Habitat Size Optimization of the O'Neill – Glaser Economic Model for Space Solar Satellite Production

Michael Detweiler
Junction Solutions
Englewood, CO

Peter A. Curreri, Ph.D.
NASA Marshall Space Flight Center
Huntsville, AL

ABSTRACT

Gerard K. O'Neill combined his concept for large free space habitats with Peter Glaser's concept for Space Solar Power Satellites (SPS), and with the use of extraterrestrial (Lunar and asteroid) materials, to form an economic model. This economic model for SPS production and human space settlement was published in the journal *Science* (1975), studied in detail during two Cal Tech/NASA Ames Summer Studies (1974, 1976) and presented to the Senate Committee on Science and Technology (1975). The model showed that after a substantial investment in space infrastructure mainly to create lunar mining and in space manufacturing facilities the production of SPS could be achieved with a very high profit margin and economic break even would occur in 20 – 30 project years (dependent upon program decisions), after which large profits would be accrued in additional to enabling tens of thousands of permanent settlers in free space habitats. The program was not implemented primarily because of the high initial program costs and long time to economic breakeven and profitability. In the work described in this paper, the O'Neill – Glaser financial model was rebuilt, tested, and modernized to more current inflation and energy costs. Analysis of the results show that the use of space resources and space based labor is essential to the plans economic viability. However in the past implementation of the model the habitat size was fixed to meet O'Neill's vision of large vista environments of sizes that accommodate 40 thousand to 4 million people. The first of these habitats would take decades to complete. Space based labor (colonists living, some with their families, in permanent nearly Earth-supply independent O'Neill habitats) is a prime cost saver for the O'Neill – Glaser model. Thus, in our study we allowed the habitat size to vary in order to determine the economic optimum. As in the original O'Neill – Glaser model, the first ten program years (Phase 1) are reserved to build the lunar mining base (which would employ about 200 people) and the in space manufacturing facility. This construction would be accomplished primarily with Earth derived materials. After completion of this infrastructure all manufacturing would utilize 90% or more of lunar materials greatly decreasing launch costs. The resulting financial optimum habitat sizes for the O'Neill – Glaser model is from 60 – 360 person bolo habitats. This size range was optimum because the first O'Neill habitat and SPS could be built in the first year of the SPS/Habitat construction phase (Phase 2). In addition, our analysis shows that after these smaller O'Neill habitats are built (in the quantity needed to support SPS construction) for 10 years, the manufacturing capability in space becomes so large that it is insensitive to habitat size

enabling the economic construction of large vista habitats as envisioned by O'Neill.

1. INTRODUCTION

Space offers countless raw materials and opportunities for exploration and profit [1]. However, the large gravity field of Earth makes any forays into space very expensive. In the mid 1970s the idea was formed [2] to create large space habitats in the 5th LaGrange Point (L5) that would be employed to construct Space Solar Power Satellites (SPS). The LaGrange Points are regions in space near the Earth and the Moon where the gravitational fields of the two bodies cancel. These Satellites [3] would beam power down to Earth, converting the energy of the Sun in space into a cheap and abundant energy source on Earth. In 1975 NASA began to study these concepts. One of the first comprehensive reports was from the 1975 summer study hosted at the Ames NASA Center entitled "Space Settlements: a Design Study." The study advocated a combination of 10,000 person habitats and other facilities to meet the projected energy needs for new power generation in the US and the rest of the world. This required an investment of $1,400 Billion (in 2005 dollars) and had an economic break-even time of 38 years [4]. The uncertainties associated with this large investment and time scale for economic return made the 1975 NASA study proposed program cost prohibitive even with its large potential benefits. The purpose of this paper is to study how the initial cost and economic break-even time can be minimized by varying habitat size. The details of the 1975 NASA report provide a set of engineering parameters and financial assumptions which were used for the calculations. The cost data was inflated to 2005 dollars and the US and world energy requirements and energy costs were updated to 2005 values. With this basis we studied the optimum geometry and size of habitats in order to maximize the potential economic benefit of space habitats and SPS.

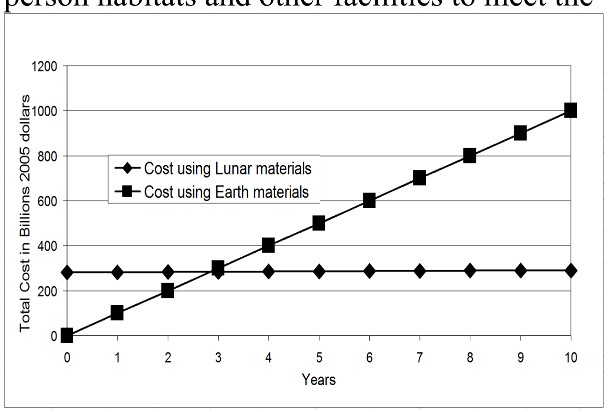

FIGURE 1. The economics of using space resources relative to Earth launch is compared by showing the cumulative cost for sending 50 kt/yr of material from the Earth or from the Moon. The cost from the Moon includes the $283 billion required to build a lunar base and other necessary infrastructure.

