOOO)
C
C
C*****FINDS MAXIMUM PDV FOR INPUT TECHNOLOGY
C
C
      IF (PEAK.GE.GRAND) GO TO 5678
      PEAK=GRAND
      TOPK=KOOO
      TOPM=MNM
5678  WRITE (2,2000) GRAND, JFL
2000  FORMAT (2F25.5)
      WRITE (1,2000) TOPK, TOPM
      STOP
      END


C*****************************************************************************
C
C
C                              CURVZ.FTN
C
C         THIS PROGRAM INTERPOLATES 5 PDV VALUES AND 4 TIME
C         VALUES FOR CONTOURING.  THE PDV VALUES ARE ENTERED
C         BY THE USER WHILE THE TIME VALUES ARE FIXED
C         AT .75, 1.0, 1.25, AND 1.5 YEARS. AN ARRAY IS FORMED
C         FOR EACH VARIABLE USING THE OUTPUT OF THE PROGRAM "MODEL"
C         EACH VALUE IS THEN LINEARLY INTERPOLATED - FIRST IN THE
C         M-DOT DIRECTION, AND THEN IN THE KO DIRECTION.
C
C     INPUTS
C        FILE 2 : OUTPUT OF "MODEL"
C        TERMINAL : 5 PDV VALUES FOR CONTOURING
C
C     OUTPUTS
C        FILE 3 : POINTS WITH TIME = .75
C        FILE 4 : POINTS WITH TIME = 1.0
C        FILE 7 : POINTS WITH TIME = 1.25
C        FILE 8 : POINTS WITH TIME = 1.5
C        FILE 9 : POINTS WITH 1ST PDV VALUE
C        FILE 10: POINTS WITH 2ND PDV VALUE
C        FILE 11: POINTS WITH 3RD PDV VALUE
C        FILE 12: POINTS WITH 4TH PDV VALUE
C        FILE 13: POINTS WITH 5TH PDV VALUE
C
C
C*****************************************************************************
      REAL KF
      DIMENSION PDV(51,51), YRS(51,51)
      CALL ASSIGN (2, 'DD:')            CALL ASSIGN (9, 'DD:')
      CALL ASSIGN (3, 'DD:')            CALL ASSIGN (10, 'DD:')
      CALL ASSIGN (4, 'DD:')            CALL ASSIGN (11, 'DD:')
      CALL ASSIGN (7, 'DD:')            CALL ASSIGN (12, 'DD:')
      CALL ASSIGN (8, 'DD:')            CALL ASSIGN (13, 'DD:')
```

```
C
C
C*****ASKS FOR 5 PDV VALUES TO BE CONTOURED
C
C
      WRITE (5,10)
 10   FORMAT (' ENTER 5 PDV VALUES FOR MAPPING:')
      READ (5,20) PARM1
      READ (5,20) PARM2
      READ (5,20) PARM3
      READ (5,20) PARM4
      READ (5,20) PARM5
 20   FORMAT (F25.5)
 45   FORMAT (F20.5)
      LIMX=50
      LIMY=50
C
C
C*****SETS UP ARRAYS FOR PDV AND TIME
C
C
 95   DO 500 IRK=1, 50
      DO 500 IBET=1, 50
      READ (2,100) APDV, AYRS
 100  FORMAT (2F25.5)
      PDV(IRK, IBET)= APDV
      YRS(IRK, IBET)=AYRS
 500  CONTINUE
C
C
C*****INTERPOLATES IN THE M-DOT DIRECTION
C
C
      DO 2000 IX=1, LIMX
      YY=1.
      CAPTB=YRS(IX,1)-.75
      QT30B=YRS(IX,1)-1.0
      QT50B=YRS(IX,1)-1.25
      QT99B=YRS(IX,1)-1.5
      V050B=PDV(IX,1)-PARM1
      V200B=PDV(IX,1)-PARM2
      V500B=PDV(IX,1)-PARM3
      V999B=PDV(IX,1)-PARM4
      V25TB=PDV(IX,1)-PARM5
      DO 2000 IY=1, LIMY
      CAPTA=YRS(IX,IY)-.75
      QT30A=YRS(IX,IY)-1.0
      QT50A=YRS(IX,IY)-1.25
      QT99A=YRS(IX,IY)-1.5
      V050A=PDV(IX,IY)-PARM1
      V200A=PDV(IX,IY)-PARM2
      V500A=PDV(IX,IY)-PARM3
      V999A=PDV(IX,IY)-PARM4
      V25TA=PDV(IX,IY)-PARM5
 1030 X=1990.*FLOAT(IX)+500.
      YC=1990.*FLOAT(IY)+500.
