Chapter 4

A BUYER'S GUIDE TO SPACE INFRASTRUCTURE

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A BUYER'S GUIDE TO SPACE INFRASTRUCTURE

SUMMARY

If the United States decides to acquire a substantial amount of long-term space infrastructure, there are various ways to proceed that should be carefully considered, including the degree to which new technology would be used, whether NASA should set design or performance specifications, and the roles of the private sector and international partners. The costs and capabilities of a number of possible infrastructure options are compared in a table format. The cost drivers associated with the listed options and OTA's approach to cost estimation are discussed. The next section examines a number of tradeoffs that should be considered regarding the use of automation and people in a "space station. " Buyers may reasonably decide to acquire space infrastructure using an average annual funding rate rather than a "lump sum" approach. Possible infrastructure that could be obtained using average annual funding rates of $0.1, $0.3, $1, and $3 billion (1 984$) are presented. The functions that NASA intends to provide in a "space *station"* are listed, and alternative infrastructures that could provide those functions are indicated. [1]

[1] In addition to the two OTA workshops mentioned specifically in the following text, sources of information for ch. 4 include the same references noted in ch. 3 for possible infrastructure elements and their estimated acquisition costs.

PROCUREMENT OPTIONS

If there is an affirmative answer to the questions of **whether to acquire long-term in-space infrastructure (and, if so, how much, of what kind, and when), there yet remains the decision of how it is to be acquired. In many respects, this** second decision is just as important as the first. The mode of acquiring new, long-term, in-space assets and services should be influenced by a clear understanding of the contemporary context in which space activities are carried on. And the decision as to how to acquire these assets and services will have a significant impact on the future of space activities.

The pioneering, generous, and effective efforts of the U.S. Government, and of NASA in particular, have resulted in the spread of civilian space capabilities and expertise throughout much of the world, to the point where they are now essentially beyond the power of the United States to control even if it is of a mind to do so. Many of the nations of Europe, and Japan, Canada, India, Brazil, and the People's Republic of China as well, are increasingly positioning themselves to pursue their own interests in space, independent of what the United States might desire. Other countries' evident success with Spacelab, with Ariane and its launch complex, and in the field of satellite communications has given them great confidence in their abilities to work in full collaboration with the United States on major space programs and, before long, to undertake such programs without the United States, should they then deem that to be appropriate.

The U.S. private space industry is also fully capable of developing all or most of the ensemble of low-Earth-orbit (LEO) infrastructure elements needed to provide a more-than-adequate initial operating capability (IOC) of the type now being studied by NASA. With the important exception of satellite communications, our industry in the past has undertaken work exclusively under contract to the Government. However, the past several years has seen the beginning of important space activities undertaken wholly on private initiative.

Some of these private sector activities and some of those undertaken by other countries will be

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in direct competition with what many in NASA now perceive to be their own important institutional interests.

With the completion of the Shuttle development program now in sight, the United States faces a major decision as to whether–and, if so, how–to redeploy a large fraction of NASA's resources. Under present circumstances, NASA, as in the past, would prefer to undertake another large technological program, similar to the Shuttle, to serve as the major agency focus, rather than to spread its efforts over a number of activities that could be more demanding and more useful. Of the various candidate activities, NASA has chosen to concentrate on the acquisition of a great deal of long-term, habitable LEO infrastructure.

Congress and the President have approved NASA's request to initiate a "space station" program, and NASA appears to be moving to acquire such infrastructure in much the same fashion that it acquired the Shuttle:

- A great deal of new technology would be developed, acquired, and used, essentially all of which would be publicly funded.
- NASA would arrive at and issue detailed engineering specifications for, and exercise close management control over, the technology to be acquired.
- This infrastructure would be procured by NASA with Federal funds. The U.S. private sector would not be prompted to use its own resources to provide a substantial portion of the infrastructure.
- The international role would be limited. NASA would not seek the kind of close collaboration that would result in shared authority, even if it might provide substantial capital cost reduction for the United States.

A significantly different acquisition approach would have the following elements:

- As far as is reasonably possible, already developed, tested, and paid-for technology would be used to achieve an adequate IOC, with development of new technology undertaken only where demonstrably required to lower overall cost of ownership.
- NASA would prompt our private commercial-industrial-financial sectors to develop and produce, with their own resources and on a genuinely competitive basis, as many of the Government-required civilian "space station' assets and services as they can; NASA would facilitate their efforts to do so; and they could be offered to NASA on a sale, lease, or payment-for-service-provided basis.
- NASA, in obtaining the elements not provided by the private sector, would emphasize management methods specifically designed to take the best advantage of the now quite sophisticated U.S. space industry (see app. D, "Synopsis of the OTA Workshop on Cost Containment of Civilian Space infrastructure [Civilian "Space Station"] Elements).
- NASA would negotiate collaborative agreements with other cooperating countries that would see all partners share in the benefits of such an IOC at a reduced acquisition cost to the U.S. Government for its share.

This second approach would imply that NASA would hand off much (perhaps most) of the more mundane "space station" work by paying the private sector to do it, thereby conserving its skills and resources so that they could be focused on more challenging space goals and objectives, including the development of the very advanced technology (e.g., bipropellant engines, a reusable orbital transfer vehicle, . . .) required, an activity which, for the most part, the private sector cannot justify.

These two options are at opposite ends of a spectrum of approaches to the acquisition of long-term space infrastructure. in determining which approaches from this spectrum are most likely to influence the evolution of space activities in a desirable direction, Congress may wish to consider the following questions:

- Should the Government be allocating its professional skills and experience to the development of: 1) incremental or 2) fundamental advances in technology?