Two of the main themes that this paper builds upon are that space labor and space resources are cheaper than Earth based labor and resources when working in space. The use of space resources is imperative to enable economically reasonable space exploration [5], settlement [6], and space industrialization and solar power development [7]. Launching advanced lightweight solar power satellites from Earth can be cheaper than using space resources when few units are launched [8]; however, Earth launched solar power satellites, even using advanced technologies, are not economically competitive [9] unless Earth launch costs can be greatly reduced. Space solar power satellites might be constructed autonomously from Earth, but only with significant advancements in technology [10]. Using space resources, such as metals from the Moon as construction materials, has a high initial cost but a much lower cost per unit produced and transported into space. Figure 1 shows the difference in cost when bringing just 50 kilotons per year to L5 from the Earth or Moon. The costs given for transporting materials from the Earth is cost by the amount of material launched. The costs for sending materials from the Moon are obtained by adding the expenses of building the lunar infrastructure to those of sending the material from the Moon to L5. Fifty kilotons is enough material for the construction of a 766 person habitat (with shielding) or enough to construct about 62.5% of a 10 GW solar power satellite. For Figure 1, a launch cost of $1000 per kilogram is assumed (compared to current costs of about $10,000/kilogram). Also assumed for the space resources calculation is a $283 billion estimate for the start-up costs, which is the value assumed in the 1975 NASA Report [4] inflated to 2005 dollars. The method for obtaining the yearly costs of the space resources will be covered in detail in the Methods section of this report. In short, while SPS lunched from Earth are still not economically viable, utilizing space resources for SPS construction is economically compelling after about the third satellite even using decades old technologies. The energy required for transporting materials to L5 or to Geosynchronous Orbit (GEO) is a factor of almost 20 times greater from the

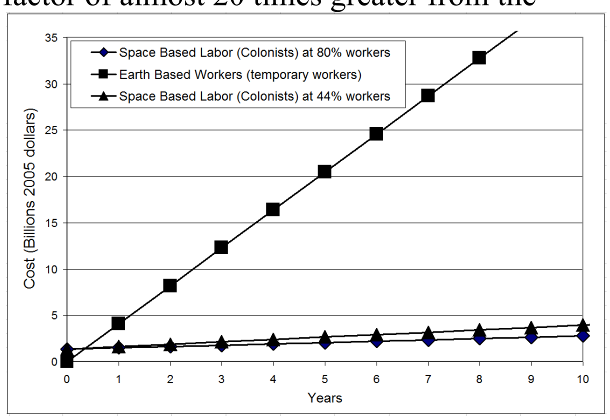

FIGURE 2. Cost for 614 Earth based labor versus space based labor.

Earth than from the Moon, thus using lunar materials has high economic benefit. Figure 1 shows that the costs of infrastructure to transport and process the lunar materials ($283 billion) are recovered in less than 3 years. After 10 years, the cost of transporting material from the Moon is cheaper by $700 billion. In addition to the large economic benefit, using space resources has the added bonus of building infrastructure for further space development and exploration such as ventures to asteroids or Mars and enables the human settlement of space. The benefit of the investment in space resource utilization continues indefinitely into the future.

Space based labor also proves to be far cheaper than Earth based labor for large space endeavors. Space labor is the labor of people living in space almost completely independent from Earth. If a community is created in space which creates its own products and grows its own food, it is cheaper than a community in space using Earth supplies because of the exorbitant costs of transportation from Earth to space. Workers based in space using Earth resources require a constant resupply of materials launched from Earth. They must be rotated back to Earth every six months, and their salary must also be supplied from Earth. Workers living in a near independent and moderately comfortable permanent space habitat could be paid mostly using goods constructed in space. Each habitat could have a large agriculture section, in which food is grown. Living in permanent habitats also has the added benefit of attracting individuals who are betting their future on the project. Creating temporary, unshielded "construction shacks," (as was done in part in the NASA study [4]) has high cost for transportation and re-supply of the workers. The economic consequence of this can be seen in Figure 2. The cost of Earth based workers is obtained by multiplying 614 workers by their wages of $38,420 and the cost of buying and sending 1.67 tons (at $19.11 per kilogram) of resupply material from Earth. The cost of Space based labor is obtained by the cost of building and maintaining one space habitat for 614 workers, and paying each space settler the equivalent to launching 100 kg from Earth. In the habitats for the space settlers only a fraction of the inhabitants work in construction. The habitat in which only 44% are workers will be larger than the habitat in which 80% are workers. Examining Figure 2, it is apparent that the costs of using Earth based personnel (salary, transportation, and resupply costs) quickly exceeds the cost of using space based labor housed in the space habitats described later in this paper after less than a years of operation. Using space settlers instead of temporary workers not only begins the human settlement of space, but also provides much cheaper, more comfortable and dedicated workers for the project.

2. METHODS

In previous papers [11] the concept of a minimum habitat size for beginning space settlement was introduced. The study described in the current paper (presented previously in abbreviated form [12]) was designed to test the effects of Space Habitat size on the economics of Space Solar Power Satellites construction. The model for the underlying engineering concepts was the 1975 NASA report [4] that was considered the most comprehensive prior treatment of the topic. All the costs have been updated according to the inflation rate of 383.42% from the year 1975 to 2005 [13].

In the NASA study [4] the first 10 year period was utilized for research and development, lunar base construction, and other initiation costs. To expedite comparison of habitat size, this study assumes the common cost equal to the inflated value derived in the NASA study [4] for the first 10 years and begins the comparison at year 10 of the project. Each of the figures in the Results section thus starts at project year 10. This corresponds to beginning the analysis when the necessary infrastructure is in place to begin building.

A summary of the activity during these ten years as envisioned in the NASA study [4] is as follows: The first five years are devoted to research and basic construction on Earth. At year 5 a temporary habitat for 200 people is created in Low Earth Orbit (LEO). With a 10 Megawatt (MW) nuclear power plant and a material fabrication plant, the station at LEO starts creating products. At year 9 a L5 space station is created along with the transfer of three 20 MW solar power satellites to provide power for the station. Lunar Landers, which have been researched from year three, are then created. On year ten, a 120MW nuclear power plant is landed on the Moon. Also in this year, the Interlibrational Transfer Vehicle (ITV), the mass driver, and the mass catcher are fully developed. These three pieces of equipment take the raw materials from the Moon and transport them to their destination. The Lunar Base begins operation on Year 10. The total cost for this is estimated to be $283 billion in 2005 dollars.

