START UP CONSIDERATIONS FOR A SPACE MANUFACTURING ENTERPRISE

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Abstract

We discuss costing considerations for inclusion in planning a Space Manufacturing Enterprise. Cost Categories are: RDT&E, Procurement, Lift (of materiel and personnel to low earth orbit), Depreciation, Space Personnel, Mission Control, Administration, Interest, Inflation and Taxes. A hypothetical facility is examined. Assumed RDT&E begins in 1980, with actual Space operations beginning in 1985. Habitats and work facilities are established in Low Earth Orbit, on and near the Moon, and at a manufacturing facility in Space where ore from the Lunar Surface can be chemically processed, fabricated and combined with special components from Earth to produce Solar Power Satellites (SPS's). Each SPS, placed in geosynchronous orbit, transmits, via microwave, 10 gigawatts of received power to suitable earth stations. Four SPS's are built during the 1985-92 development period. The facility can then provide 2.4 SPS's per year through the efforts of 3,096 workers in Space in the steady state. Raw costs to reach steady state are estimated at $101.6 billion (1975 dollars). The 1980 Present Value Discount Cost (exclusive of taxes and inflation) is $44.6 billion. The initial investment is recovered by 1994, and the average rate of return before taxes by the year 2000 is 7.4% per year.

Introduction

Vajk, Engel and Shettler [1] reported on "Habitat and Logistic Support Requirements for the Initiation of a Space Manufacturing Enterprise". Here we continue this discussion by focussing on the cost considerations which must be taken into account in planning such an enterprise. We will also comment on the necessity for allowing long lead time for preparations required prior to the actual commencement of the construction of the enterprise. Finally we will discuss the benefits to be gained by the establishment of such an enterprise, and we will indicate possible areas for research to improve understanding of certain facets of the enterprise and to point the way toward further extension of the basic concept.

In this paper, we discuss the cost and planning considerations which were uncovered during the research we reported on earlier. This work[1] centered on a specific scenario which was described in a fair amount of detail. We will repeat key elements of this scenario so that the reader can place the results presented here into a suitable frame of reference.

Summary of Scenario

Space operations leading to construction of a Space Manufacturing Enterprise are begun in 1985. The first phase in development of this enterprise is completed in 1992. The enterprise consists of three major components: one in Low Earth Orbit (LEO), one on and near the surface of the Moon (LUNAR), and the third, the major Space Manufacturing facility (SMF) in a suitably chosen orbit readily accessible from LEO and LUNAR. Each of these components include adequate living quarters or habitats to house the personnel at these facilities, and a portion of the total manufacturing plant at which appropriate functions can be carried out.

Material and personnel are brought from Earth to the LEO component initially via the NASA shuttle. As facilities are expanded and the rate at which Earth Material and Personnel are required to be brought into Space increases beyond the capability of the NASA Shuttle System, further Earth to LEO deliveries will be accomplished by means of a Shuttle-derived heavy lift vehicle (SD/HLV) and later a more advanced reusable single-stage-to-orbit launch vehicle (SSTO).

In addition to the shuttle operation just described, the enterprise must acquire, assemble and place into Space, a Space Fleet consisting of various chemically propelled orbital transfer vehicles (OTV's) to move personnel among the components of the enterprise, Mass Driver Reaction Engines (MDRE's)[2] to move materiel, and the necessary depots and propellants to support these vehicles.

The entire enterprise is rendered less expensive through the development of an ability to mine the surface of the Moon as discussed elsewhere [3]-[7]. The ore thus obtained is launched from the Moon's surface to a "Catcher" in Lunar Orbit by means of a Mass Driver[8]-[12] which has already been demonstrated in bench-top prototype form[13]. From the catcher the ore is loaded onto MDRE's (some of the ore being used to propel the MDRE's) and carried to the SMF where it is refined and processed into usable form for structural materials, shielding (by habitats to protect the interior from excessive solar radiation) and oxygen for life-support.

Much of the ore thus carried to the SMF is used to construct Solar Power Satellites (SPS's) which are the useful product provided by this enterprise. In the development explored in this paper, it is assumed that 91% of the mass of each SPS is provided from lunar ore and the remaining 9% consists of high technology components and material not readily obtainable from lunar ore hence is brought up from Earth. The SPS's constructed each have a total mass of 100,000 metric tons. When completed they are towed into geo-synchronous orbit above the Earth's equator and placed into operation. They convert solar energy into electrical energy which is beamed down to Earth via microwave and received at the rate of 10 gigawatts of power per SPS at suitable constructed receiving stations which feed the power into the local electrical power grids. During the first phase of the development of the enterprise, four of these SPS's are put into operation, and, after 1992, the enterprise is able to build 2.4 new SPS's per year.

