APPENDIXES

Appendix A

RESULTS OF PRINCIPAL NASA STUDIES ON SPACE STATION USES AND FUNCTIONAL REQUIREMENTS

Early in 1982, NASA established working groups to prepare for and coordinate a planning program to acquire a long-term in-space inhabited infrastructure, i.e,, a civilian "space station. " A Space Station Steering Committee at NASA headquarters led a two-pronged effort. A Technology Steering Committee had the task of assessing the current state of technology and planning any needed development activities for the program. At the same time, a Space Station Task Force became the principal planning group to consider types of activities (user needs/desires) to be carried out with any new long-term infrastructure, system physical characteristics, concept development, and management organization.

To support the Task Force as well as help clarify various issues involved, NASA authorized a series of parallel investigations of the potential desires for, and characteristics of, such infrastructure. These studies (costing more than $6 million altogether) were made by eight U.S. aerospace companies (with their associated subcontractors). In addition, the European Space Agency, Canada, and Japan funded essentially parallel user studies of their own. Related investigations of possible nonaerospace industry interest in space use were made by two consulting firms.

Major Findings of the U.S. Aerospace Industry "Mission Analysis Studies"

In anticipation that the United States could decide to build a publicly funded, habitable, permanent civilian "space station", NASA asked eight aerospace industry contractor groups to perform independent "mission analysis" studies to indicate what it could be used for (the desires and/or needs), what capabilities it should have to meet them (its attributes), what its fundamental characteristics and components might be like (its architecture), and what costs and benefits to the Nation might be expected of such a space program conducted over the remainder of the 20th century. Emphasis was to be on the user communities, national conceptual uses, and general architectures, not specific configurations.

in essence, they were asked to answer the questions "If the United States were to acquire an initial civilian "space station" complex in low-Earth-orbit (LEO) in the 1990's, who could use it, how could they use it, what attributes, capabilities, and types of components should it therefore have, what would it cost, when could it become available, and what benefits could its use provide?"

The contractor groups (in each case a prime contractor, usually with several subcontractors) communicated with the individuals, organizations, and institutions that might be expected to make use of such in-space infrastructure to ascertain the important present and potential desires and/or needs for it, with emphasis on those uses that would require or materially benefit from it. They then analyzed these various uses as a sequenced set of activities, so as to identify and characterize infrastructure attributes and capabilities that would be necessary in order to meet them. Sufficient study of major components and architectural options was made to provide reasonable indications of how adequate infrastructure could be provided.

They next provided programmatic and scheduling plans in order to predict when various portions of the program could become operational. Finally, costs of establishing the overall space infrastructure were estimated and the economic benefits projected that they foresaw through its use. The companies drew conclusions and made recommendations regarding further developments.

The eight prime contractors performing these studies were Boeing Aerospace Co., General Dynamics Corp. (Convair Division), Grumman Aerospace Corp., Lockheed Missiles and Space Co., Martin Marietta Corp., McDonnell Douglas Astronautics Co., Rockwell International, and TRW. About 20 other high-technology companies were involved as subcontractors. The final reports were submitted on April 22, 1983. Their results have been published in a series of volumes entitled "Space Station Needs, Attributes, and Architectural Options."

The major findings of these contractor studies are outlined below.

Users and Uses (Mission Requirements)

The aerospace contractors actively sought out the interests of potential users of LEO infrastructure in order to project what kind and extent of activities its support assets and services should provide. Users were

I The Department of Defense also participated with NASA in these studies, and paid 5 percent of their cost. For the most part, the studies related to national security are classified, and no further reference will be made to them here.

categorized under the three broad areas of science and applications, commercialization, and technology development.

