SPACE INDUSTRIALIZATION - RATIONALES AND KEY TECHNOLOGIES,

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Industrialization describes the broad range of activities by which man gathers and manipulates materials, using energy to produce the thousands of goods and devices necessary to the support of civilizations on earth. The continuing development of our skill in the manipulation of matter, and especially recently in our ability to make matter manipulate information (for example, computers and communication networks) is the physical foundation upon which advanced civilizations rest. In the broadest context "space industrialization" must also refer to as broad or eventually even a broader range of activities, which will aid the advancement of civilizations on the earth, but will also create a new extraterrestrial economy and culture in space. It is not reasonable at this point in time to attempt a detailed description of the myriad of specific products, devices, and human activities which are necessary to constitute a space industry. Rather, I wish to focus on three primary facets - matter, energy, and skill.

Figure 1 presents one way of grasping the role of matter in an industrial society. This is a qualitative distribution of cost of goods or end-use-material on a dollars ($) per kilogram basis (horizontal axis) versus the total output of goods (billions $) at a given $/Kg-value. It must be noted that this is a qualitative curve based on a general awareness of the features of the United States economy. Mathematically the curve represents the equation

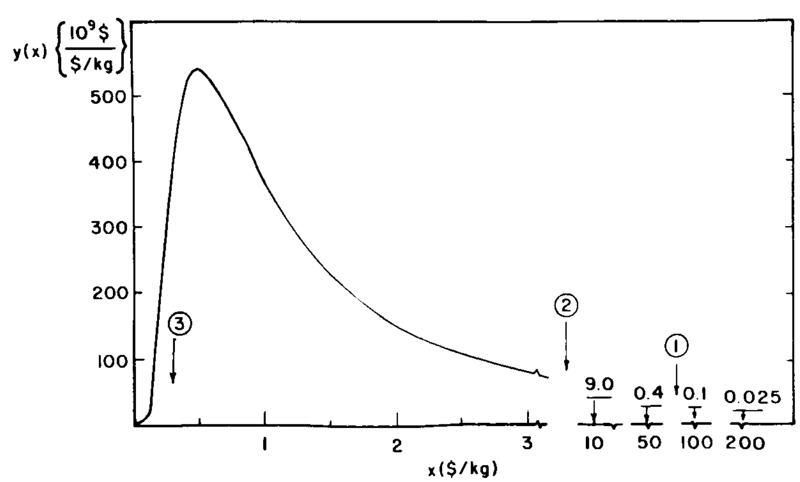
$$y(x) = I/[(e^{\frac{1}{x}})x^2]$$

where x corresponds to $/Kg of end products and y corresponds to billions (10^9) $ of goods at a given $/Kg value. The equation is normalized to an economy with $I=1,000\times10^9$ $ annual output of goods. Services are not included. The form of the equation is not qualitatively correct for $x \lesssim 0.2$$/Kg (left of "3") because water supplies, pollution control and other processes are present in the national economy which account for $10^{10}$$/yr, but handle such vast quantities of materials that the $/Kg value is very low. The high $/Kg section (right of "2") of the curve ($x > 10$$/Kg) is in rough qualitative agreement with a similar analysis by Woodcock (1973). The numbers on the right side (i.e. 9.0, 0.4, 0.1, & 0.0025) indicate the total dollar value of goods with worth greater than 10, 50, 100 and 200 $/Kg respectively in $10^9$$.

Notice that most of the industrial goods are restricted to a very small range of $/Kg values. Probably 99% of the products output of a nation such as the U. S. is restricted to items selling for less than 10$/Kg. The majority of goods (examples - food, cars, gasoline, houses) fall between 0.1$/Kg and 2$/Kg. The cost of final products will always be more than the weighted costs of the materials which compose them. Thus, if the raw materials which go into a product average 1$/Kg, then the potential market for the final product is restricted to the portion of figure 1 with x > 1$/Kg. This relates to the possibility of producing items in space. If the space shuttle is used to carry the raw materials into low earth orbit, then the raw materials acquire a value in excess of 50$/Kg and thus any products derived in low earth orbit from this material must be worth several times 50$/Kg to be saleable. However, the total value of goods with x > 50$/Kg is rather small when compared to the national economy or even compared to the cost of the shuttle program. Woodcock (1973) estimated the maximum possible market for such goods to be only a fraction of a billion (10^9) $/yr (i.e. the integral of the curve from x = 50 $/Kg to infinity). Even the most advanced schemes for earth to orbit transportation do not forecast launch costs less than 3 to 10 $/Kg by the year 2000. A lower limit on the cost for which material could conceivably be transported up to earth orbit is set by the cost of the energy required. Let us imagine a device exists which converts electrical energy with 100% efficiency into kinetic and potential energy and that 100% of the mass lifted is payload. Then, at a 25 mills/kilowatt-hour electrical rate, one would require approximately 30¢/Kg to eject material into orbit from the earth. Such an achievement would open a vast potential for space industrialization (all the area under the curve to the right of arrow #3). However, no such scheme has even been proposed at this point in time. However, several schemes have been suggested by which material could be ejected from the moon into deep space, or possibly to low earth orbit at low costs. Thus, lunar materials may be able to supply a large fraction of the raw materials necessary to create economically attractive products for use in space and on the earth.