- Which approach is most likely to stimulate the "commercialization of space"?
- What level of international collaboration is really desirable?
- What other large and important space ends should be addressed in the next decade or two in addition to the acquisition of in-space infrastructure methods and means?

Box F—[illegible]

OTA suggests that, unless overriding [illegible] be developed for use in publicly funded [illegible]

[illegible]

A CATALOG OF SPACE INFRASTRUCTURE

The fact that the United States has already developed a wide variety of space capabilities means that it has genuine choices—both of what infrastructure elements it places in orbit and of how these elements are to be acquired and used. It is around these choices that the difficult issues lie; by and large, the technology is either in hand or can be readily developed.

It must be emphasized that the particular constellation of space infrastructure elements which NASA currently aspires to develop, construct, deploy, and operate is only one alternative in a wide range of options. Simply put, there is no such thing as **"the** space station. " What is under discussion is a **variety of sets of infrastructure elements, ranging from modest extensions of current capabilities to vastly more sophisticated, capable, and costly ensembles than NASA is now suggesting.**

As one way of presenting the variety of technology options available, OTA has prepared tables 6 and 7.[2]

Photo credit: National Aeronautics and Space Administration

One option for modestly increased length **of stay in space is a Shuttle Orbiter modified for extended flight—the Extended Duration Orbiter, or EDO. Such a configuration might involve large solar panels for extended electrical power, as shown here.**

[2]These tables were prepared in response to the congressional committees which requested this assessment, Ch. 3 discusses infrastructure options in detail.

Table 6.—Comparison of Some Options[a] for "Low Earth" Orbit Independently Operating Infrastructure

	Shuttle Orbiter	Extended Duration Orbiter: Phase I	Extended Duration Orbiter: Phase II	Free-flying spacelab (developed as permanent infrastructure)	NASA infrastructure aspirations: Initial operational capability	NASA infrastructure aspirations: Mature, fully developed
Date available (assuming start in 1985)	Now	1988	1990	1990	1992	1996-2000
Cost[b] (billions of fiscal year 1984 dollars)	None	0.2	0.5	2-3	8	20
Characteristics						
Power to users (kW)	7		20	6	60	200
Pressurized volume (m^3)	60			100	200	300
			(with spacelab habitat)			
Nominal crew size	6	5	5	3	8	20
Miscellaneous	Can accept Spacelab	No new technology	New technology required; modest laboratory space	Modest crew accommodations	Orbital maneuvering vehicle plus two free-flying unpressurized platforms	Reusable orbital transfer vehicle plus several more platforms
Capabilities[c]						
Time on Orbit	10 days	20 days	50 days	Unlimited (60-90 day resupply)	Unlimited (90 day resupply)	Unlimited (90 day resupply)
Laboratories for:						
Life sciences	Moderate	Moderate	Considerable	Extensive	Extensive	Extensive
Space science/applications	Modest	Modest	Modest	Modest	Extensive	Extensive
Materials science	Some	Some	Moderate	Moderate	Extensive	Extensive
Technology development	Modest	Modest	Some	Moderate	Extensive	Extensive
Observatories	No	Modest	Modest	Modest	Extensive	Extensive
Data/communication node	No	No	No	No	Considerable	Extensive
Servicing of satellites	Modest	Modest	Modest	Modest	Considerable	Extensive
Manufacturing facility (materials processing)	No	No	Modest	Modest	Considerable	Extensive
Large structure assembly	No	No	No	Modest	Moderate	Extensive
Transportation node	No	No	No	No	Moderate	Extensive
Fuel and supply depot	No	No	No	No	No	Considerable
Response to reasons advanced for space infrastructure						
Maintain U.S. space leadership and technology capability	No	Modest	Modest	Modest	Considerable	Extensive
Respond to U.S.S.R. space activities	No	Modest	Modest	Modest	Considerable	Extensive
Enable long-term human presence in space	No	Modest	Modest	Considerable	Extensive	Extensive
Attention-getting heroic public spectacle	No	Modest	Modest	Modest	Modest	Modest
Extended international cooperation	Modest	Modest	Moderate	Moderate	Moderate	Moderate
Promote U.S. commercialization of space	Modest	Modest	Modest	Considerable	Considerable	Considerable
Maintain vigorous NASA engineering capability	No	No	No	Modest	Extensive	Extensive
Enhance national security, broadly defined	No	No	No	Modest	Unclear	Unclear
Space travel for non-technicians	Modest	Modest	Modest	Modest	Considerable	Considerable

[a] Listed options are illustrative examples; the list is not exhaustive.
[b] Costs include design, development, and production; launch and operational costs are not included. Some costs are estimated by the Office of Technology Assessment; others were provided to OTA.
[c] Clearly judgmental.
[d] Including launch to the Moon, Mars, and aome asteroids.