The fields of astrophysics and solar physics, life sciences, environmental sciences and Earth observation, materials processing, and communications sciences all offered examples of possible uses of an initial complex. Over the longer term, it could be used as a base for launching lunar, asteroid and interplanetary research spacecraft. Advantages of having a human crew were seen in instrument and equipment servicing (predominantly for Earth observation, plasma physics and astrophysics) and human involvement in research (predominantly in materials processing, life sciences and solar physics). Research in most life sciences, and some materials and astro/solar physics was deemed impractical without direct human participation; one contractor concluded that 41 of 75 science activities would benefit from a human presence. The servicing of equipment would produce the side benefit of seeing instrument assets in space accumulated. Long-term operations would be especially important to some research.

The permanent infrastructure would include "free-flying" tended platforms to ensure isolation (where needed) from the possible dynamic disturbance or contamination of various kinds that might be present in an inhabited location.

Commercial possibilities were suggested for remote Earth sensing in the fields of petroleum and mineral prospecting, and agricultural forecasts; for materials processing; for on-orbit satellite launching of meteorological, navigation, and communications satellites to higher, even to geostationary Earth orbit (GEO), and for satellite servicing (although CEO servicing would not be possible using the initial infrastructure now envisioned by NASA).

Almost all Earth resources observation from space currently employs satellites without a crew and their use will continue; however, the contractors found advantages in using people to select surface locations to be studied, instruments, and observational parameters. Having space infrastructure also would enable concurrent multidisciplinary observations, and the crew would add the flexibility to modify the instruments during long-term observation periods.

The economical processing of some materials under conditions of near-zero gravity is one of the more intriguing possibilities for eventual commercial exploitation, with such materials as pharmaceuticals, alloys, semiconductors, and optical fibers as products. (Market demand for each of these products is seen by some of the more optimistic contractor groups as having the potential to grow to the multibillion-dollar-per-year level by the year 2000 if they could be made available at acceptable prices).

McDonnell Douglas Corp. has already pioneered in exploring the use of the electrophoresis process to produce pharmaceutical materials aboard the Shuttle. Electrophoresis is a separation process in which electrically charged particles suspended in a solution migrate through the fluid in the presence of an applied electrical field. If the particles are of microscopic or larger size, a common process limitation is a sedimentation of the particles under gravitational conditions. The effective absence of gravitational attraction when conducted in orbit around the Earth permits the process of separation and purification of such materials as proteins and pharmaceuticals to proceed at rates 500 to 1,000 times faster than on the surface of the Earth.

Several other companies are giving serious consideration to studying and manufacturing materials in space. However, the contractor groups agreed that the concept-to-market process generally takes many years, that a space research laboratory is required, that for at least some of the studies professionals in situ and continuous operations are very important desiderata, and that for most production processes, very large amounts of electrical power (in present space terms) would be essential.

Satellite communications is already a 20-year-old, highly successful, world-wide commercial space enterprise. It is seen as a business that should continue to expand rapidly. The required technology should move in the direction of large, dynamically controlled, multi-antenna subsystems, on-board switching, and high r.f. power, for which a "space station" may well be seen by some as essential (or at least desirable) for efficient structural assembly and deployment, testing and check-out, lower-cost transportation to geostationary orbit—and eventually, perhaps, the servicing of GEO satellites.

Satellite servicing is seen as enabling resupply and repair of co-orbiting space vehicles, and those in other orbits, such as polar or geostationary. In the latter case, a Reusable Orbital Transfer Vehicle (ROTV) would be needed to deploy or retrieve the spacecraft, as (according to several contractors) extensive servicing would usually by done in, or in the vicinity of, a central "space station" complex.

LEO infrastructure is seen by the contractor groups as enabling space technology development on all fronts–developments of interest to materials processing, communications, flight controls, fluidics, large space structures, on-orbit assembly and test, robotics, etc. All of these would benefit because of the sophistication of the support equipment that could be provided them, the longer time available for work in orbit than is provided by the Shuttle, and the extensive crew involvement needed, at least for the foreseeable future, for construction, calibration, and test.