Costing

In estimating costs associated with establishing this enterprise the following cost categories have been considered:

1. Res., Dev., Test and Eval.
2. Procurement
3. Lift (from Earth to LEO)
4. Depreciation
5. Space Personnel
6. Mission Control
7. Administration
8. Interest
9. Inflation
10. Taxes
11. Annual Raw Costs

Assumptions and methodologies employed in estimating these costs, and results obtained, will now be presented. All costs are presented in terms of 1975 dollars.

1. Res., Dev., Test and Eval.

Research, Development, Test and Evaluation (RDT&E) of all classes of items to be procured and placed into Space for the enterprise must be completed before the first item in each class is launched. This will generally be accomplished over the five year period proceeding procurement with costs spread evenly over the period. Major 1987 procurements for the SMF manufacturing plant and the Space Fleet have their RDT&E costs spread over the seven years of 1980 - 1986, and the procurement in 1991 of six SSTO's is preceeded by RDT&E with its costs spread over the eleven year period 1980 - 1990.

RDT&E costs generally varied from $14 to $16 million per metric ton. Estimation of these costs has generally been accomplished be methods described by O'Neill [2] and Driggers [10], as amplified by them in further informal conversations with the authors. A detailed listing of items requiring RDT&E and their procurement schedules is found in the Scenario as summarized here and described more fully in our earlier paper.[1]

Examples of some major RDT&E items, their masses and costs are found in Table 1.

Table 1: Sample RDT&E Items

Item	Mass (Metric Tons)	RDT&E Cost (Millions)
MDRE	174	$174
Environment Control Life Support Pod	10.5	651
Caisson	29	812
Electrolysis & Liquefaction System	27	812
Mass Driver	575	1,300
Sacking Factory	50	700
Lunar Surface Vehicle and Tools	15	615
Lunar Lander	12	2,500
SD/HLV[14]		1,300
Heavy MDRE	226	420
SSTO[15]		7,000

2. Procurement

Items are assumed to be procured after any necessary RDT&E as described above in time for launching as required in the Scenario [1]. Masses are stipulated in the complete scenario for all items that must be procured. Procurement costs, generally between $300 to $1000 per kilogram, have been estimated by the methods described by O'Neill [2] and Driggers [10].

Examples of some major procurement items, their masses and procurement costs are found in Table 2.

Table 2: Sample Procurement Items

Item	Mass (Metric Tons)	Procure-ment Costs (Millions)
Mass Driver	575	$525
MDRE	174	174
Sacking Factory	50	25
SD/HLV	--	100
SSTO	--	250

3. Lift (from Earth to LEO)

Initially, lift of personnel and cargo from Earth to Low Earth Orbit is via the NASA Shuttle (STS). Later, as the required rates of lift increase beyond the capabilities of the shuttle system (which is expected to be able to launch a maximum of 60 flights per year), first a Shuttle Derived Heavy Lift Vehicle (SD/HLV)[14], and then a single - stage - to - Orbit Vehicle (SSTO)[15] will be required. Characteristics of these three vehicles are listed in Table 5 of our earlier paper [1], and summarized here in Table 3.

Table 3. Characteristics of Earth to LEO Vehicles

Vehicle	Cargo Capacity/ Flight (Metric Ton)	Lift Costs/Flight (Millions)
STS	29	$20
SD/HLV	113	19.60
SSTO	227	3.6

Total Materiel lifted, classified by ultimate destination, LEO, LUNAR, SMF, Fleet or SPS, and total tonnage of personnel and baggage are shown in Table 4, for each of the years 1985 - 1992. Personnel and baggage (including about 650 pounds per person lifted) are also shown.

Lift costs are determined by the total called for in each year, the capacity of the lift vehicles per flight which determines the number of flights required, and the lift cost charged per flight of each vehicle. Table 3, showing characteristics of the lift vehicles, combined with the lift requirements shown in Table 4 combine to yield total lift costs. The STS is used for materiel and personnel during 1985 through 1987 at the rate of 60 flights per year, and in 1988 through 1990 as required for personnel only at the rates of 7, 16 and 41 flights per year respectively. The SD/HLV, carrying materiel only, makes 80 flights in 1987, 100 in 1988, 120 in 1989 and 120 in 1990. The SSTO makes 100 flights carrying materiel and personnel in 1991 and 115 flights in 1992.

4. Depreciation

While it may be unduly conservative (i.e. expensive) and simplistic, we have assumed straight line, ten year life depreciation on the procurement cost of all non-consumable items lifted from Earth. In addition we have similarly calculated depreciation on lift costs (as replacement items must also be lifted). This has been done by taking the ratio of mass of depreciation materiel to the overall capacity of the vehicle flights carrying it in each year, and multiplying that ratio by the lift cost of those vehicle flights. Again this is conservative as lift is more expensive in the early years, so that replacement lift in late years will be less expensive than the allowance provided for this function.