Space Solar Power Satellite construction offsets the costs of large scale human habitation in space and provides return on the investment. To determine how many new SPS per year are required, the growth rate of the demand for electricity in the world is assumed to be a steady 2.4 percent per year. The total demand for electricity during 2004 was 1,875 GigaWatts [14, 15]. For this analysis, a start date of 2010 is used, so year 12 of the report (the first year SPS are created) would correspond to the year 2022.

The business plan for the SPS industry is to capture the world growth and replacement market for electricity, so only 2.4% of this electricity is provided by space industry. The replacement market is 4.32 times smaller than the growth market. So the total electrical needs fulfilled by space power are taken to be 2.96% of the total world electricity requirement. The model for market penetration for the first 10 years is as follows: 10, 12, 16, 20, 25, 32, 49, 45, 50, and 60 percent of the world electrical growth and replacement market. For the years after, this market penetration is taken to be 100 percent of the growth and replacement market. This market penetration is achieved by pricing the electricity 20% below all competing Earth based sources.

The demand formula is then

$$D = 1{,}875 \cdot 1.024^{y-2004} \cdot \left(0.024 + {0.024}/{4.32}\right) \cdot p \qquad (1)$$

To find the number of 10 GW SPS that are created each year, the demand found by Equation (1), is divided by 10 GW, and then rounded to the nearest whole number. These SPS then generate income. The business plan is to charge 80% of the current industrial average price for electricity. The average price in the United States is 891 mils (where 1 mil =0.01¢), and so 80% of this is 712 mils (Public Policy Institute, 2007). The economic benefit, b, in billions, of the SPS program could then be calculated as the total population of SPS, p_s, times the 10 million kilowatt-hours they produce multiplied by their operational time (95%) times the amount of hours per year they are operational, times the price per kilowatt-hour (in billions).

$$b = p_s \cdot 10^7 \cdot 0.95 \cdot 24 \cdot 365 \cdot 0.0712 \times 10^{-9} \quad (2)$$

The Solar Power Satellites (modeled after the Glaser design [3]) are made of 80 kt of material and take 2,950 worker-years to complete. Some of this material is purchased on Earth and transported to L5. The cost of this material is $17.67 billion to purchase and $11.04 billion to transport. The amount of material required from Earth is assumed to decrease at an 80% learning curve, decreasing the purchase and transport cost. The amount of labor required is taken to stay the same as a worst case scenario, except when otherwise stated. When these SPS learning curves are incorporated into the model, a more conservative learning curve of 90% is used to account for the differing levels of expertise of the crews working on the Satellites. There is also a maintenance cost for the SPS. This fee is $115 million per year, which can be approximated over the lifetime of the satellite by multiplying by 10. So the total maintenance cost per satellite is $1.15 billion. The learning curve can be produced using the formula:

$$w = a \cdot u^{\ln(c)/\ln(2)} \qquad (3)$$

The standard learning curve of 80% (c = 0.8) which has been found to be a reliable model in airplane construction [16]. This means that each time the amount of machines created doubles, the work and price decrease by 80%. The bulk of the material for the construction of the satellites and the habitats must be transported from the Moon. The cost of the transportation to L5 and the cost of construction (inflated to 2005 dollars) at L5are taken from the 1975 NASA report [4]. The costs associated with the transportation of material come from the Mass Driver, the Mass Catcher, and the Interlibrational Transfer Vehicle (ITV). These are the machines which move the material. The Mass Driver launches the lunar soil or regolith from the surface of the Moon, the Mass Catcher collects this material at L2, and the ITV transports the regolith to L5. The ITV, the Mass Driver, and the Mass Catcher each have costs associated with them. Every year, there must be enough of each to handle the mass needs of that year. But since these continue working, only as many need to be created each year to handle the increase in tonnage over the last greatest tonnage requirement. These costs as well as the mass transfer capacity of each machine are reproduced in Table 1. The transportation costs from the Earth to the place of construction are estimated at $1,840 per kilogram ($480/kg in 1975 dollars), which is taken from the NASA report [4] for transfer from Earth to L5. Even though current launch costs are higher this rate was considered reasonable when the required increase in launches per year is considered.

Since the radius of the bolo spheres are small compared to the length of the rotation tether between them, most of the bolo volume is between 0.8 and 1 gravity. The volume of the bolo can thus be divided into decks in the classic metallic view of space stations. Our proposed bolo design consists of one double sphere on each end of a rotation tether. The outer compartment would be shielded for habitation. Each of these inhabited spheres would be next to another sphere, this one shielded for agriculture. The tonnage of lunar material needed for a bolo can be found the same way as for two spheres, since only two of the spheres are shielded. The structural weight of the agricultural spheres are assumed to be $400 \cdot {33.3^3}/{r^3}$ tons. This is obtained using the structural weight of a 33.3m bolo in the 1975 NASA Ames report [4]. The population of a bolo can be found by calculating the volume of the habitable spheres and dividing it by $35\text{m}^2 * 3.1\text{m}$. Thirty five m^2 is the amount of space an individual needs in a high density environment (not including space for food production) and 3.1m is a reasonable height for each deck. After financial break even, as will be discussed later, habitats can economically be built assuming 47m^2 for the amount of space an individual needs corresponding to a low density "large vista" environment. The two habitation spheres with their high shielding mass would act as the primary counterweights allowing for the rotation of the bolo.

TABLE 1. Costs and Mass Transfer Capacity of In Space Transfer Machines

Machine Name	Transfer Capacity (kt/yr)	Cost Per Unit (in Millions, 2005 Dollars)	Transportation Costs (in Millions, 2005 Dollars. At $1840 per kg).
Interlibrational Transfer Vehicle	500	11.5	9.2
Mass Catcher	313	2.3	1.84
Mass Driver	625	172.81	228.7

Some figures use models with a learning curve for the habitats. For these, an 80% learning curve is used on the labor required. However, the learning curve is assumed to stop after a 75% decrease.