Examples of habitable infrastructure are shown in table 1. First, the present Shuttle Orbiter and its possible modifications for somewhat extended (but not permanent) stays on orbit (i.e., a so-called Extended Duration Orbiter—EDO) are listed, followed by one version of Space lab developed into a free-flying inhabited facility. Finally, the present NASA-envisioned space station" concept is given, including both the IOC version with an estimated completion in 1992,

Table 7.—Space Infrastructure Platforms[a] That Could Be Semiced by Shuttle or an Orbital Maneuvering Vehicle

	Unpressurized coorbiting platforms (serviced by means of extravehicular activity)				Pressurized platforms (serviced internally while docked)	
	SPAS	MESA	LEASECRAFT	EURECA	Space Industries' Platform	European Modified Spacelab
Date available (now, or approximate, assuming start in 1985)	Now	Now	1986	1987	Late 1980's	1989
cod' (billions of fiscal year 1984 dollars)	0.005	0.01	0.2	0.2	0.3	0.6
Characteristics						
Power to users (kW)	0.6	0.1	6	2	20	6
Pressurized volume (ft^3)	None	None	None	None	2,500	3,000
Nominal crew size	None	None	None	None	1-3 only when docked	3
Miscellaneous	3,000 lb Payload	200 lb Payload	20,000 lb Payload	2,000 lb Payload	25,000 lb Payload	20,000 lb Payload
Capabilities[c]						
Time on orbit	10 days	8 months	Unlimited	6 months	3-6 months	Unlimited
Laboratories for:						
Life sciences	No	No	Modest	Modest	Modest	Moderate
Space science/applications	Modest	Modest	Modest	Modest	No	Moderate
Materials science	Modest	No	Modest	Modest	Moderate	Moderate
Technology development	No	No	Modest	Modest	Moderate	Modest
Observatories	No	No	Modest	Modest	Modest	Moderate
Data/communication node	No	No	No	No	No	No
Servicing of satellites	No	No	No	No	No	No
Manufacturing facility (materials processing)	No	No	Considerable	Modest	Extensive	Considerable
Large structure assembly	No	No	No	No	No	No
Transportation node (assembly, checkout, and launch)	No	No	No	No	No	No
Fuel and supply depot	No	No	No	No	No	No
Response to reasons advanced for space infrastructure						
Maintain U.S. space leadership and technology capability	No	No	Modest	No	Modest	No
Respond to U.S.S.R. space activities	No	No	Modest	No	Modest	Modest
Enable long-term human presence in space	No	No	No	No	No	No
Attention-getting heroic public spectacle	No	No	No	No	No	No
Extended international cooperation	Yes	No	No	Yes	No	Unclear
Promote U.S. commercialization of space	Unclear	Modest	Considerable	No	Considerable	No
Maintain vigorous NASA engineering capability	No	No	No	No	No	No
Enhance national security, broadly defined	No	No	No	No	No	No
Space travel for non-technicians	No	No	No	No	No	No

[a]Listed platforms are illustrative examples; the list is not exhaustive.
[b]Costs include design, development, and production; launch and operational costs are not included. Some costs are estimated by the Office of Technology Assessment; others were provided to OTA.
[c]Clearly judgmental.

and a mature, fully developed facility (1996-2000).

The parameters for each option that may be used for rough comparative purposes are:

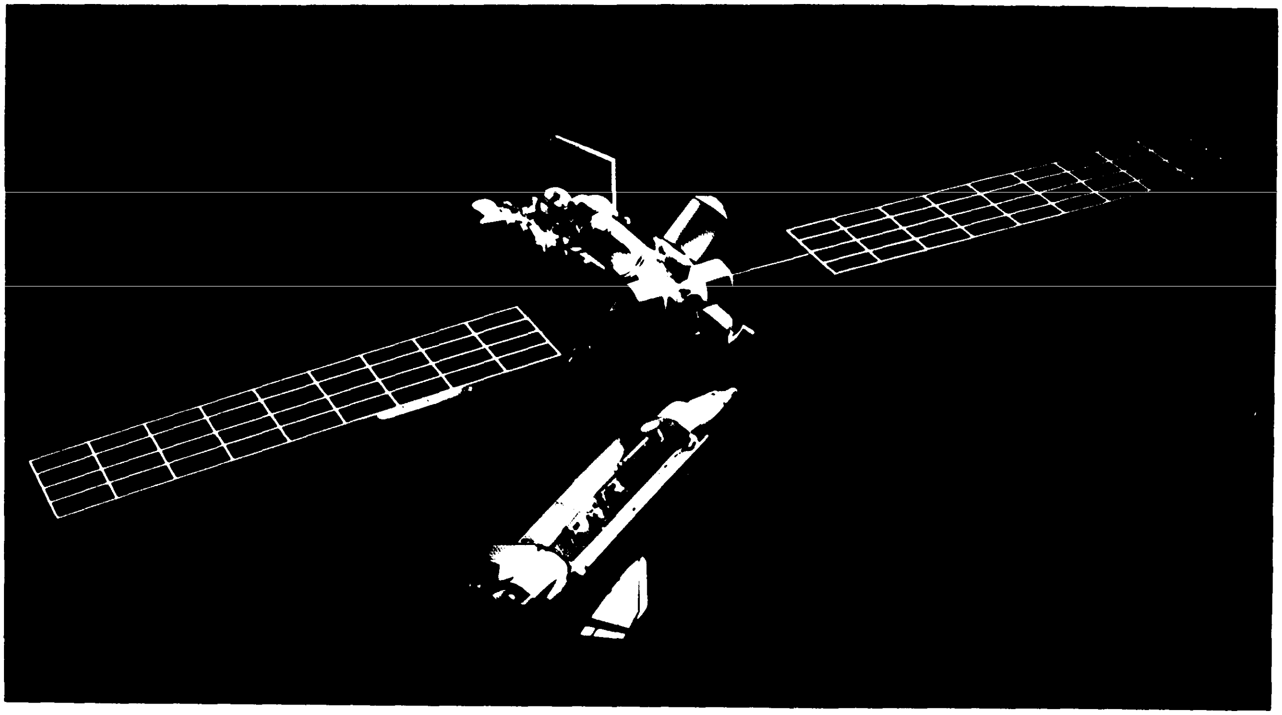
- Approximate date of availability—assuming that an acquisition (in contrast to a study) "go-ahead" were included in the fiscal year 1987 budget.
- Cost (in fiscal year 1984 dollars)–to produce the capabilities shown. The estimates are based on sources such as industry reviews, company publications and meeting presentations, aerospace periodicals, and NASA information releases. Inasmuch as some options utilize existing hardware, the costs do not reflect similar proportions of development and production efforts for the various options.