Table 4: Total Earth to LEO Lift (Metric Tons)

YEAR	Materiel for: LEO	LUNAR	SMF	FLEET	SPS	ΣMATERIAL	PERSONNEL AND BAGGAGE	TOTAL LIFT
1985	257	1,243	---	222	---	1,722	9	1,731
86	174	69	---	1,486	---	1,728	10	1,738
87	75	708	3,143	4,696	2,000	10,622	34	10,656
88	75	951	4,103	5,423	650	11,202	203	11,405
89	46	153	4,608	6,711	2,000	13,518	464	13,982
90	46	46	5,006	3,027	5,350	13,475	1,189	14,664
91	46	46	6,727	3,021	12,000	21,840	735	22,575
92	46	96	2,875	908	21,600	25,525	482	26,007
Total during build-up	765	3,312	26,462	25,494	43,600	99,632	3,126	102,758

Items not depreciated were: Life support consumables, propellants (for chemically propelled personnel carriers in the space fleet), sacks (for carrying ore to be ejected from the Mass Driver to the Catcher), Spare Parts, and the pelletizer (as it is required only in the early years when it is necessary to grind up external hydrogen tanks from the STS's to obtain reaction mass in suitable form to propel MDRE's). In addition, the SD/HLV's and the 174 ton MDRE's are regarded as expendable, as they are no longer used after being replaced by larger vehicles, hence they are not depreciated. No allowance is made to possible salvage value that might be recoverable on these vehicles when they are no longer in use. Finally, Earth materiel used in SPS construction is not depreciated, as that materiel is incorporated in SPS's the depreciation of which, once they have been completed, is not relevant to the purposes of this study.

5. Space Personnel

Space Personnel lifted to LEO for employment there or transfer to an employment at LUNAR or the SMF are lifted in quantities and mixes of occupational specialty on launch schedules to conform with the scenario.(1)

Space personnel related costs include:

Application processing costs (readers).

Screening and testing costs (testers and testing facilities).

General training costs (instructors and training facilities to prepare candidates for life in space.

Special training costs (training for working in space, probably covered by contract to a qualified agency such as NASA).

Debriefing.

Salaries and fringe benefits of space destined employees are determined during their entire tours from screening through debriefing.

It is assumed that:

1/10 of applicants accepted for screening and testing will be hired for entry into the training program.

3/4 of the trainees complete general training successfully.

1/2 of the advanced trainees complete special training.

98% of the space personnel who complete all training, are launched into space and complete a year's tour in space.

Screening testing and training take up about two years time.

Near the end of 1990, over 1,000 people have completed tours at the SMF according to the Scenario. It is assumed that experience gained in administering the program makes it possible to screen applicants more efficiently so that the fraction of applicants accepted for screening and testing will be increased from 1/10 to 1/4, after 1990. Also, it is assumed that tours at the SMF will be increased from one to two years at this time (as the SMF habitats are large enough to be spun so as to provide artificial gravity) while personnel at LEO and LUNAR will continue to have one year tours (since these locations do not have the possibility of providing adequate gravity).

In accordance with these assumptions, we see that until 1990, 80 people must have been accepted for screening, testing and training approximately two years before required launch time for every 3 required in space, or 26 2/3 for every one person required in space. After 1990 this ratio improves and becomes 32 to 3 or 10 2/3 to 1. Thus every position at LEO and LUNAR requires entry into the overall screening, testing and training program of 10 2/3 people annually while for the SMF which has two year tours the ratio further improves to 4 1/3 to 1. Thus by 1989 the selection testing and training program must, in order to supply the required 48 people at LEO, 48 people at LUNAR and 3000 at the SMF required in 1991 and thereafter must be able to process (10 2/3 x 2 x 48) + (5 1/3 x 3000) or 17,024 people annually, as opposed to the figure of 26 2/3 x 3096 or 82,560, which would have been required in accordance with the earlier standards.

While the above assumptions were made after discussions with scientists and administrators familiar with the training requirements of the NASA Program and military and industrial programs also, the estimates made here are the sole responsibility of the authors. We recognize that there is not much firm data and experience with a Space Program involving large numbers of people living and working in Space for extended periods of time, so that the estimates presented here are little more than educated guesses. Clearly further research on these matters is required, if a project of this sort is to be carried forward seriously. Nevertheless, the relative magnitude of these Space Personnel costs seems to be small enough that further attention to this subject does not seem warranted at present.

6. Mission Control

We have all seen the television broadcasts of manned Space Flights, with impressive views of the banks of personnel, video displays and computers massed together in Mission Control to keep in touch with a single vehicle in Space so as to provide it with the added back-up of safety and control that can be delivered from the ground. If such a control program were to be instituted for the series of flights involved in the construction and operation of this space enterprise, it would become very cumbersome.