The concept for an Interlibrational Transfer Vehicle in the NASA report [4] uses some cargo (lunar regolith) for reaction mass to achieve propulsion. A round trip requires a quarter of the cargo for propellant. Thus 625 kt must be put in an ITV for it to transport 500 kt of material to L5. Therefore the Mass Drivers and Mass Catchers must move 1.25 times the amount of material needed.

Each Mass Driver requires power from a lunar rectenna which receives power from a solar power satellite orbiting the Moon. Each Mass Driver requires 0.1071 of the power received by the rectenna. Each rectenna costs $8.7 billion. The price and labor decrease with an 80% learning curve based on how many are produced. Given the amount of mass drivers for a year, the amount of rectenna needed and their operating costs can be calculated.

The regolith is processed and turned into usable products at L5 in the Material Processing and Fabrication Plants. Each of these is sized to process 1 Mt of lunar rocks per year. The number of plants built each year is that required for the construction of the SPS and habitats. While the first of these plants comes from Earth, each of the following will be built using material from the Moon. Each plant is made of 10.8 kt of material that must be transported from the Moon to L5.

To develop a scenario that could begin implementation with current launch systems, we studied an initial 50 space worker startup that begins by building smaller 384 person habitats (compared to the 5000 space worker startup prior to the construction of the 10,000 person habitats used in the NASA study [4]). In the case of habitats that cannot be built in a single year, it is assumed that there are no extra workers brought in, and the number of workers stays at 50. Once a habitat is complete, all workers live in the habitat and there are no Earth-based workers that require 6 month rotation between Earth and space. To maximize the economic payback, there must be just enough total workers in space each year to construct the SPS for that year, as well as to build habitats to keep up with the increased demand for SPS. As was assumed in the NASA study [4], the settlers are paid in materials constructed on the habitats, as well as by 100 kg/year from Earth. The materials from Earth are assumed to be purchased at $19.2 per kilogram, and transported to L5 at $1,840 per kilogram.

To maintain the operations on the Moon, 70 workers are needed to create each mass driver and 75 workers are required for the maintenance of the mass drivers. The amount of workers decreases at an 80% learning curve. Also, new lunar rectennas need to be built by lunar workers. Each lunar rectenna requires 277 workers for construction. Twenty percent of the workers on the Moon are assumed to be working on other lunar base related tasks. The lunar base could hold agriculture, and be mostly independent from Earth; thus lunar workers are assumed to be paid the same as settlers.

The cost of the initial supplying of the habitats is taken from the 1975 NASA report [4]. This calculation is for the transportation of nitrogen and hydrogen from Earth, the transportation of plants and animals, the purchase and transportation of some equipment from Earth, and for the transport of the settlers from Earth. The NASA study [4] concludes that this is $29.02 billion (2005 dollars) for every 10,000 people. Since this cost is directly proportional to the amount of settlers, to find the cost per habitat, multiply the $29.02 billion times the amount of settlers in the habitat over 10,000. Using the above, the cost and benefit per year can be calculated when given the tonnage and personnel capacity of a certain space habitat. But these factors must be calculated as well. For this, simple geometry as well as previous models done by the 1975 Ames sponsored NASA report [4] are used.

3. RESULTS and DISCUSSION

Analytical and spread sheet models were developed using the methods described above and refined to predict as close as possible the economic data reported in the 1975 NASA report [4]. These models then allow the systematic study of effects of variables such as habitat size, that were not previously analyzed in depth, on the economics of SPS production.

3.1 The Economic Advantage of Beginning with Small Permanent Space Habitats

The primary hypothesis tested in this study is that starting with small permanent space habitats yields improved economics compared to the classic approach of temporary space workers building large (10,000 person or more) habitats. To test this hypothesis a model was created to directly compare habitat sizes with the 1975 Ames hosted NASA study [4] model. In order to fix variables other than habitat size, this initial calculation relies on the NASA study data completely, and uses all the data corresponding to a 1975 start date including using 1975 dollars. The in space society productivity is also calculated based on the NASA study value of 44% per habitat working on SPS and new permanent habitation. The shield weight is 5 tons per square meter. A learning curve similar to that found in the NASA study is applied to the work required for SPS. Eighty percent learning curves are used for the habitats, and are added to the cost for buying the material for the Mass Catchers, Mass Drivers, and

ITVs. The benefit from the SPS is reduced to the 1975 value of 141 mills per kilowatt hour. Following the NASA study, the cost of transportation is reduced in year 22 from $480 per kilogram (in 1975 dollars) to $110 per kilogram. While there was not enough information to duplicate all the details of the NASA report we believe that the calculation has fidelity within 5 %.

Figure 3 shows the comparison between small bolo habitats and the large torus habitats built using temporary space workers housed in orbital construction shacks. The bolo program relies solely on permanent space labor and use no temporary space construction shacks after the first year. The results given in Figure 3 show that the small bolos, relative to the large vista cylinders, require only about one quarter of the investment, and reach economic break-even 10 years sooner.