 1090 PR1=CAPTA*CAPTB
      IF (PR1.GE.0.) GO TO 1100
      Y=YC-CAPTA*(YC-YY)/(CAPTA-CAPTB)
      WRITE (3,9999) X, Y
 1100 CAPTB=CAPTA
      PR2=QT30A*QT30B
      IF (PR2.GE.0.) GO TO 1200
      Y=YC-QT30A*(YC-YY)/(QT30A-QT30B)
      WRITE (4,9999) X, Y
 1200 QT30B=QT30A
      PR3=QT50A*QT50B
      IF (PR3.GE.0.) GO TO 1300
      Y=YC-QT50A*(YC-YY)/(QT50A-QT50B)
      WRITE (7,9999) X, Y
 1300 QT50B=QT50A
      PR4=QT99A*QT99B
      IF (PR4.GE.0.) GO TO 1400
      Y=YC-QT99A*(YC-YY)/(QT99A-QT99B)
      WRITE (8,9999) X, Y
 1400 QT99B=QT99A
      PR5=V050A*V050B
      IF (PR5.GE.0.) GO TO 1500
      Y=YC-V050A*(YC-YY)/(V050A-V050B)
      WRITE (9,9999) X, Y
 1500 V050B=V050A
      PR6=V200A*V200B
      IF (PR6.GE.0.) GO TO 1600
      Y=YC-V200A*(YC-YY)/(V200A-V200B)
      WRITE (10,9999) X, Y
 1600 V200B=V200A
      PR7=V500A*V500B
      IF (PR7.GE.0.) GO TO 1700
      Y=YC-V500A*(YC-YY)/(V500A-V500B)
      WRITE (11,9999) X, Y
 1700 V500B=V500A
      PR8=V999A*V999B
      IF (PR8.GE.0.) GO TO 1800
      Y=YC-V999A*(YC-YY)/(V999A-V999B)
      WRITE (12,9999) X, Y
 1800 V999B=V999A
      PR9=V25TA*V25TB
      IF (PR9.GE.0.) GO TO 1900
      Y=YC-V25TA*(YC-YY)/(V25TA-V25TB)
      WRITE (13,9999) X, Y
 1900 V25TB=V25TA
      YY=YC
 2000 CONTINUE
C
C
C*****INTERPOLATES IN THE KO DIRECTION
C
C
      DO 3000 IY=1, LIMY
      XX=1.
      CAPTB=YRS(1,IY)-.75
      QT30B=YRS(1,IY)-1.0
      QT50B=YRS(1,IY)-1.25
      QT99B=YRS(1,IY)-1.5
      V050B=PDV(1,IY)-PARM1
      V200B=PDV(1,IY)-PARM2
      V500B=PDV(1,IY)-PARM3
      V999B=PDV(1,IY)-PARM4
      V25TB=PDV(1,IY)-PARM5
      DO 3000 IX=1, LIMX
      CAPTA=YRS(IX,IY)-.75
      QT30A=YRS(IX,IY)-1.0
      QT50A=YRS(IX,IY)-1.25
      QT99A=YRS(IX,IY)-1.5
      V050A=PDV(IX,IY)-PARM1
      V200A=PDV(IX,IY)-PARM2
      V500A=PDV(IX,IY)-PARM3
      V999A=PDV(IX,IY)-PARM4
      V25TA=PDV(IX,IY)-PARM5
 2030 XC=1990.*FLOAT(IX)+500.
      Y=1990.*FLOAT(IY)+500.