In our attempts to deal with this portion of the problem, we found little in the way of experience with comparable programs to provide useful guidance (as we have reported in our discussion of Space Personnel related costs). We have made assumptions to enable us to estimate reasonable costs to be associated with Mission Control as follows:

A manned mission control position is required for each vehicle in the space fleet, one for control associated with the LEO facility, one for the LUNAR facility and one for each 500 personnel at the SMF (rounded up). The Scenario enables a determination to be made of the number of vehicles in the Fleet and the number of personnel at SMF so that the numbers of control positions required for the years 1985 through 1992 are 7, 9, 18, 25, 40, 73, and 76 respectively.

Each mission controller is employed for 8 hours per day, 5 days per week, 48 weeks per year, or 1,920 hours per year. Since there are 8,760 hours in a year, it follows that 8,760/1,920 = 4.6 mission controllers must be employed per control position required.

Combining the number of control positions each year with an assumed $50,000 yearly cost per controller enables the overall mission control costs to be determined.

7. Administrative Costs

Again, in the absence of firm data, an assumption has been made to provide for administrative costs.

We assume that administrative costs in each year are one third the Space Personnel related costs discussed in 5. above, and that these costs will commence at the level required for initial operations (first Space Personnel are hired in 1983) at the time RDT&E commences in 1980.

8. Interest

It is assumed that liquid assets of the enterprise can be managed so as to accrue interest at the rate of 10% per year. For this reason, present value discounting (which will be discussed later) will also be accomplished at the rate of 10% per year. Variations in this interest rate can readily be made the subject of a sensitivity analysis.

9. Inflation

The effect of inflation can be handled by increasing raw costs of whatever type by the annual inflation rate compounded from the base year to the year in question. Thus if the inflation factor for t years from the base year is $(1+r)^t$. Combining this with the interest factor for present value discounting of $(1.1)^{-t}$ yields a combined inflation, and interest discount factor of $(\frac{1+r}{1.1})^t$ for t years from the same base year.

In this paper we have done all costing in terms in 1975 dollars so that we have taken r as zero. A serious attempt to deal with the effects of inflation requires determination of r for the various classes of costs to be considered. For present purposes it suffices to say that if the inflation rate remains positive and under 10%, the adjusted costs will lie between the discounted costs and the raw costs provided in this paper.

10. Taxes

The effect of taxes on the financial condition of the enterprise under study is a function of the nature of its organization and ownership, possible special legislation, and the overall profit and loss position before taxes for each year of its operation.

If, for example, the enterprise is set up as a governmentally owned or sponsored organization, it might be tax-exempt. This might also be the case if the organization is established under international auspices, say as a U.N. enterprise. On the other hand, a privately owned commercial organization, even though sponsored by the government (the Communications Satellite Corporation is an organization of this type that might be studied for comparative analysis) might be subject to income taxes as well as other possible taxes (property taxes, etc.).

It also seems to be reasonable to observe that taxes will be absent or negligible during the formative years of the enterprise when it is spending money faster than it earns it. As will be seen shortly, this is the condition in which this enterprise exists until 1991, so that taxes over the period 1980 - 1992 should be virtually non-existent.

We have taken taxes as zero in this paper so that estimates of return represent return before taxes.

11. Annual Raw Costs

The costs discussed in the ten categories preceeding this section have been determined in accordance with the Scenario and assumptions presented here. They are shown in Table 5 and indicate a total undiscounted raw cost for the build-up period of 1980 through 1992 of $101.6 billion 1975 dollars, and an annual raw cost thereafter of $10.3 billion. Since we are, for the present, omitting the effects of interest, inflation and taxes, only the first seven cost categories are included in this table.