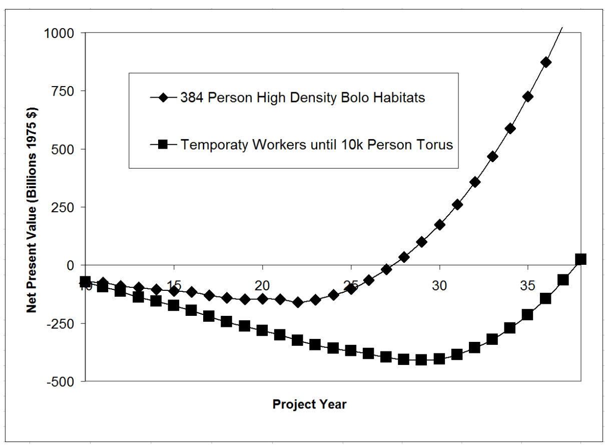

FIGURE 3. A Comparison of small bolos to the 1975 NASA Ames study [4] using an almost identical model (1975 economics). This shows the economic benefit of early spaced based labor achieved through smaller permanent habitats

3.2 The Economic Effects of Space Worker Productivity and Learning Curves

The value for worker productivity per man year, MY, used is taken from the NASA report [4] to be 12 tons of structural mass per year for habitat construction and 28 tons per year for SPS construction. In the 30 years since the Ames hosted NASA study, technology has advanced substantially yielding increases in automation and human productivity. Technology and automation improvements since 1975 combined with the smaller scale of the proposed bolo habitats makes an increase in worker productivity for space construction likely. To account for this productivity increase we maintain the tons per man year numbers above but assume that the society productivity increases so that now only 20% of the settlers are needed for maintenance and other projects on the habitats, which permits 80% (instead of 44%) of the settlers to build SPS and more space habitats. The economic difference caused by this increase in productivity would result in an economic break even about 2.5 years sooner as can be seen in Figure 4.

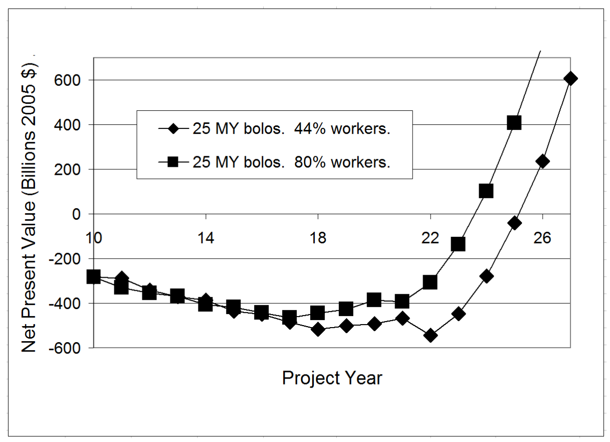

FIGURE 4. Estimate of the economic benefits from productivity increases since 1975 (2005 energy demand and water shielding**)**

The economic calculations given in the 1975 NASA study [4] employ 80% learning curves for habitat construction and 90% for SPS construction. The economic effect of these learning curves can be seen in Figure 5. For the case of 25 MY bolos, using the learning curves to reduce the manpower needed to create each SPS reduces the time needed to break even by about half a year. The 90% learning curve for SPS along with an 80%

learning curve for the habitats can be considered a probable scenario, while the series without the these learning curves could be a worst case scenario. However, for simplicity in the rest of this paper comparisons do not include the habitat or SPS learning curves. These figures are thus conservative, and show a worst case learning scenario in terms of economic costs and time to break even.

3.3 Selection of Habitat Geometry and Initial Space Worker Population

Previous designs for space habitats studied include the torus, sphere, cylinder and bolo. In each of these models, the agriculture is assumed to be kept in a low-shielding structure separate from the inhabited colony. Table 2 shows critical parameters for the large habitats as well as for some of the smaller habitats.

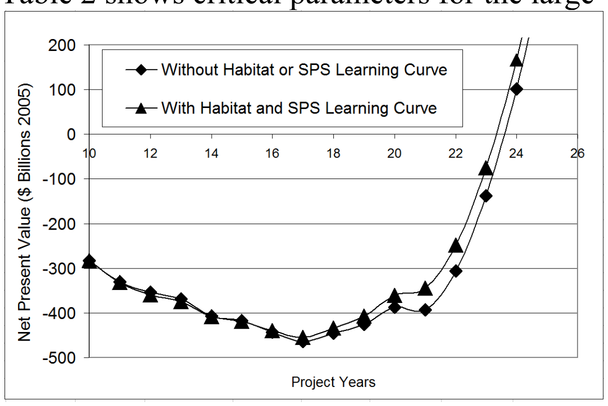

FIGURE 5. The effects of learning curves on the economics of 5 Man Year 384 person habitats (2005 costs and efficiencies)

For the following calculations we assume that habitats must have a three meter thick passive shielding to protect the colony's inhabitants from radiation. Since it is now known that the lunar poles contain excess hydrogen and possibly water ice, water is used as the shield material, allowing for lighter shielding than rock, and also providing a large water storage facility for the colonists. This water could either be obtained from the lunar surface directly, or by combining the oxygen from the lunar soil with hydrogen. The air in the structure is assumed to be at ½ Earth atmospheric pressure. The structural support would have to keep the air at ½ atmospheres as well as to support the spinning of the structure.

The classical free space settlements as analyzed by the 1975 NASA report [4] are large habitats with populations of 10,000 people or more. However, because of the massive size, a large Earth based space labor force is needed for years before the first of these habitats is built. In order to be economically feasible, construction of a large habitat (Table 2) requires thousands of temporary workers for a number of years.

TABLE 2. Characteristics of Habitats of Various Geometries and Population Densities

Habitat	Population	Con-struction Time (MY)	Structural Weight (kt)	Shield Weight (kt)	Dimensions (m)	Rotation Rate (RPM)
Cylinder	50,000	44,260	531.2	8,620	R = 245, L = 1,500	2
Sphere	50,000	167,583	2011	12,892	R = 741	1.15
Torus	45,000	1,825	21.9	14,404	R1 = 320, R 2 = 40	1.75
HD Bolo	384	5	.06	13	R = 17.08, Tether = 422	2
HD Bolo	1,922	25	.3	35.57	R = 29.2, Tether = 373	2
HD Bolo	3,846	50	.6	55.32	R = 36.8, Tether =343	2
LD Bolo	48,700	850	10.2	348.3	R = 94.6, Tether = 874	1.25

Starting construction with only 50 workers a year, a 50,000 man cylinder would take about 200 years to complete! Beginning habitat construction with, for example, 25 man year construction time (1,922 person) Bolo habitats, enables the first two permanent habitats to be constructed in the first year with an Earth based work force of only 50 people. Subsequent space based labor would then be exclusively provided by more economical space based labor.