 2090 PR1=CAPTA*CAPTB
      IF (PR1.GE.0.) GO TO 2100
      X=XC-CAPTA*(XC-XX)/(CAPTA-CAPTB)
      WRITE (3,9999) X, Y
 2100 CAPTB=CAPTA
      PR2=QT30A*QT30B
      IF (PR2.GE.0.) GO TO 2200
      X=XC-QT30A*(XC-XX)/(QT30A-QT30B)
      WRITE (4,9999) X, Y
 2200 QT30B=QT30A
      PR3=QT50A*QT50B
      IF (PR3.GE.0.) GO TO 2300
      X=XC-QT50A*(XC-XX)/(QT50A-QT50B)
      WRITE (7,9999) X, Y
 2300 QT50B=QT50A
      PR4=QT99A*QT99B
      IF (PR4.GE.0.) GO TO 2400
      X=XC-QT99A*(XC-XX)/(QT99A-QT99B)
      WRITE (8,9999) X, Y
 2400 QT99B=QT99A
      PR5=V050A*V050B
      IF (PR5.GE.0.) GO TO 2500
      X=XC-V050A*(XC-XX)/(V050A-V050B)
      WRITE (9,9999) X, Y
 2500 V050B=V050A
      PR6=V200A*V200B
      IF (PR6.GE.0.) GO TO 2600
      X=XC-V200A*(XC-XX)/(V200A-V200B)
      WRITE (10,9999) X, Y
 2600 V200B=V200A
      PR7=V500A*V500B
      IF (PR7.GE.0.) GO TO 2700
      X=XC-V500A*(XC-XX)/(V500A-V500B)
      WRITE (11,9999) X, Y
 2700 V500B=V500A
      PR8=V999A*V999B
      IF (PR8.GE.0.) GO TO 2800
      X=XC-V999A*(XC-XX)/(V999A-V999B)
      WRITE (12,9999) X, Y
 2800 V999B=V999A
      PR9=V25TA*V25TB
      IF (PR9.GE.0.) GO TO 2900
      X=XC-V25TA*(XC-XX)/(V25TA-V25TB)
      WRITE (13,9999) X, Y
 2900 V25TB=V25TA
      XX=XC
 3000 CONTINUE
 9999 FORMAT (2F25.5)
      STOP
      END
```

Additional Engineering Parameters

		Mining	Benefi-ciation	Lunar Launch*	Refining	Manufac-turing
Requirements for Process Expendables	$\frac{T/yr}{T \text{ process capital}}$	8×10^{-4}	8×10^{-4}	1.6	.18	.01
Cost of Process Expendables	$\frac{\$}{T}$	2000	2000	1000	6000	5000
Requirements for Replace-ment Parts	$\frac{T/yr}{T \text{ process capital}}$	8×10^{-2}	8×10^{-2}	.1	.12	.1
Personnel Requirements	$\frac{\text{men}}{T \text{ process capital}}$	.05	.05	.05	.04	.08
Energy Requirements	$\frac{MW}{T \text{ process captial}}$	10^{-4}	10^{-4}	.08	.06	.2
Productivity	$\frac{T/yr \text{ output}}{T \text{ process capital}}$	8000	8000	160	60	10
Retention	$\frac{T \text{ out}}{T \text{ in}}$	1.0	.2	.9	1.0	.95

*Assume electrically powered mass driver

Detailed Description of Base Case Technology

The base case technology is designed to produce solar power satellites. Lunar soil is mined and beneficiated on the moon and then launched into space by a lunar mass driver. Finally, the lunar materials are refined and processed into useful products in Earth orbit. The underlying assumptions are as follows:

Capital

Final capital mass	100,000 tons
Space production ratio	.85
Process capital	$11,000/ton
Energy production	14 tons/MW on the moon 10 tons/MW in space $6,000/ton

Expendables

Space production ratio	.3
Replacement parts	$11,000/ton
Personnel support	.01 tons/man/day $3,000/ton
Personnel	100% overhead 4 shifts/year (2 crews times 2 rotations) $100,000/year wage

Output and Related Expendables

Revenue	$100,000/year/ton SPS
Rectenna capital	$45,000/ton SPS
Rectenna expendables	$1,350/year/ton SPS (only output-related expendable)

Transportation

Cargo	$1 million/ton into orbit*
Personnel	$2 million/ton onto the moon ± One man = .085 ton
Vehicle	$250 million/Shuttle Three-week turn around time 30 tons/flight $6,000/ton
Discount Rate	10%

*This assumes 1980's projected costs for operation of the Space Transportation System from Earth to LEO.