Phased Activities (Mission Sets)

The contractor groups assembled sets of activities and operations responding to needs and desires expressed by potential **users** in order to estimate the assets and services required to support them for varying stay times in space. The preferred orbits were seen to be a low-Earth-orbit whose plane would be at 28.50 inclination to the Equator (typical of launches from Kennedy Space Center, FL), a 57° inclination (possible from KSC with a more northerly insertion direction) and a polar orbit (available with launch from Vandenberg AFB, CA). In some cases, staging to geostationary orbit or to escape velocity (for lunar, asteroid and/or planetary flights) would be necessary.

Most of the studies identified several hundred possible uses and desires, a number well in excess of what might be accommodated during the 1990s. When examined in the context of realistic technical progress, the likelihood that such uses/desires would actually develop, and the benefits made available through such use, etc., the vast majority of those potential uses could be supported with infrastructure located in the low inclination orbit of 28.5°. This is exemplified by a typical distribution of activities shown in table A-1 as recommended by one of the contractor groups. The activities in this baseline set are noted as being best accommodated either by attaching them to a central, inhabited infrastructure complex, or locating them on free-flying platforms that would be tended only intermittently by crew members.

Inasmuch as some 70 percent or more of the potential needs/desires could be accomplished in the 28.5° orbit, it was the unanimous recommendation of all the contractor groups that any initial inhabited infrastructure be located in this orbital plane. Free-flying platforms, either co-orbiting or in polar orbit, could accommodate most of the remaining missions.

One example of the number of inhabited infrastructure-attached payload elements at any time (so-called station occupancy) is shown in figure A-1, in which the initial operational capability was assumed to occur during 1990. The projected activities are seen to reach a high number quite early in the development cycle.

Functional Capabilities

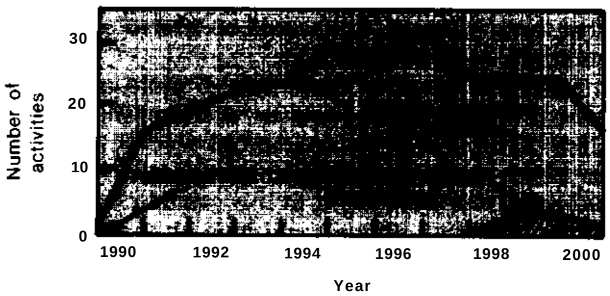
NASA has recently indicated that it expects proposed new space infrastructure to provide the set of functions described in chapter 2. One contractor's visualization of these functions is given in figure A-2, while table A-2 illustrates the corresponding attributes required for space infrastructure designed to accomplish the functions. Translated into physical quantities, the requirements for power, pressurized volume, crew size and Shuttle launches are typified by figure A-3. The initial power needs for the central space complex of the infrastructure are modest, about 25 kW, but as

Table A-1 .—One Contractor Group's Mission Set

	Attached to central infrastructure complex in LEO		Free-flyers				
	Inclination plane		Inclination plane (LEO)				
	28.5"	Polar	28.5°	57"	Polar	GEO	Escape
Science and applications:							
Astrophysics	7		6	3	1	1	
Earth and planetary	5	3		1	7		12
Environmental observations	7	4	1	7	4	3	
Life sciences	7						
Materials processes	2						
Commercial:							
Earth and ocean				1	2	1	
Communications	6					5	
Materials processes	14		1				
Industrial services	5		1				
Technology development:	33						
Operations:						2	
	86	7	9	12	14	12	12
Total mission set	152						

SOURCE: Based on information contained in the study led by the General Dynamics Corp

Figure A-l.—One Contractor's Time-Phased Set of Activities Involving Work Crews



Conclusion: 28.5-deg station captures approximately 92°/0 of activities involving crews.