In order to compare the economies of space habitats of different sizes we begin an analysis using an initial space work force of 4000 people. Figure 6 compares the different designs explained in the previous section. From Figure 6 it is apparent that even with an initial space workforce of 4000 people (more optimized for the large habitats), the smaller bolos are the most profitable solution.

The habitat geometry (as illustrated in Figure 6) that is the most economically optimum for early construction is the bolo. We next examine the sensitivity of the economics to habitat size. Figure 7 shows the economics of the 4,000 person start and of the 50 person start as a function of bolo size. For the Bolo sizes considered (2-200 man years, MY, construction time), a 4000 person start represents an initial excess of workers and a

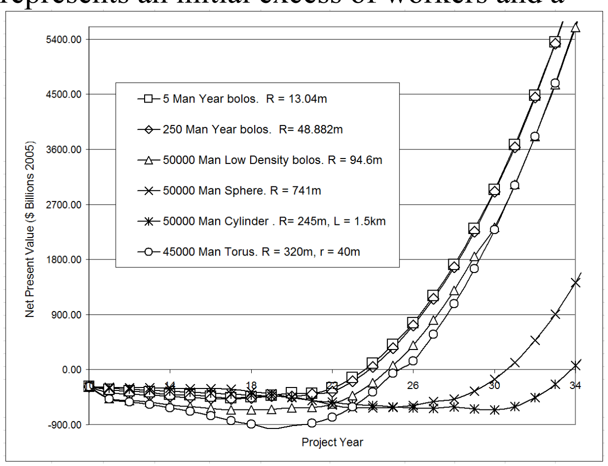

FIGURE 6. Habitat geometry comparison (4000 person start) using the 2005 baseline power demand and assumptions shows that the bolos are the most profitable.

50 person start represents a modest starting population. From Figure 7 it is apparent that when the habitats get too small, or too large, the economic potential decreases.

Considering the 50 person start series, habitats that are too large will decrease profits because they increase the SPS construction start time relative to expenses and thus greatly decrease out year revenues. However, since smaller designs have a small volume to shielding tonnage ratio making designs that are too small also decrease out year profits. This is illustrated in the 50 person start series in Figure 7. For the 4,000 person start the sizes that are the most profitable are between 2 and 65 Man Years. In the 50 man start series, only bolo sizes from 4-8 MY are economically optimum and the 5 year bolo has the best possible economic gain.

Figure 8 shows the economic difference between starting with a space work force of 4,000 people compared to 50 people. Starting with 50 workers, only a temporary structure for one year needs to be built. Starting with 4,000 workers, larger temporary housing needs to be built up over several years before the construction of the first permanent habitat. Thus, for any bolo habitat smaller than 50 MY, we can take advantage of the inexpensive space based labor after the first year of

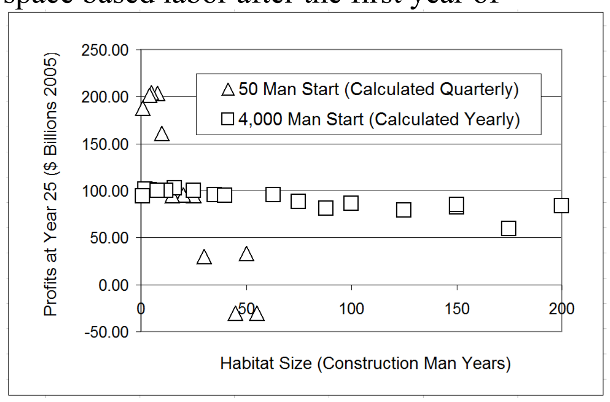

FIGURE 7. Choosing habitat size for optimum economic gain, the points represent the total income by year 24.

construction. Starting with the same 50 person workforce, it would take decades to complete the first 10,000 person permanent large vista space habitat.

Figure 9 shows the details of the economics for bolo sizes 5, 50 and 100 MY construction time showing the best economics is obtained for the 5 MY construction scenario.

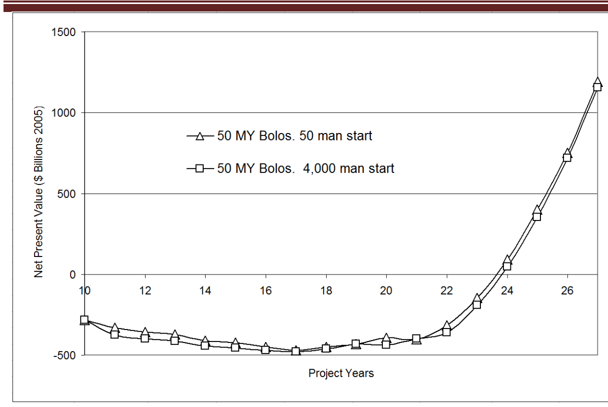

FIGURE 8. Small bolos enable a modest first year habitat construction work force of 50 workers after which the workers live in permanent space habitats lowering costs and enabling space colonization.

A model for a 5 Man Year Bolo Habitat would have two 6.5 kiloton shields. The radius of each of the inhabited spheres is 17.08 m, and each sphere holds 192 settlers. If spun at 2 rotations per minute, the length from the end of the habitat to the center of mass would be 245m, which would give 1 gravity of acceleration at the end of the inhabited spheres. Each habitation sphere would have an associated lower shielding agriculture sphere.