- Characteristics–several design parameters and sizing factors that provide the bases for infrastructure capabilities.
- Capabilities—the types of functional activities that the listed infrastructure could support, and the degree to which these activities might be accomplished.
- Responsiveness of a given infrastructure-to the various reasons put forward for having a civiliann "space station, " including any long-term presence of human beings in space .

If great and long-range space activities (for instance, the establishment of a lunar human settlement or the return of materials from the asteroids or Mars) come under consideration, they would appear to be achievable using a sophisticated reusable orbit transfer vehicle (ROTV) coupled with on-orbit assembly, check-out, launch, and recovery. The one option listed in table I that could provide these capabilities is the NASA fully developed infrastructure.

Examples of uninhabitable "free-flying' space platforms are shown in table 2. These platforms, or others, could be used in conjunction with, and serviced by, any of the options listed in table 1. In this way, additional capabilities could be added to the infrastructures given in table 1, SPAS and MESA are currently existing commercial platforms that were financecj and developed by the private sector. LEAS ECRAFT is also a private venture now under development.

Some cautions should be noted in the interpretation of this information. General descriptions of the various options are given, an estimates of their capabilities. These capabilities can be expected to change in some cases. Most of the capabilities have been described by qualitative adjectives. Quantitative estimates are rounded off to one figure. In the fifth section of the tables, "Response to the Reasons Advanced for Space Infrastructure, " the comparisons clearly must be qualitative and judgmental in nature and are presented simply to bring these factors to the attention of the reader. For instance, as a particular item the Spacelab option of table 2 is only one of several that have been put forward; one by European Space Agency (ESA) countries could definitely augment international cooperation if it were implemented.



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COST DRIVERS

Beyond the observation that, in some general fashion, the cost will increase with the capability and sophistication of the infrastructure acquired, it is difficult to estimate the eventual cost of this capability to the Government. At least all of the following factors could have an important influence on this cost:

1. the total capability acquired–which, as suggested by the examples listed in the tables of infrastructure options, can encompass a considerable range;
2. the extent to which already developed, tested, and paid-for technology is used, v. a focus on new technology with its higher development cost and greater risk of cost overruns;
3. the substitution, where feasible, of automated systems for the accomplishment of tasks previously undertaken only by human beings;
4. the manner by which the infrastructure is acquired, i.e., the extent to which NASA puts the engineering challenge on the space industry by issuing performance specifications, rather than continuing to issue detailed engineering specifications and managing the acquisition process in detail;
5. the effectiveness of NASA's efforts to persuade our private sector to develop infrastructure assets and services "on their own, " and to provide them to the Government at purchase, lease, or service-payment prices lower than those achievable by the Government;
6. the effectiveness of NASA's efforts to effect eventual private sector operation of the infrastructure and its related activities;
7. the extent to which large and rapid expansion of military space research, development, test, and evaluation (RDT&E) activities increases costs in the civilian space sector also;[3]
8. the extent to which any "Christmas-tree effect" takes place within NASA, whereby the infrastructure acquisition management is persuaded by the NASA Centers to allow the cost of desirable but nonessential RDT&E activities to be included in the acquisition; and
9. the effectiveness of NASA's efforts to arrive at large-scale collaboration and related cost-sharing arrangements with other countries.

These points address only the initial capital cost of this infrastructure—to this cost must be added its ongoing operation and maintenance costs; the cost of instruments, furnaces, etc., needed for scientific experimentation in association with its use; and the interest cost of any money borrowed to fund the acquisition program. And it must be remembered, too, that the infrastructure will eventually become obsolete or wear out.

It is clear that there are many opportunities to reduce infrastructure net cost that could be grasped by a vigorous, imaginative, and determined NASA management.[4]

These considerations suggest that, over the next year or two, at least as much attention should be given to identifying the best ways by which the country should set about the permanent development of space as there is given to any technological advances and operational capabilities that are to be obtained.

[3] Classified material was not used in preparing this report.
[4] Cost reduction measures are discussed in app. D of this report.

[illegible]

PEOPLE AND AUTOMATION IN SPACE

One of the most important, and vexing, infrastructure issues is that of the proper mix of sophisticated people and sophisticated machines (automation) to be employed in work activities in spaces

[5]In arriving at judgments on various "man/machine" issues OTA, in close concert with senior congressional staff members, designed and convened a workshop which brought together many of the Nation's experts in "smart machine" development from the Government, industry, and academic communities with OTA and congressional staff professionals.

The OTA conclusions are as follows:

1. **If specifically designed to do so, any civilian "space station" program could effectively serve as a high-visibility focus for promoting research and development in all disciplines in the field of automation.** important advances in terrestrial applications of automation could be expected to follow from a vigorous space automation program.
2. **However, there is a firm consensus among**

scientists and engineers in the various automation disciplines that current automated equipment could not accomplish many of the functions envisioned by NASA for an early 1990s "space station. " This situation results, in part, because NASA has invested relatively few resources to develop automated capabilities specifically for general-purpose infrastructure-support (in contrast with special-purpose scientific) space activities. In addition, the academic and industrial advanced automation research community numbers only a few hundred.