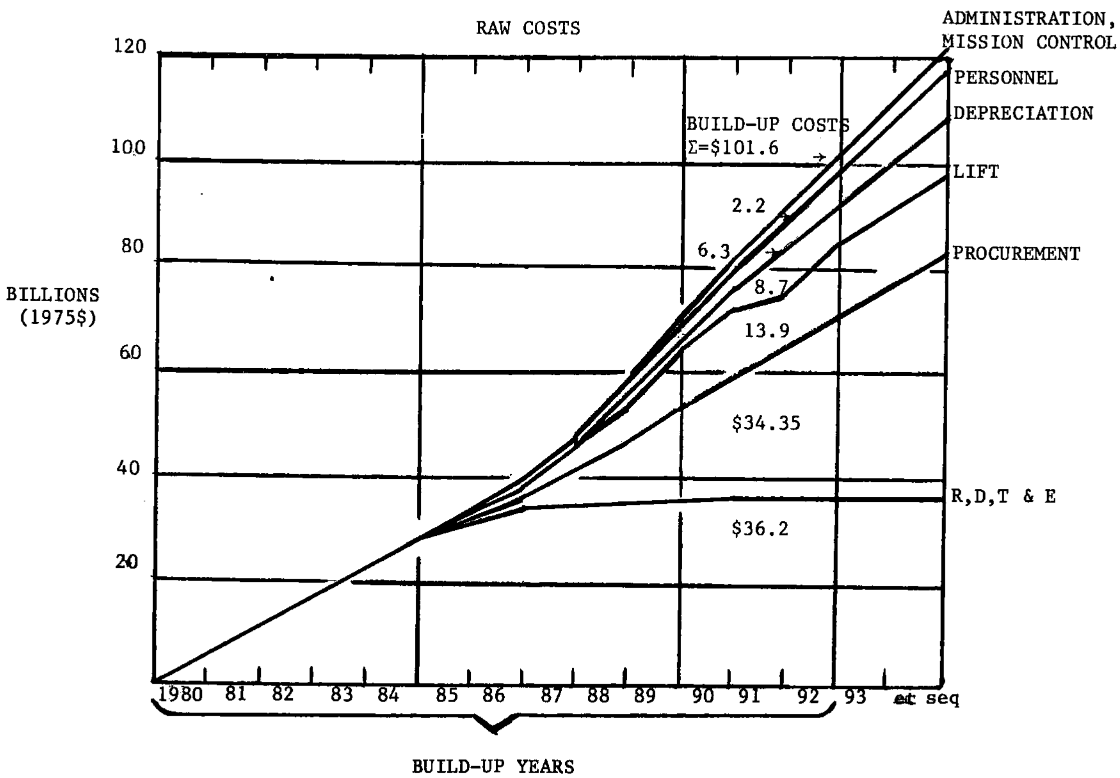
The same results are also shown in Figure 1 to facilitate an examination of the relative magnitudes and rates of change of the various cost categories. It can be seen that during the build up phase the single largest cost category is RDT&E which contributes just over one-third to the total build up cost, and as the build-up phase is completed it levels off and discontinues thereafter. Procurement is the next largest cost category, contributing one-third during the build up phase and is the most significant single cost thereafter. The remaining four categories together comprise almost one-third during the build-up phase and slightly more than half of the annual cost thereafter. These results are probably about right for the build-up phase overall, but the lack of firm information concerning the categories 5, 6 and 7 does not allow much confidence to be placed in conclusions concerning costs after 1992. Still the proportion of annual costs in these categories may be large enough to warrant further research in those areas.

Table 5: RAW COSTS
(BILLIONS OF $)

	1980	81	82	83	84	85	86	87	88	89	90	91	92	93 et seq
1. R,D,T & E	5.1	5.5	5.7	5.8	5.8	2.2	3.5	.7	.6	.6	.6	0	0	0
2. Procurement						1.4	.7	4.9	4.6	7.1	4.1	6.3	5.4	5.4
3. Lift						1.2	1.2	2.8	2.1	2.7	3.2	.4	.4	.4
4. Depreciation														
of 2.							.1	.2	.6	1.0	1.7	1.9	2.2	2.2
of 3.							.1	.1	.1	.3	.4	.04	.05	.05
5. Space Personnel				.003	.023	.026	.086	.4	.6	1.6	1.1	.8	1.6	1.6
6. Mission Control						.002	.002	.004	.006	.009	.02	.02	.02	.02
7. Administration	.001	.001	.001	.001	.008	.009	.03	.1	.2	.5	.4	.3	.5	.5
Annual Totals	5.1	5.5	5.7	5.8	5.8	4.9	5.7	9.2	8.9	13.8	11.4	9.7	10.3	10.3

$101.6 BILLION UNDISCOUNTED

Figure 1.



Income and Other Benefits

1. Income for the Space Manufacturing Enterprise

It is assumed that income for this enterprise will be derived from sales of the SPS's produced. The price charged is $10 billion per SPS. This has been selected as being comparable (in 1975 dollars) with the procurement cost of conventional electrical generating equipment on earth. Since the incremental cost of operation after 1992 can be seen, in Figure 5, to be $10.3 billion per year and 2.4 SPS's are produced each year from 1993 on (for an average annual income of $24 billion), it is clear that this price enable the enterprise to start operating at a profit (in fact the break even sales price is $4.272 million per SPS) and, once it has earned back its original building expenses to provide a respectable rate of return before taxes. This price is very competitive with generator costs, as no fuel is required for the SPS to produce energy. Each SPS is always in full sunlight (that would otherwise miss Earth altogether) and that is a free source of energy.

It is important to clarify what is and what is not included in the sales price of the SPS's, to discuss alternative means of reimbursing the enterprise for the power its SPS's can provide, and to consider other possible sources of income in addition to the SPS's.

One may question the wisdom of selling the SPS's. We have assumed that this is the procedure to follow, as this is the quickest way to convert the asset that an SPS represents into liquid assets on Earth that can be used for reinvestment, or to finance operating costs of the parent enterprise. Another alternative that can be considered is to charge for delivered power at a suitable rate per gigawatt-year. While rates could be established that would be as profitable in the long run as selling the SPS's, rentals would not return income as rapidly in the short run, so that the initial investment could not be paid off as rapidly as it could be by sale of the SPS's. It seems, therefore, that the rental alternative might not be attractive unless the enterprise is operated as a governmental agency (national, multi-national, U.N., or what have you) which is not constrained to provide a return on the original investment.