Differential value of all goods in billions of dollars per dollar per kilogram value (B$/$Kg) versus the intrinsic unit value ($/Kg) of the goods in dollars per kilogram.

Figure 1



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Approximate cost analyses have been done on one of the processes involving the use of magnetically levitated buckets containing 10's kilogram slugs of lunar materials (O'Neill, 1974). The buckets are accelerated to escape velocity along a lunar track by linear induction motors. Upon reaching escape velocity, the material is kicked out and travels to a collection point in deep space. The bucket is decelerated and then circled to the return portion of the track and refilled for subsequent runs. It is conceivable that such a system could deliver lunar material to deep space for a few cents(10^{-2}\$) per kilogram following development of the "mature" launch and catching system. This low figure is made possible by the low escape velocity of the moon and the fact that the moon does not have an atmosphere. Only 1/22 of the energy is required to eject material from the moon as from the earth. Absence of a lunar atmosphere means that payloads traveling at lunar escape velocity (≈5700 Km/hour) do not require protection from the atmosphere such as being in a spacecraft. More than 70% of the ejection energy can go directly into the payload. Holbrow and Driggers (these abstracts) suggest the use of gas cannons (closed to the escape of the working gas) which could eject 10-100 kiloton payloads. This last approach offers the possibility of placing a small reaction control system and heat shield on these large payloads. The payloads could be targeted to perform a grazing reentry through the earth's upper atmosphere, undergo a subsequent apogee orbit correction and then be in earth orbit. This may be a manner by which to deliver inexpensively a source of raw materials (particularly oxygen) to low earth orbit.

If one or more of these schemes can be demonstrated and implemented, then a large fraction (next abstract) of the materials necessary for particular space industrialization efforts could be available and many of the economic processes encompassed by figure 1 would become conceivable. It should be remembered that one is after the raw materials at a low cost. The production machines can be far more expensive because such machines process many times their own mass of materials. One could generally afford to ship such processing machinery to orbit in the space shuttle.

Energy is a major factor which encourages us to consider space industrialization. Terrestrial energy needs have increased to such huge levels that serious consideration can be given to constructing large power stations in space which convert solar energy into microwave power and then beam microwaves to the earth for reconversion to terrestrial electricity. Investments of 100's billions of dollars would be required. Such enormous expenditures are comparable with the trillion (10^{12}\$) dollars of capital investment which U. S. utilities expect to make by the year 2000 (O'Neill 1975). In addition, the techniques for concentrating sunlight to run boilers (i.e. - for electrical turbines) or producing electricity by photoconversion insure a source of cheap, clean and inexhaustible energy for industrial operations in space. The basic resources of materials (lunar, asteroidal, etc.) and energy are abundant in the solar system for development of space industrialization. The critical resource, and the one which probably needs the greatest development, is the skill to utilize these inanimate resources.

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Several types of skills will be required. This special session concentrated on the technical aspects - how to get the materials, how to process the materials, implications of lunar or asteroidal supplies and many others. Technically, we appear able to rationally plan how to go again to the moon and start tapping its resources. This confidence is a direct legacy of the Apollo program. The immediate problem is to define an approach whereby such a program can gather support. NASA faces an extremely difficult problem in this respect. Table 1 is useful in understanding the difficulties.

In 1965 (Table 1a) NASA was the significant economic power in the United States with respect to research and development and also was very significant nationally with respect to cash flow or people employed (directly or through contracts). NASA ranked in terms of cash flow as the fourth largest industrial economic entity in the United States. In 1965 NASA could and did firmly guide the major research and development directions of the United States simply by buying the resources necessary to accomplish its appointed goals. This dominant approach is no longer possible or even conceivable in the future. A glance at Table 1b reveals the fundamental changes that have taken place in the national economy and NASA's status in this economy. In 1974 the total NASA cash flow of 3.3B$* placed it between the Borden Milk Company (New York) and Reynolds Tobacco or approximately 47½ on the scale of the Fortune 500. "Business Week" (28 June 1976) presented a detailed report of private research and development expenditures for 1975. Total private R & D expenditures in the U. S. exceeded 15B$ or approximately 5 times that available to NASA. The U. S. government expended approximately 9B$ on private contractors and 11B$ in government facilities for a total R & D expenditure of 35B$. Most of the priorities which dictate how these funds are spent are set by non-NASA considerations, such as environmental protection, engineering development, or consumer product development. For the private R & D approximately 3.5% went to basic science, 20% to applied science projects and 76.5% to development work. This is far from an unhealthy situation for NASA. The point is simply that NASA may not again buy dominance in the R & D market place. Rather, if NASA is to have a significant long term effect on the direction of the nation's technological development it must adopt new strategies. If NASA is to successfully guide the nation into a new capability of space industrialization, it must somehow make the potential gains and risks of industrial operations in space clear to the many private sectors and aid the interested entrepreneurial organizations in establishing real operations in space. Reiterating this point, present efforts by NASA to develop space industrialization in the new context of the space shuttle continue to attempt to buy industrial participation on contract to identify potential products, develop at NASA's expense possible specific industrial processes to manufacture the products and then publicize (i.e. sell concepts) these possible products to industry. The markets for very expensive goods (greater than 50$/Kg) are very limited and, therefore, there are very few entrepreneurs interested in the available possibilities. NASA must reverse the situation. It must be demonstrated that a cheap source of materials (less than 1$/Kg) can be available in space. Thus, a far larger fraction of the nation's entrepreneurs can reasonably consider initiating their operations in space at their own expense. Then NASA can provide the