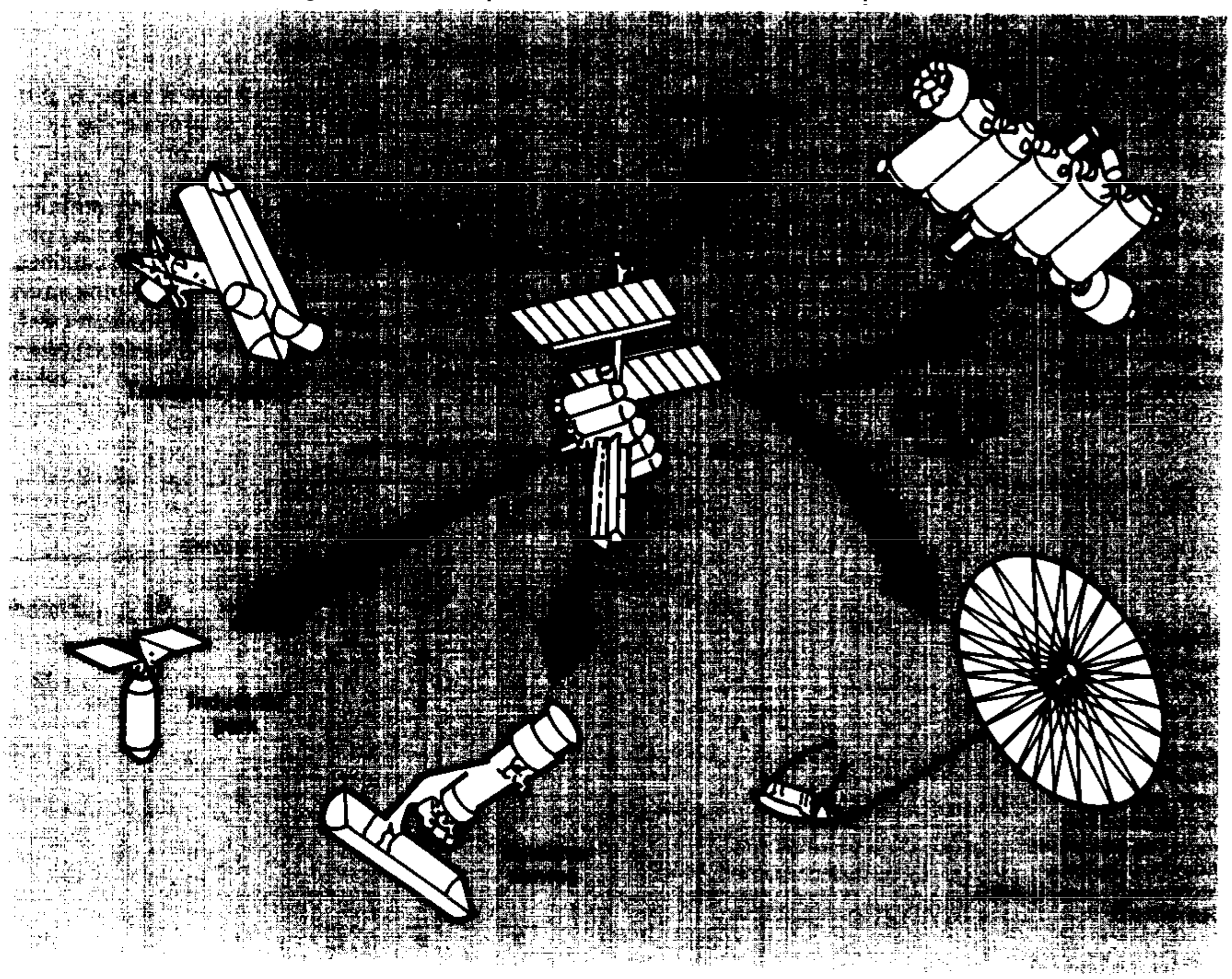
SOURCE Based on Informatlon contained in the study led by General Dynamics Corp

the experiment load increases so does the power requirement. If materials processing in space takes place on a commercial scale now visualized by some, the power demands could then become quite large. It is likely that, eventually, much of the materials processing production would be carried out on platforms with their own solar array power supplies; they would coorbit with the central complex.

In the view of most contractor groups, an initial operational crew would consist of some three persons, with the crew size growing to as many as 8 to 10 in the mid 1990s. Corresponding pressurized volume for the crew and some operations might grow from about 200 m^3 to 600 m^3.