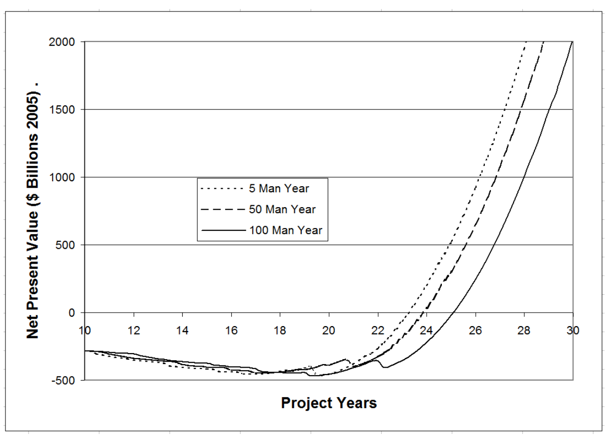

FIGURE 9. The economics of bolo habitats as a function of size with an optimum at 5 Man Years (384 person habitat).

3.5 Progressing from a Space Power Intensive to a Space Real Estate Intensive Economy

Since the growth economics is based on the SPS demand of that year, the economics of building small bolos does not change much with the initial workforce.

3.4 Optimizing Habitat Size

When 100% market penetration is achieved, the increase in production of the SPS slows considerably, but the profits rise dramatically. At this point in time, about 24 years into the program, the industrial capacity above that needed to continue meeting the world power demand can be applied to building habitation. In other words the excess capacity can be applied to space real estate production. Large cylinders could be built, with the previously built habitats put inside the cylinder as houses or apartment buildings. Some of the connection tubes would be left on the habitats and attached to the center of the cylinder as a support structure. Also, the water from the bolo's shields could be pumped into the cylinder's shields. This would allow all the settlers to be moved into a large, spacious environment. The population density could decrease substantially. At this point of great profit, new habitats could be built in a large-scale fashion with beautiful vistas as envisioned in the Gerard O'Neill space settlements (1974).

With the excess space industrial capacity, enabled by SPS profits, applied to developing space habitation, the population in space could substantially increase over the next decades. Starting with just 50 people living in space habitats at year 11 of the project, between 35 and 45 thousand people would live in space by year 28 (Figure10). This would be a major step in the human settlement of space.

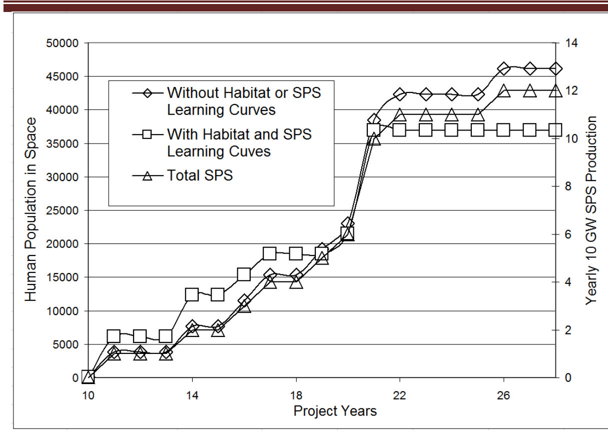

FIGURE 10. Population living in space as optimized to produce space solar power satellites (SPS) and capital profits

If the profits are spent on increasing the population in space, as shown in Figure 11, the space population growth could be staggering. Figure 12 shows the space population if the workers start building 45,000 person tori or more small bolo habitats. However, we suggest that after the costs of the project are paid back to investors with interest in about project year 25, the program should transition to providing the maximal additional space habitation. We should remember that the program has achieved the production all future electricity demand in a carbon free manner and for only 80% of projected Earth electricity prices. The Earth and its inhabitants will reap this dividend for the foreseeable future.

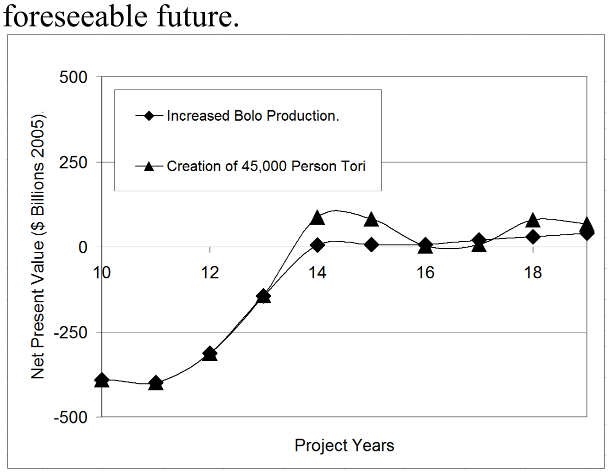

FIGURE 11. Financial curves assuming that after financial break-even profits are applied to maximize the human population living in space transitioning from primarily a space energy production to primarily a space real estate production economy.

We suggest that after financial break even, that the endeavor be considered as a world utility. The additional income should be applied to maximize the available real estate in space. This scenario is shown in Figure 12. It can be seen that if the profits after financial break-even are invested into building habitats and providing transportation of settlers into space, one million people could be living in space by about project year 30. It is also seen in Figure 12 that after financial break even, the industrial capacity in space is so large that the finances are no longer sensitive to habitat size. Thus the large vista habitats envisioned by O'Neill can be constructed with little financial penalty.

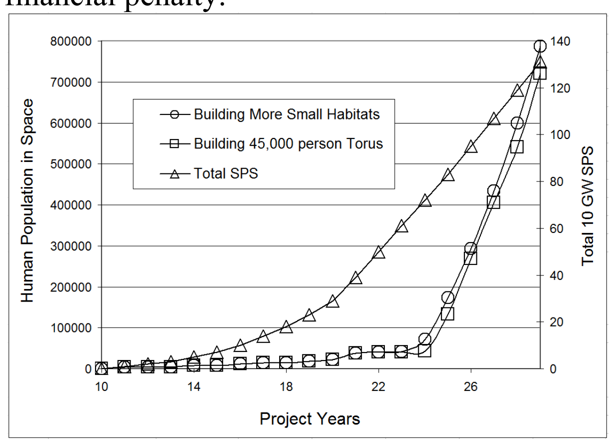

FIGURE 8. Population living in space if the SPS profits are invested in space real estate.