*B$ = $10^9$$

TABLE 1a

1965 FORTUNE 500 INDUSTRIALS

Rank	Company	Gross Sales	Net	Employees
		(10^9\$)	(10^9\$)	(10^3 people)
1.	GM	17.0	1.7	661
2.	Standard Oil	10.8	1.1	147
3.	Ford Motor	9.7	0.51	337
	NASA	6.9	--	411*
4.	General Electric	4.9	0.24	262
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50.	Dow Chemical	1.1	0.09	33

* NASA SP-4012 (government and primary and subcontractors)

TABLE 1b

1974 FORTUNE 500 INDUSTRIALS

Rank	Company	Gross Sales	Net	Employees
		(10^9\$)	(10^9\$)	(10^3 people)
1.	Exxon	42	3.1	133
2.	GM	31.5	0.95	734
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47.	Borden Milk (N.Y.)	3.3	.08	47
	NASA	3.3	---	120*
48.	Reynolds Tobacco	3.2	0.3	32

* NASA historical pocket statistics - January 1975, p. D-12 (government and primary and subcontractors)

guidance on technical matters necessary to judge the reasonableness of the many schemes. In this manner, far larger economic resources can be attracted to space industrialization than can be provided by NASA.

For space industrialization the goal is the identification of realistic economic functions and their attendant risks rather than specific products. This point is more understandable by referring again to Figure 1. Suppose a source of materials is made available in low earth orbit at a cost of 1$/Kg. Figure 1 indicates that approximately 500B$ of goods might be considered for production from this material. However, the figure gives no aid in identifying what to make or the possible functions and associated costs to produce those goods. One very small, but useful, task would be to identify the products which compose this overall curve and how the curve and mix of goods changes with time. This would allow entrepreneurs to quickly grasp whether or not space production is of any conceivable interest to them for the goods with which they are familiar.

A general strategy should encompass these functions: (1) a clear theoretical exploration of space industrialization; (2) demonstration of the key gathering and processing functions in space; and (3) maximum involvement of private and governmental interests through all stages of these processes. This is a very different strategy than that involved in the development of Apollo or even the space shuttle. In those efforts there was a clear singular technical goal to be achieved. Consider each of the three strategy elements in turn.

(1) A major effort is needed to establish a new field of economics. "Physical Economics" seems an appropriate designator. In this field one considers in detail the many functions that control economic processes and asks the question - "What happens if this process(es) is conducted in space?" This is not simply an examination of the effect of zero-gravity easing the movement of large structures, or even the reconsideration of many industrial processes adapted to space. Rather, it is essentially a new field of study or inquiry which addresses man's demonstrated and projected ability to organize matter, energy, and his society in the three dimensional context of space. It is likely that a variety of new permanent institutions could be formed to address this question and be structured so as to continually involve private, academic and governmental organizations. This effort must be long term and very large, probably involving tens of thousands of people over the next 20 years. The product would be a clear understanding of new and realistic growth directions for industry and society into space, the identification of critical problems, and the creation of a new technocracy capable of managing space industry.

(2) There is an established pattern of government/industry cooperation in the development of new technological hardware. Technical feasibility is established by the government or under government funding and then industry establishes the economically viable industrial operations. Nuclear reactor and aircraft developments are prime examples. This pattern will persist in space industrialization. It seems reasonable that NASA should concentrate on

identifying and bringing to fruition the minimum number of key-systems which demonstrate that supplying material, energy, and initial working facilities to the new industrial activities in space is possible. A major problem and necessary planning constraint is the continuous identification and implementation of short term goals and pay-offs, rather than concentrating exclusively on super programs of 15 to 30 years duration, such as satellite solar power stations. An example of a shorter term goal could be a source of oxygen in earth orbit (derived from lunar materials) for partial refueling of space vehicles.

(3) The programs must actively involve the maximum number of people so as to shorten the learning period for the development of this new widespread expertise in space industrialization, to promote widespread support for the program and to develop the widest range of new concepts to be developed in space.

We face an interesting and exciting problem in the promotion of space industrialization. The expertise in science and engineering clearly exists to create near-earth and deep space habitats from lunar materials and eventually from the asteroidal material. Undoubtedly, the physical, engineering and economic factors of habitat construction and power station fabrication can be clearly defined and then judged as to their worth to us. The immediate and very challenging task is to organize the resources of society now external to the space program to support space industrialization as active participants.

References

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