Five or six Shuttle flights would be required to establish the **IOC** infrastructure suggested in the studies.

Figure A-2. —A Representative Set of Functional Capabilities



SOURCE Based on information **contained in the study led by Grumman Aerospace Corp**

Table A.2.—One Contractor's Estimate of Required Infrastructure Attributes

Accommodates activities with work crews:
- **Micro-gravity**
  - **— Life sciences**
  - **— Materials processing**
  - **— Technology development**
- **Outward looking**
  - **— Astrophysics**
- **Earth pointing**
  - **— Earth exploration**
  - **— Environmental observation**

Supports free-flyer activities:
- **LEO/H EO satellites/platforms**
  - **— Emplacement**
  - **— Service**
  - **— Retrieval**
- **GEO satellites/platforms**
  - **— Emplacement**
  - **— Service**
- **Planetary satellites**
  - **— Boost**

Provides resources:
- **Work crew time**
- **Power**
- **Data processing**
- **Command and control**
- **Thermal control**
- **Stable platform**
- **Pressurized volume**
- **Exterior mounting**

Provides functions:
- **Assembly and construction**
- **Checkout**
- **Service**
- **Reconfiguration**
- **Maintenance and repair**
- **Transportation**
- **Storage**

SOURCE: Based on Information contained in the study led by the General Dynamics Corp

Contractors estimated that civilian projects would require six or seven flights per year (fig. A-3). While three or four supply visits per year by the Shuttle would be needed for ongoing operations and maintenance (O&M), these could be partial-load deliveries combined with other loads.

Infrastructure Elements (Architecture)

It is at the implementation stage that the contractor groups' reports suggest quite different approaches to providing those in-space infrastructure elements needed to meet the user needs/desires. One conceptual array of components is illustrated in figure A-4. The central complex would be in communication with other elements including free flyers, free-flying platforms, a reusable orbital transfer vehicle, the Shuttle Orbiter, and ground stations via the Tracking and Data Relay Satellite communications system.

The components suggested by one of the contractor groups for the first central complex are indicated in figure A-5. A central command/habitability module provides overall infrastructure command and control, data handling, communications, and accommodations for a crew of four. (Several of the contractor groups' studies suggest three crew members at the outset.) Directly attached is the energy module where solar cell arrays and batteries provide electrical power and its conditioning and storage. (In this illustration, the energy module is pressurized; some studies suggest that it be mounted externally.) The third, logistics, module stores and makes available consumables and equipment delivered by the Shuttle. With only these three infrastructure elements, a crew could live in orbit satisfactorily for extended periods but would be able to accomplish relatively little scientific or other activity beyond those experiments that could be accommodated in the available internal space.

Additional elements shown in figure A-5 are the airlocks to permit people to move in and out of the habitability module and to conduct activities in space (so-called extravehicular activity (EVA)), an astronomy service pallet to enable mounting of scientific observatory equipment, and a payload service pallet to permit servicing of satellites and such auxiliary vehicles as an orbital maneuvering vehicle. The final unit suggested for the IOC is a materials processing laboratory.