We assume that the sales price for an SPS covers the placement into geo-synchronous orbit of an operating SPS, initially beaming electrical power at the rate of 10 gigawatts to a suitably located Earth Station. The receiving facilities (antenna, converters, power grid into which the Earth Station is connected, etc.) are not part of the deal. Those facilities must be provided by the customer.

We further assume that the parent enterprise will not be responsible for operation and maintenance costs connected with the use of the SPS's. It is clear, however, that the enterprise is the logical entity to accomplish operation and maintenance of the SPS's, regardless of who owns them, and it seems quite reasonable to anticipate that profitable arrangements could be made for providing such services.

If, for example, one were to assume a twenty year life for an operating SPS, it would seem to be reasonable to charge $500 million per year for operation and maintenance of each satellite in operation. This would provide an increasing arithmetic progression of additional annual income that could become quite lucrative. After about eight years of operation, the annual operations and maintenance fee would match the annual sales income, and would increase even more thereafter. Of course there would be costs associated with providing such services, but if the annual construction costs are less than the annual income from sales, it should be evident that costs of operation and maintenance should be far less than the income generated by operation and maintenance fees.

In addition to the possibility of earning income from operation and maintenance fees, other possible sources of income for the Space Manufacturing Enterprise can be envisioned. One of the most obvious sources is the rental of reserve space in the habitats of the enterprise to clients who wish to work or experiment in the environment of space. Reserve space for on the order of 48 people exists starting about in 1987 at LEO and LUNAR, and reserve space is gradually built up at the SMF so that by 1992 there are 276 more habitat spaces available than the 3000 required to house the people working there. Income from rental of such reserve space would easily grow from about $50 million per year in 1987 to $275 million per year in 1992 and thereafter. This, of course, is paltry compared to the income anticipated from SPS sales, hence has not been considered further in this paper.

A possibly more lucrative source of income might be the rental of otherwise unused mining, refining and processing facilities when the plant has reached full size by the end of 1992. This would be possible because the overall production capacity of the plant will have to be greater than is required to produce 2.4 SPS's per year (which is the steady state goal of this development). Again, this possibility has not been further examined at this time, because the expected income that might be derived is speculative, and also for another reason.

The presence of excess production capacity (which had originally been required to bring to the desired 2.4 SPS per year production capability) suggests the very real possibility of further expansion of the enterprise bejond the 1996 level. This possibility will be discussed later in this paper.

In summary of the above, it may be seen that at the assumed sale price of $10 billion per SPS, since one SPS has been produced before the end of 1990, another in 1991, two in 1992, and 2.4 per year thereafter, the sales income becomes $10 billion in 1990, $10 billion in 1991, $20 billion in 1992, and an average of $24 billion per year thereafter.

2. Other Benfits

In addition to receiving income from the sale or rental of its products and facilities, as discussed in the previous section of this paper, the Space Manufacturing Enterprise, both by its existence and the goods and services it produces, provides benefits to individuals and organizations other than the enterprise itself.

The chief product provided by the enterprise is SPS's which transmit electrical energy to Earth. This brings a profit to the organizations that get the energy from the SPS's and re-sell it to other organizations and individuals. More importantly, however, the production of electrical energy by SPS's far outside the Earth's atmosphere is a clean and inexpensive way of providing energy to the Earth's population. In an era when petroleum reserves are dwindling fast, this kind of energy may be an important addition to our energy supply. The enterprise delivers 82.5 gigawatt years of power by the end of 1993 according to the Scenario analyzed in this paper, 64 gigawatt years in 1994 and 64 + 24t gigawatt years, in the t^{th} year thereafter.

The enterprise also provides three other benefits. It provides employment to its own employees (at the level of 3096 in Space plus on the order of 1,000 on Earth in permanent employment (administrators, mission controllers, screeners, testers and trainers of candidates for Space employment). Additionally it provides employment to the workers who produce the goods that are manufactured on Earth for launching into space by the enterprise.

By virtue of the necessity of providing livable habitats for its employees in Space, the enterprise, by 1992, has essentially constructed a town with over 3,000 inhabitants and a profitable industry. More importantly the experience gained in accomplishing this will be invaluable as a jumping off point for the initiation of larger settlements in Space, and additional industries, research activities and other activities of immense potential and actual value for Mankind.

Analysis

Having presented the raw costs and annual incomes that may be associated with the Scenario under study, it is possible to draw up a hypothetical financial forecast for this Space Manufacturing Enterprise. As discussed earlier, we will not consider the effects of inflation and taxes in this discusstion, and we restrict our consideration of income to the income derived from sales of SPS's. We will produce this financial forecast in two stages. First we will derive the start-up cost required to set this operation in motion and keep it going until it is self-sustaining. Then we will determine the total worth of the enterprise as a function of time and illustrate the rate of return that can be achieved.