±This assumes availability of lunar oxygen in LEO. The costs would be approximately 2 times greater for all propellant supplied from Earth.

Appendix 2. Base Case Technology

Input Parameters for Computer Program

A	1.0
B	1.0
C	1.0
F	$1,421,000/ton expendable
G	$1,173,000/ton capital
P1 (fleet cost)	$555,555/ton per year transport capability
P2 (revenues)	$1,000,000,000,000
P3 (fixed R&D costs)	$150,000,000,000
P4 (R & D bias)	$0./ton
RATE	1.1
RHO	2.55 tons output/yr/ton capital
RM(m)	.30 tons expendables from lunar soil/ton capital
RN(n)	.85 tons capital from lunar soil/ton capital
WANT (SMF mass)	100,000 tons
Z	.1545 tons expendable/yr/ton capital

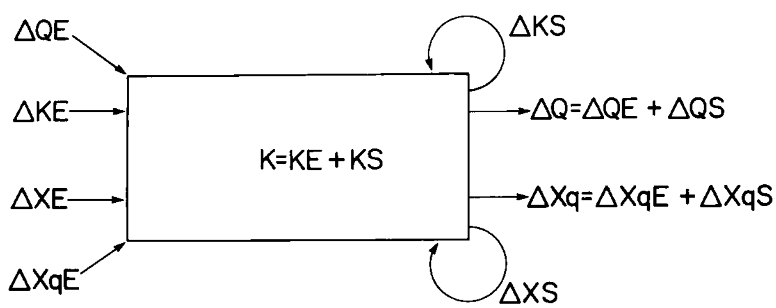

Figure 1. Material flow through the space industrial complex.

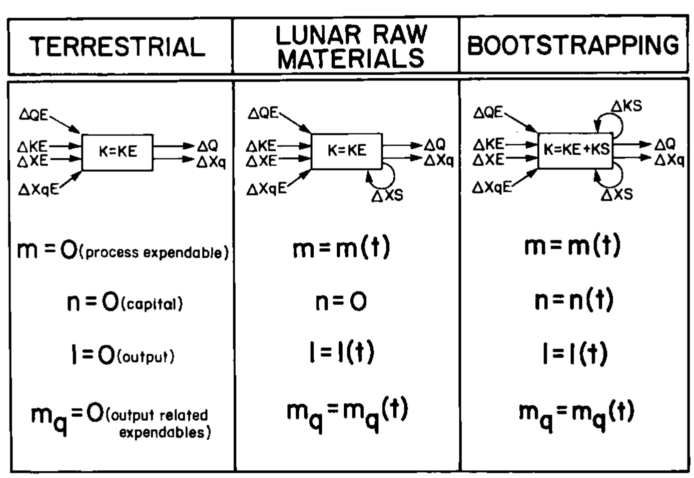

Figure 2. Strategies for space industrialization.

Fractions of various mass flows made of extraterrestrial materials.

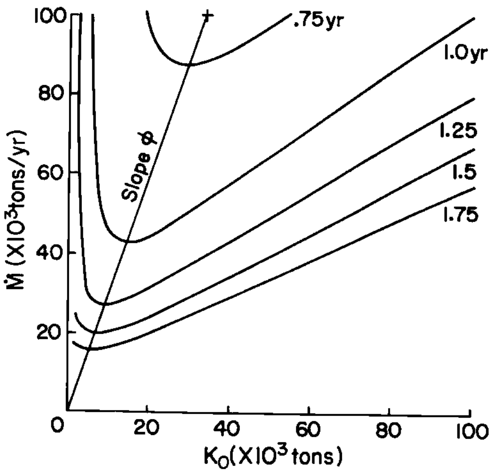

Figure 3. Isocost curves for establishing an SMF of 100,000 tons ($ billions).