3. Therefore, if the kind of overall operational "space station" now envisioned by **NASA is to be functioning by the early** 1990s, **it will have to include people. Conversely, if it is to be wholly or mostly automated, it could not become operational until** 5 **to 10 years thereafter, even with a major automation R&D effort.** However, if any of the aspirations of those now conducting research and development in the space materials processing area are realized, and one or more processes are found suitable for long-term production, then elements of the infrastructure that would be devoted to such production, such as platforms co-orbiting near any central complex, could be singled out for early, specific, sophisticated-machine R&D focus.
4. Conceptually, space infrastructure could be designed either to include a human work crew or to depend on unattended sophisticated machines. Despite the fact that the relative efficiency and/or effectiveness of these two quite different approaches have been **extensively debated for years, no consensus has emerged.** This absence of consensus results from a number of factors: the state-of-the-art for sophisticated machines; the amount of experience we have had to date in the actual conduct of space support operations is quite small; and, in such operations, NASA has placed more emphasis on human beings than on machines;

   For the foreseeable future, therefore, only a general continuum of conclusions can be outlined:

   - machines generally will be unable to anticipate and deal with genuinely unknown circumstances and surprises;
   - people will need the assistance of machines to gain speed, strength, and memory; to improve their sensory capabilities and their mobility; and to provide them with artificial senses via radar, lidar, radiation detection, etc.;
   - machines employed for ongoing R&D and commercial-industrial operations will require human oversight and assistance; and
   - machines, maintained by people or not, as circumstances suggest," should do all hazardous and very-long-term repetitive work.
5. **In the matter of relative cost of automated and space facilities including people, the expense of developing and providing safe, sanitary, and suitable living and working facilities for human beings has to be weighed against the costs of providing analogous automated capabilities. The former will certainly be relatively expensive; the latter may well cost more than some advocates imagine, especially if as much capability is expected of the machines as of a professional human work crew. With respect to doing useful work in space, human beings represent in-hand technology. Cost alone does not provide sufficient ground for choosing between automated and manned facilities.**
6. **However, there are three reasons advanced for having men and women in space, only one of which is to do useful work. The other reasons are: to serve as subjects for scientific study and to engage in any other kind of human activity. With respect to the second and third reasons, the question of humans or machines does not even arise.** Only the purpose of doing useful work has been extensively studied and, as indicated in the preceding points, no clear and gen-

eral present advantage for having people or sophisticated machines there has emerged. If the Nation decides, as a matter of policy, to have some of its people remain away from Earth for long periods, then staffed space facilities, allowing for the study of human physiology, psychology, and social behavior, must be acquired. If, similarly, the Nation decides, as a matter of policy, to enable people to pursue in space a variety of cultural activities other than work then, again, only their presence there will suffice.

ALTERNATIVE FUNDING RATES

Chapters 5 and 6 discuss a space infrastructure acquisition program that would involve an initial decision on the purposes of, and the objectives to be achieved in, the civilian space area, followed by the design of that infrastructure with appropriate functional capabilities to support the attainment of these objectives. An estimate of the cost and schedule associated with the attainment of these objectives, along with the acquisition of such infrastructure, is also presented.

An alternative approach could simply establish annual expenditure levels for in-space infrastructure acquisition. Thus, to provide an independent basis of comparison with the civilian "space station" program now favored by NASA, OTA has estimated what new space capabilities could be acquired, by when, if various annual average Government funding rates were established to do so. No changes to present NASA acquisition procedures or NASA anticipated acquisition costs are assumed. Arbitrary annual average funding levels of $0,1, $0.3, $1, and $3 billion per year (1984$) were chosen to illustrate the number and kind of space infrastructure elements that could be acquired over periods of 5, 10, or 15 years.

The results of these 12 funding scenarios are given in table 8, which shows the funding rate, number of years, total expenditure, and kinds of infrastructure elements acquired. The elements are divided into those that can operate independently (e. g., the Shuttle Orbiter and a "space station" central base) and those that depend on being serviced or maintained from one of the independent elements (i.e., by an orbital maneuvering vehicle (OMV), a local in-space transportation system operated from a "space station" control element, or directly by the Shuttle).

Table 8 lists the following (among other) elements of space infrastructure that could be acquired over various acquisition intervals:

- For $0.1 billion per year: probably no "permanently manned" facility could be obtained even by the year 2000. Further extension of capabilities of the Shuttle system and unpressurized platform developments could be obtained. The acquisitions could be: a development of the EDO Phase 1, for 20-day orbit stays, over a 5-year period; or EDO Phase 11, for 50-day orbit stays, over 10 years or longer, plus two or three free-flying unpressurized platforms such as EURECA, LEASECRAFT, and/or the Space Industries' platform (assuming that the Government would make an outright purchase of such platforms).
- At $0.3 billion per year: within 5 years, the acquisitions could be an EDO I I plus several (perhaps pressurized) platforms. Over 10 years, there could be acquired: 1) the first permanently orbiting, Spacelab-derived habitable modules in 28.5° orbit that could support three people, 2) an OMV (enabling servicing of nearby satellites), and 3) a few free-flying platforms. In 15 years, there could be obtained either: 1) two free-flying Spacelabs, one in polar orbit, one at 28.5°, or 2) much more capable permanent infrastructure at 28.5° than that which could be acquired in 10 years.
- For $1 billion per year: within 5 years, there could be acquired: 1) a permanent LEO facility operating as a transportation node (obtained as a new design by NASA), 2) an OMV, 3) an ROTV capable of transporting spacecraft to and from geostationary and

Box H.—The Self-Replicating Machine: A Route to the Solar System

by Dr. Robert Frosch,* Vice President, General Motors Corp.