4. CONCLUSIONS AND OPPORTUNITIES FOR FUTURE RESEARCH

Creating large space habitats by launching all materials from Earth is prohibitively expensive. However using space resources and space based labor to build space solar power satellites can yield extraordinary profits after a few decades. The economic viability of this program depends on the use of space resources and space based labor. To maximize the return on the investment, the early use of high density bolo habitats is required. Other shapes do not allow for the small initial scale required for a quick increase in space based labor based on settlers in permanent free space habitats. This study found that 5 Man Year, or 384 person bolo high density habitats is the most economically advantageous for the classical O'Neill – Glaser model assumptions. The program investments are returned with interest by year 24, and over 45,000 people would be living O'Neill habitats in free space. All new and replacement world energy demand would be met by carbon emission free space solar power at only 80 % of Earth energy costs.

We suggest that after financial break even, that the endeavor be considered as a world utility. The additional income should be applied to maximize the available real estate in space. If the profits after financial break-even are invested into building habitats and providing transportation of settlers into space, one million people could be living in space by about project year 30 living in the large vista habitats envisioned by O'Neill.

In order to study the effects of initial habitat size on the O'Neill – Glaser model economics we purposefully did not update the technologies and financial parametric values from those used in the classical 1975 economic model as described by O'Neill in Science. We suggest that a new study be undertaken to update the financial and technological parameters of the O'Neill – Glaser model but with care not to eliminate its essence, that is achieving human settlement of space in conjunction with the implementation space solar power.

NOMENCLATURE

c = the learning curve
D = demand in GW
p = market penetration for that year in fraction form
b = the economic benefit in billions of dollars
p_s, = total population of SPS
u = the amount of units created previously
w = work done per unit
y = the year

ACKNOWLEDGMENTS

The work done by the first author was made possible by the MSFC Summer Intern Program supported by the Maine Space Grant Consortium. The support of many program management and NASA leaders was essential in making this work possible; especially the group leads Tim Vaughn and Joe Howell; and Carole Mclemore, John Fikes who managed the MSFC In Situ Resource Utilization effort. We would like to thank those who make the NASA Intern Program possible including Frank Six, Mona Miller and Tina Haymaker. The efforts of Jerry Sanders, JSC, as the NASA In Situ Resource Utilization lead and Michael Wargo, the NASA Exploration Lead Scientist, have been particularly essential for continued progress in the study of lunar resource utilization.

REFERENCES

1. Lewis, J.S., *Mining the Sky*, Helix Books, Reading, MA 1996.

2. O'Neill, G.K, "Space Colonies and Energy Supply to Earth," *Science*, **10**, 943-947, 1975.

3. Glaser, P.E., et al., *Feasibility Study of a Satellite Solar Power Station*, CR-2357, NASA Lewis Research Center, Cleveland, OH, 1974.

4. Johnson, R. and Holbrow, C., *Space Settlements: a Design Study*, NASA SP-413, NASA Ames Research Center, Moffett Field, CA, 1977.

5. Hoffman, S. J. and Kaplan, D. L.., "Human Exploration of Mars: The

Reference Mission of the NASA Mars Exploration Study Team," Lyndon B. Johnson Space Center, Houston, TX, (1997), http://exploration.jsc.nass.gov/marsref/contents.html.

6. Billingham, J., Gilbreath, W., and O'Leary, B., eds. *Space Resources and Space Settlements*, SP-428, NASA, Washington, D.C., 1979.

7. O'Leary, B., *Space Industrialization*, CRC Press, FL, 1982.

8. Mankins, J. C., "A Fresh Look at Space Solar Power: New Architectures, Concepts, and Technologies," International Astronautical Federation IAF-97-R.2.03, 1997.

9. Geuder, N., et al, "Comparison of Solar Terrestrial and Space Power Generation for Europe," 4th International Conference on Solar Power from Space – SPS'04, 30 June – 2 July 2004, Granada, Spain.

10. Bekey G., Bekey, I., Criswell D., Friedman G., Greenwood D., Miller D., and Will P., "Final Report of the NSF-NASA Workshop on Autonomous Construction and Manufacturing for Space Electrical Power Systems," 4-7 April, Arlington, Virginia.

11. Curreri, P.A., "A Minimized Technological Approach Towards Human Self Sufficiency off Earth," *Space Technology and Applications International Forum 2007,* edited by M.S. El-Genk, American Institute of Physics Conference Proceedings CP880, pgs. 904-910.

12. Detweiler, M.K. and Curreri, P.A., "The Space Homestead and Creation of Real Estate and Industry beyond Earth," *Space Technology and Applications International Forum 2008*, edited by M.S. El-Genk, American Institute of Physics Conference Proceedings CP969, pgs. 925-933.

13. Halfhill, T., "Tom's Price Inflation Calculator," http://www.halfhill.com/inflation.html, accessed 12 July 2007.

14. Energy Information Administration, "Official Energy Statistics of the U.S. Government," (1997) http://www.eia.doe.gov/oiaf/ieo/electricity.html, accessed July 12, 2007.

15. Public Policy Institute of New York State, Inc., "Average Retail Price of Electricity, 2006," (2007), http://www.ppinys.org/reports/jtf/electricprices.html, accessed 12 July 2007.

16. Asher, H., *Cost-Quantity Relationships in the Airframe Industry*, The Rand Corporation, 1956, Page 35.