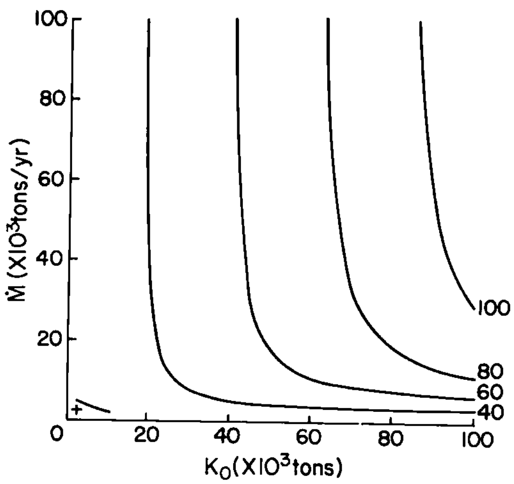

Figure 4. Isotime curves for establishing the SMF.

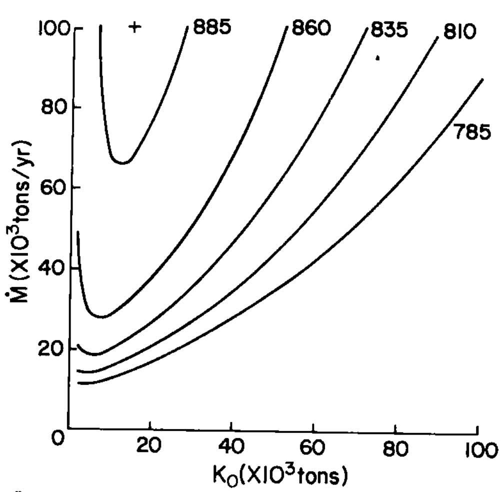

Figure 5. PDV for all space operations ($ billions).

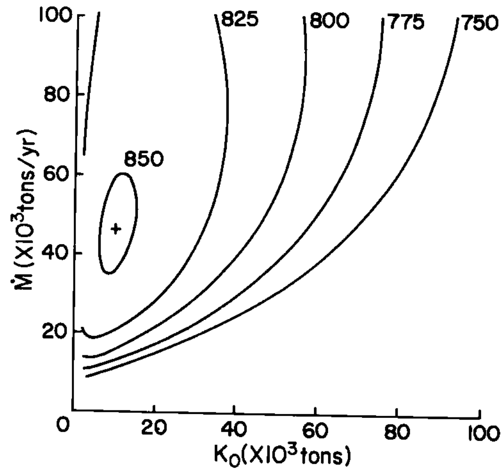

Figure 6. PDV for entire project except R & D ($ billions). Inclusion of R & D costs changes only the absolute magnitudes, and not the relative positions, of the curves.

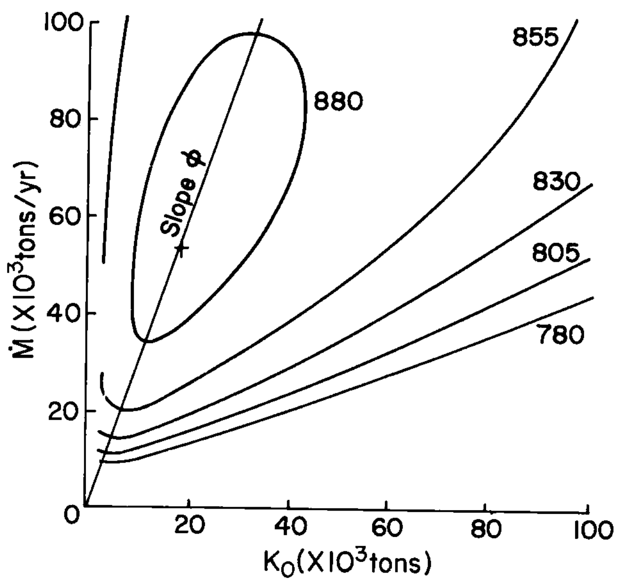

Figure 7. PDV of entire project excluding costs of R & D ($ billions). Inclusion of R & D costs changes only the absolute magnitudes, and not the relative positions, of the curves.