Humans are gradually making problems for the environmental systems of the-Earth that are the support systems of all forms of life. It seems a poor idea to continue to do so without considering the possibility of adding some redundancy to our basic life support systems. The Earth has only a tiny fraction of the energy, materials, and places available in the solar system, albeit the only fraction on which we now know how to live in a self-sustaining way. We need to give serious consideration to building toward the possibility of economically sustained life off the Earth, elsewhere in the solar system. For if we can mine and manufacture elsewhere, we may really be able to reduce demands on the Earth in a meaningful ecological way.

To do so economically implies doing so without continuous major export from the Earth of the principal energy and material required by people located elsewhere and engaged in these industrial activities. A large initial investment might be required to get started, but once started, the remote activities should be self-sustaining, even capable of returning a surplus to Earth in repayment of the initial investment, or in trade for things brought from the Earth.

There appears to be a technologically sensible route to this end. Furthermore, the route emerges naturally from current technological development trends. It appears feasible to develop self-replicating, or nearly self-replicating, factories fueled by solar energy. Such a factory could mine the extraterrestrial (e.g., lunar) material under it or next to it, beneficiate the material, perform the necessary physical and chemical processes to provide the desired materials, and make and assemble the parts for another factory identical to itself, including the necessary solar energy plant. The new factory would proceed to do the same, the result being a machine pseudo-biology, with factories growing in numbers at an exponential rate.

Given real physical processes and real efficiencies (and an efficiency discount of 100X just for caution), the time required for a solar cell to collect enough energy to make another solar cell in this fashion appears to be on the order of several days. Thus the replication time is sufficiently short that—starting with one machine and assuming that there are no accidents, no catastrophic wear, and no hardware or software "mutation"—more than a million machines could be provided in twenty years, turning out desired materials and/or devices, and using up about one hundred square kilometers of surface area several meters deep per year in doing so.

A machine versatile enough to replicate itself is clearly a general-purpose factory. A number of such machines, "living" on solar energy and local materials, would represent a general-purpose industrial base—a base for whatever the human race cares to do in the solar system where such local materials are available in sufficient density.

Even if the factories are not quite self-replicating, it is clear that the required human resources are few; the first factory or two could clearly support the [illegible] of any necessary resources from Earth with energy, materials, or minerals. The [illegible] are not violated: the energy comes from a hot source, the Sun, and waste [illegible] a cold reservoir, the local surface and space. Great "intelligence" is not required [illegible] might be convenient: apparently, most self-reproducing molecular [illegible] intelligent."

The initial investment is large, perhaps [illegible] annual Federal deficit, but it would be made over a number of years [illegible] obvious bound. The technology of robotics, computers, and [illegible] on Earth; why not elsewhere in the solar system?

Appropriate use of LEO infrastructure could [illegible] to do such things in low g and high vacuum. It may be the least expensive place to tinker with the necessary technological developments in a realistic laboratory setting where the normal kinds of laboratory learning are possible.

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*Dr. Frosch was Administrator of NASA from 1977 to 1980.

Table 8.—Some Illustrative Space Infrastructure Acquisitions Possible at Various Annual Average Federal Funding Rates (all amounts in billions of 1984 dollars)

			Space acquisitions[a]				
				Dependent elements			
Funding rate	Number of years	Total expenditures	Independent infrastructure elements[b]	Unpressurized platforms	Pressurized platform#	Space-based transport vehicles	Beyond geostationary orbit spacecraft elements
0.1[e]	5	0.5	EDO I[f] (20 days, 5 crew)	2	—	—	—
	10	1	EDO II (50 days, 6 crew)	3	—	—	—
	15	1.5	EDO II (50 days, 6 crew)	3	1	—	—
0.3	5	1.5	EDO II (50 days, 6 crew)	3	1	—	—
	10	3	Free-flying Spacelab modules' (permanent, 3 crew)	1	1	OMV	—
	15	4.5	2 free-flying Spacelab modules in both 28 degree and polar orbits (3 crew each	2	1	OMV	
	5	5	Space transportation center (4 crew)	—	—	OMV; ROTV	—
	10	10	NASA initial operating capability "space station"[g] (8 crew)	2	1	OMV; ROTV	—
	15	15	NASA growth "space station"[g] (12 crew)	3	1	OMV;ROTV	—
	5	15	NASA growth "space station"g (12 crew)	3	1	OMV; ROTV	—
	10	30	NASA mature "space station"g (16 crew) Shuttle-Derived Cargo Vehicle (SDV)	3	2	OMV:ROTV	Lunar capable ROTV; staffed Lunar facility
	15	45	NASA mature "space station"g (18 crew, SDV)	5	3	OMV: ROTV	Lunar capable ROTV; staffed Lunar facility; Mars voyage[h]

[a]Tables 1 and 2 present characteristics and capabilities of infrastructure elements in detail.
[b]Extended Duration Orbiters (EDO) are limited in their stays on orbit; other independent elements are long-term.
[c]Platforms of the LEASECRAFT /EURECA type.
[d]Platforms of the modified free-flying Spacelab/Space Industries type with their own electrical power and pressurization systems.
[e]At $0.1 billion&r, no long-term, staffed infrastructure elements are possible.
[f]EDO I (Extended Duration Orbiter, Phase I) and the Spacelab modules have limited electrical power (about 7 kW).
[g]The NASA "'space station" elements are expected to operate as transportation and servicing centers as well as laboratories. They would have sufficient power for extensive materials processing.
[h]A significant part of the cost of a human visit to Mars could be provided in this case.

other higher orbits, and 4) the capability to support the kind of vehicles that could be developed later to travel to and from the Moon. In 10 years, the IOC infrastructure now favored by NASA could be acquired. In 15 years, nearly all of the infrastructure now seriously considered by NASA could be acquired.