1. Start-up Cost

We assume the annual raw cost as shown in Table 5. We assume the annual sales incomes for the years 1990 and thereafter as listed at the end of the section on Income for the Space Manufacturing Enterprise. We further assume, as discussed in the sub-section of Cost Considerations dealing with Interest, that liquid assets available on Earth may be invested at the rate of 10% compounded annually. We then calculate the amount of money which must be available at the start of the enterprise, to enable it to operate without borrowing until the annual volume of sales income exceeds annual operating costs. To do this we define:

B_o=desired liquid worth at beginning of year 0 (1980).

$B_t(b)$=liquid worth beginning of year t, assuming an initial worth of b.

0_t= Operating Income for year t.
=(Sales Income year t) - (Raw Costs year t).

We then observe that:

$$B_{t+1}(b)= [B_t(b)-0_t] \times 1.1 \text{ ------------------(1)}$$

as 10% per year is the rate of return on capital.

We then wish to find B_o, where:

$$B_o = \text{Minimum } b \text{ such that } B_t(b) \geq 0 \text{ -----------(2)}$$
for $1 \leq t \leq 12$, (1981-1992)

This is because all operating incomes 0_t for those years are negative whereas they are positive from 1993 on.

From equations (1) and (2), proceeding by recursion we can readily conclude that:

$$B_t(b)=(1.1)^t \times b+\sum_{i=0}^{t-1} 0_i(1.1)^{t-i},\ 1 \leq t \text{ ---------(3)}$$

and we desire that the expression on the right hand side of equation (3) shall be greater than zero for $1 \leq t \leq 12$.

This leads us to conclude that we require of b:

$$b \geq -\sum_{i=0}^{t-1} 0_i(1.1)^{t-i}/(1.1)^t \text{ for } 1 \leq t \leq 12 \text{ -------(4)}$$

If then follows from Equations (2) and (4) that

$$B_o = \underset{1 \leq t \leq 12}{\text{Min}} -\sum_{i=0}^{t-1} 0_i(1.1)^{t-i}/(1.1)^t \text{ -----------(5)}$$

Performing the above calculation (which can be done easily by hand with a programmable calculator) yields:

$$B_o = \$44.546 \text{ billion (in 1975 dollars) -----(6)}$$

We round this up to $44.6 billion as the Present Value Subsidy required to launch this Space Manufacturing Enterprise.

This figure, as stated earlier excludes the effect of interest and taxes. Taxes should be zero through 1992 in any case. Inflation between zero and 10% annually would produce a Present Value Subsidy between the $44.6 billion just derived (for no inflation) and the total undiscounted Raw Cost Figure in Table 5 of $101.6 billion (for 10% annual inflation).

2. Total Worth of the Space Manufacturing Enterprise

To calculate the total worth of the enterprise we enter the value of $44.6 (billion) for b into Equation (3) and calculate B_t for all positive integral t. From Table 5)or rather the more detailed data used to derive the entries in the table) we calculate the increment to plant worth for each year as the total of the depreciable procurement costs incurred during that year. These costs represent the worth of the non-consumable Earth Materials that were incorporated into the enterprise during the year. These costs represent the worth of the non-consumable Earth Materials that were incorporated into the enterprise during the year. Other costs are operating costs that do not add to plant worth. These incremental depreciable procurement costs are totalled accumulatively to yield:

P_t=plant worth at end of year t.

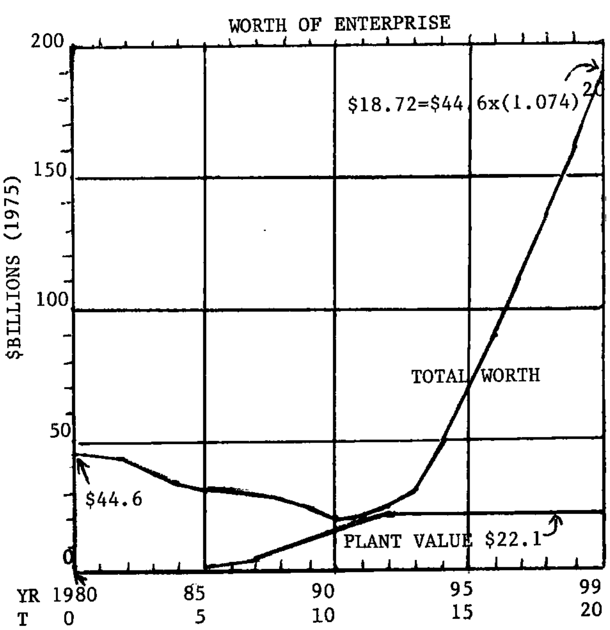
Then we have simply that the total worth of the enterprise at the end of the year t or W_t is given by

$$W_t=P_t+B_t \quad \text{-------------------------------(7)}$$

Average rates of return on the original investment may easily be calculated.