- At $3 billion per year (assuming that only funds, not technology or other factors, would be the pacing program factor): NASA's fully developed "space station" could become available in somewhat more than 5 years. In 10 years, this infrastructure plus a geostationary platform, plus a Shuttle-derived cargo vehicle (SDV) for lower cost transfer of fuel and cargo to LEO, plus a lunar facility ready for occupancy and continuing operation would become possible. In 15 years, NASA's complete infrastructure aspirations and a lunar settlement could be in hand and, perhaps also, plans for seeing a human crew travel to the vicinity of Mars and back could be well advanced.

These projections are for infrastructure acquisition only; operational costs are not included. In general, more extensive infrastructure would require larger operational costs. Also, there is a basic difference between the costs associated with using Shuttle-type vehicles and permanently orbiting facilities. The use of an EDO to conduct extended science or development activities with a crew would involve launch costs each time it went into orbit; use of a permanent facility would require resupply loads several times per year, but the cost of each flight could be shared with other payloads. For example, if 12 dedicated 30-day EDO flights were conducted per year about $1 billion (1984$) in annual transportation costs would be involved; in comparison, cost of four partial-load Shuttle launches per year to resupply a permanent facility would total $100 million to $400 million (1984$), depending on the weight of supplies carried in each flight.

CONCLUSIONS

The general conclusion of a great deal of study by the civilian space community (Government, industry, and university) is that some additional long-term in-space LEO infrastructure could be used to improve the efficiency and effectiveness of a number of present and anticipated space activities. However, our space experience to date, and science, engineering, and space operations considerations alone, are not now sufficient, by themselves, to determine the character and amount of the in-space infrastructure to be acquired soon. And in the absence of any objective external demand for its prompt acquisition, these considerations cannot determine the rate at which it should be acquired.

There are a wide variety of infrastructure options that could be chosen from to provide various kinds and amounts of in-space support assets and services. Some infrastructure options currently exist, others could be developed using **current technology, and some would require new technology. The cost to the Government of acquiring this infrastructure could be reduced, substantially, if our private** sector were to offer to provide lower unit cost portions thereof, and other portions were provided by other countries in collaborative programs within the United States.

it is clear that a number of important support assets and services could be provided with infrastructure other than that defined as "The NASA Space Station." Therefore, in considering how much of what kind of in-space infrastructure should be provided by when, reasonable ways for Congress to proceed might be:

- to select those specific support assets and services that they judge to be important, ask NASA to price them, and specify a date by which they should become available; or
- to set an annual average funding rate for the acquisition of in-space infrastructure, and allow NASA to select the assets and services to be provided and the dates of their acquisition.

And Congress could decide to what extent NASA should emphasize the acquisition of any infrastructure by our private sector and by other countries in order either to relieve the burden on the Government's budget generally, or to increase the amount, or hasten the time, by which space infrastructure would be acquired and/or other space activities were conducted.[6]

Using the first approach, Congress initially might select functions similar to those provided by the Soviet Salyut 7 (operational since 1982). Such a semi-permanent LEO laboratory could be developed using Spacelab-like modules connected to a power and support module patterned after current platform designs. It would support several crewmembers and one-third of the science, commercial, and technology development activities that NASA now suggests would be handled by their IOC. NASA's estimate is some $2 billion (1984$) for such a development.

Or, in another example, the conduct of ROTV operations might be selected as one of the main support functions to be supplied by space infrastructure. This would allow servicing and other activities in virtually all orbits, including polar, geostationary, and even lunar. In addition, such infrastructure would support the continued exploration of the solar system, which is one of NASA's most important "char ters." The cost for an ROTV and its associated LEO infrastructure has been estimated at $3 billion to $4 billion (1984$).

Of course, another example of the first approach would have Congress simply select the IOC assets and services identified by NASA and the aerospace industry that are estimated to cost $8 billion (1984$) (plus the cost of NASA staff); or even to spur the infrastructure acquisition process beyond NASA's present aspirations, and begin to move people beyond LEO.

Congress could consider alternative ways of providing those assets and services in varying degrees. For instance:

- an on-orbit **laboratory supporting research on a wide range of life, materials, and other science topics, and new technology devel-**

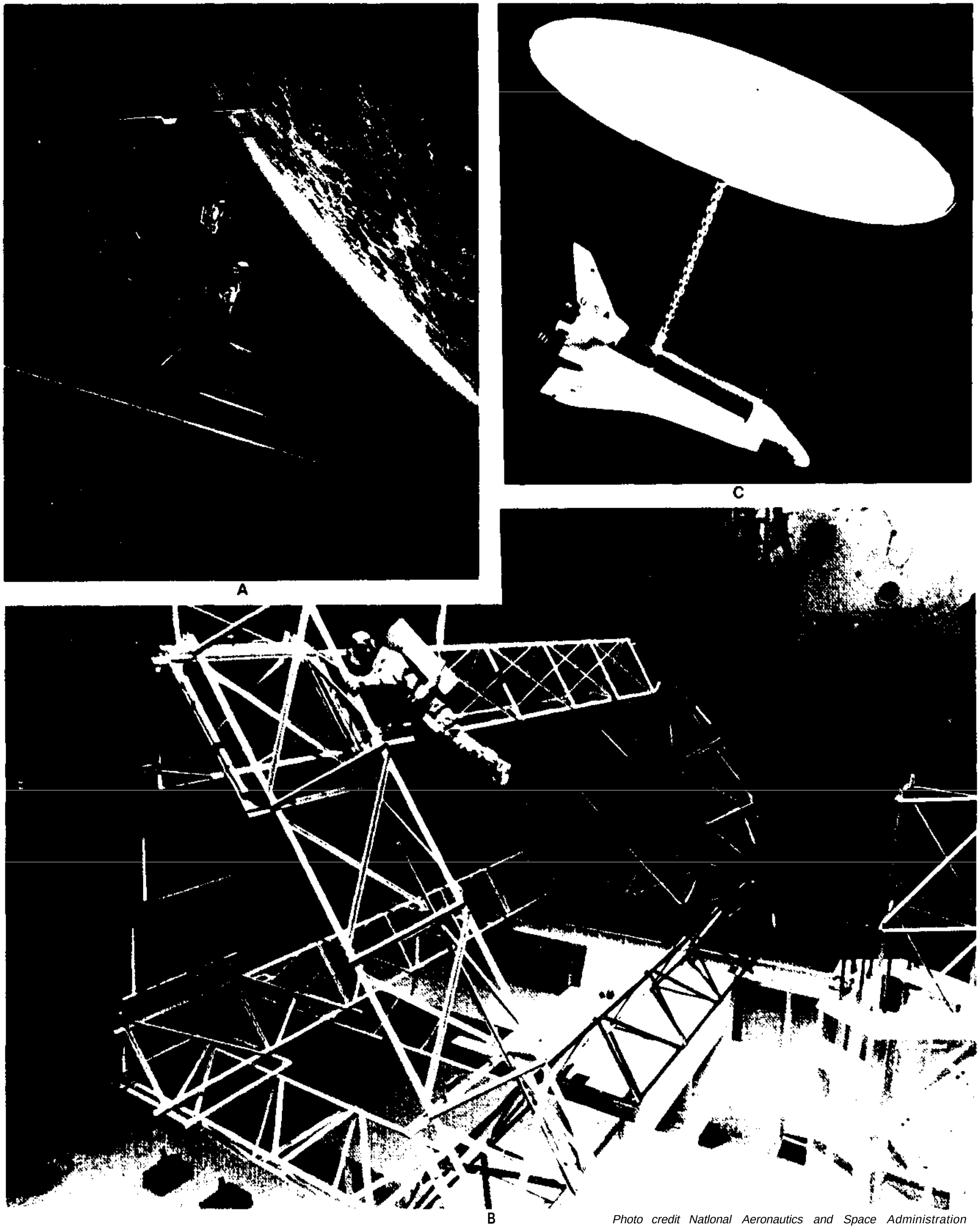
'A conceptual possibility would be for NASA to provide a core facility to which private industry could attach docking and fuel storage equipment for commercial ROTV operations.

opments (Shuttle, EDO, Spacelab, Columbus, NASA minimum cost "space station," Space Industries platform);

- permanent observatories for astronomy, and Earth remote sensing (Shuttle, EDO, Spacelab, Space Industries, SPAS, MESA, EURECA, Landsat, LEASECRAFT, Space Telescope, IRAS, 0S0 satellites, Solar Max, and other existing or planned observatories);
- a facility for microgravity **materials processing** including the manufacturing of such products as pharmaceuticals, semiconductors, glasses, and metals (Shuttle, EDO, Spacelab, LEASECRAFT, the Space Industries platform, SPAS, Columbus, EURECA, MESA);
- **servicing of satellites and platforms, including the maintenance or replacement of components, replenishment of consumables, and exchange of equipment (Shuttle, EDO, ELVs,** as well as OMVs and ROTVs operated from the Shuttle);
- a **transportation node** to assemble, check out, and launch vehicles to geosynchronous and other high orbits, and on interplanetary trips {Shuttle, EDO, Columbus, NASA minimum-cost "space station");
- an **assembly facility for large space structures** such as antennas for advanced satellite communications systems (Shuttle, EDO, Columbus, NASA minimum-cost "space station");
- a **storage depot for spare parts, fuel, and supplies for use as needed by satellites, platforms, vehicles, and people** (ETs, Columbus, LEASECRAFT, the Space Industries platform, NASA minimum-cost "space station"); and
- a **staging base for later, more ambitious** exploration and travel (Columbus, NASA minimum-cost "space station").

If Congress were to select an average annual funding rate, some examples of the approximate kind and amount of infrastructure that could be obtained over a period of some 10 years (in 1984 dollars) are, for instance:

- $0.1 billion per year: an EDO (20-day stay on-orbit) plus some free-flying platforms; or
- $0.3 billion per year: an EDO (50-day stay on-orbit), plus free-flying, pressurized infrastructure supporting several crewmembers, plus some free-flying platforms; or
- $1 billion per year: most of the NASA IOC plus an ROTV; or
- $3 billion per year: all of the NASA IOC, plus its extensions, plus an ROTV, plus a Shuttle-derived cargo vehicle, plus a "geostationary platform, plus an operating lunar settlement program.



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One alternative to the development of new technology is to use the Space Shuttle for many advanced operations in low-Earth-orbit. Shown here are: (A) satellite servicing satellite in April 1984; (B) assembly of a large structure in orbit—here simulated in water; and (C) a deployable antenna.