A graph of the results thus obtained is shown in Figure (2).

Figure 2



It can be seen that Total Worth is minimum with a value of just under $20 billion at the end of 1990. At this time virtually the entire worth of the enterprise is in the operating plant. Operations during 1991, based on costs incurred in 1990 produce Sales Income greater than costs and start to increase Total Worth thereafter. If the operation continues after 1992 at the 2.4 SPS per year level with no further plant expansion, the Plant Value stabilizes at $22.1 billion, and the Total Worth surpasses the initial investment by the end of 1994.

By the end of this century, Total Worth has increased to $187.2 billion representing an average annual rate of return over the 20 years of existence of the enterprise of 7.4%. If operations continue at this level indefinitely, the Total Worth of the Corporation becomes essentially identical to the result of compounding the initial investment of $44.6 billion at the annual rate of 10% by the year 2022 and thereafter. This is due to the fact that plant size has been stabilized in accordance with the Scenario, and all profit from operations is reinvested at 10% rather than used for further plant expansion and inherently more profitable operations.

Conclusions and Recommendations

1. Conclusions

a. We have demonstrated a methodology which can be employed to determine such factors as:

Present Value Subsidy required to initiate a Space Manufacturing Enterprise.

Detailed costs associated with the construction and operation of the Enterprise, and detailed itemization of RDT&E, and procurement required, as well as personnel required.

Rate of production of useful end products, in this case Solar Power Satellites.

Total Worth of the Enterprise as a function of time.

b. IF the technical estimates concerning material required to construct the plant, productivity capacities, habitat, life support, space vehicle requirements, Earth to Low Earth Orbit lift requirement, personnel selection testing and training, and all cost estimates are valid:

THEN we can conclude that:

A present value subsidy of between $44.6 billion and $101.6 billion (in 1975 dollars), depending upon the rate of inflation, can, if made available in 1980, underwrite this Space Manufacturing Enterprise.

The enterprise can produce 4 SPS's during 1980-1992 and 2.4 per year thereafter, each SPS delivering 10 gigawatts of power to Earth, for a total of 82.5 gigawatt years delivered by the end of 1993, 64 gigawatt years in 1994, and 64 + 24t gigawatt years in each year t years later, thereafter.

The enterprise can operate profitably from 1994 on with an average annual rate of return of 7.6% over the period 1980-2000 and about 10% by 2022 and thereafter, basing this calculation solely on income from SPS sales.

The enterprise has excess production capacity beyond the 2.4 SPS per year capability which can be used to accomplish further plant expansion.*

2. Recommendations

In view of the uncertainty connected with many of the technical and cost estimates mentioned in this paper, and in view of the apparent profit potential of this enterprise and the magnitude of the quantity of energy than can be delivered to Earth (without undesirable side fffects), we recommend to NASA and the U.S. Department of Energy that:

> A major study effort, including research to validate or improve all technical and costing estimates particularly those pertaining to personnel, mission control and administration be initiated forthwith so that, if warranted, actual construction of a Space Manufacturing Enterprise can be initiated as soon as possible.

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*One of the authors is at present embarked upon research to determine a minimum cost procedure to accomplish expansion of the plant described in this study to a size that will enable 40 SPS's to be produced per year by the year 2000. This objective has been selected as particularly meaningful; at that level 40 SPS's per year or 400 gigawatts per year is estimated as the worldwide retirement rate of electrical generating equipment by that time.

Q. Can you significantly reduce the lift cost of almost $14 billion (by 1993) by using shuttle derivatives?

A. We will be using a shuttle-derived vehicle by that time, but the trouble is we need a lot of material which means many, many flights--far more than the 60 per year that the shuttle will fly initially. The costs just go up. There's a lot of material to be brought up there.

Q. What would the present value come to if you applied a zero rate of interest?

A. $101.6 billion.

Q. In your graph of lift quantities by year, why is there such a large jump in the year 1992?

A. At that time we will have really gone full-scale into the production of solar power satellites. By 1992 we will be producing them at the rate of 2.4 per year.

Q. The proper way of accounting for benefits is the producer's surplus plus the consumer's surplus. The consumer's surplus is the value to the users of the power produced by this enterprise above and beyond what they are going to pay, integrated over all the users. The consumer's surplus is the profit made by the enterprise. I think, then, there's a problem with your benefit methodology.

A. You are probably right. One of my slides showed that the value of this enterprise increased to the point where it had a 7.4 percent average rate of return on the original investment, due to the fact that it did make a profit when it sold the satellites at the rate of $10 billion per satellite. That would be from the producer's point of view.

From the point of view of the users on Earth, we are selling these satellites according to the assumptions of this study, at a rate which is competitive with the cost of generating equipment on Earth at the present time. Therefore the people who buy these satellites could conceivably make the same rate of return that they now make with their terrestrially-based generating equipment.