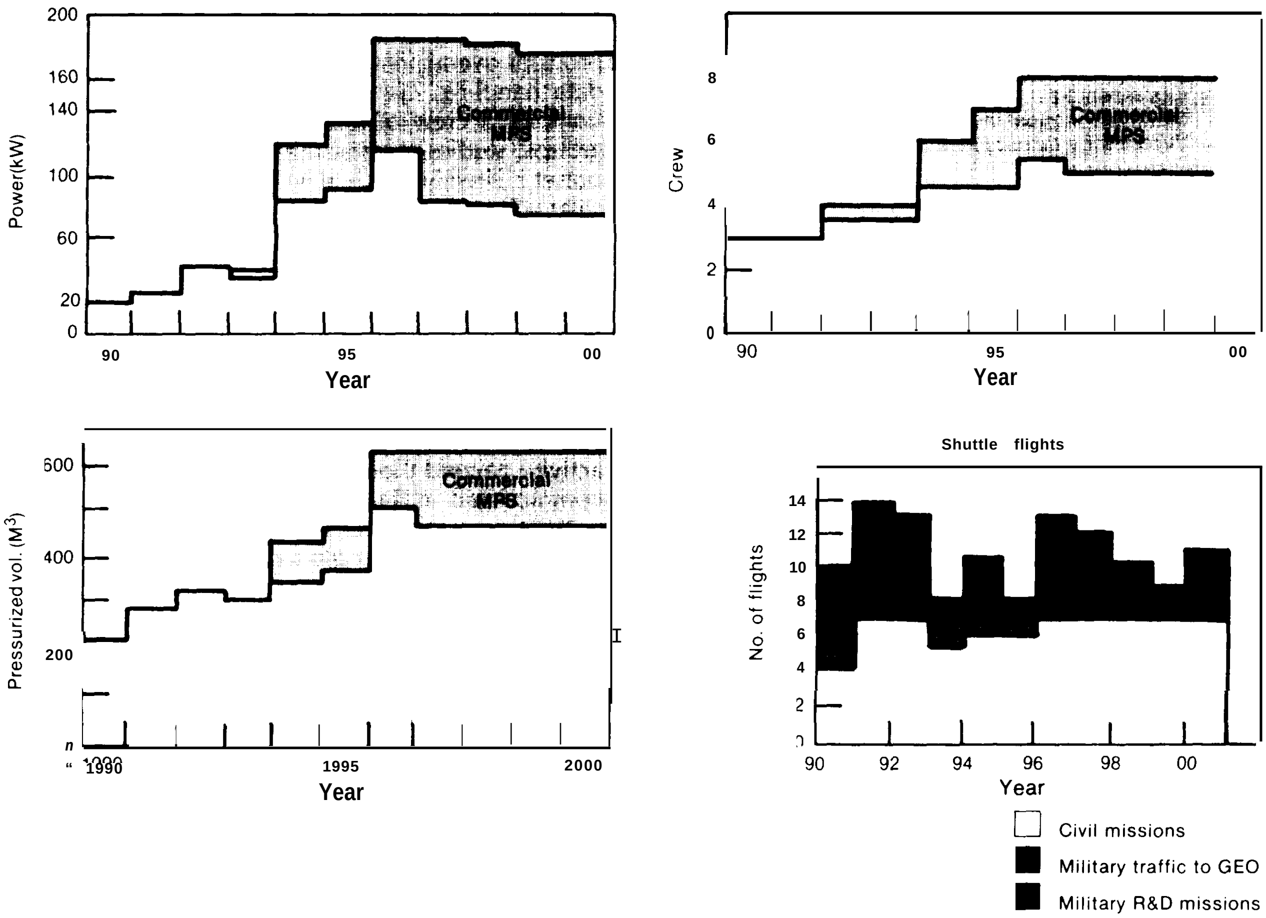
The continuous power suggested would approach 25 kW (roughly corresponding with the initial level shown in figure A-3). Inasmuch as the crew accommodations might require about half of this amount, the power available to users would allow for materials processing experiments but not for some kinds of ongoing production.

Other contractor groups would arrange the infrastructure elements differently, with a possible command module separate from an habitability module, or an operations module combining energy generation and conditioning with a command and control center and EVA facilities. Some designs would incorporate tunnels or passageways to connect different modules.

Ten or more subsystems have been suggested to enable the infrastructure elements to remain in orbit and function satisfactorily. These are itemized in the organizational diagram shown in figure A-6.

In accordance with the NASA study directions to the contractor groups to envision the use of new technology where it would be beneficial, various new materials and theoretical designs for the subsystems have been suggested. An example of one contractor group's technology recommendations is given in table A-3; while most items are considered to be currently available in a useful form, advanced technology would be required to achieve the improved capability and/or

Figure A-3.—One Contractor's Estimate of Resources and Services



SOURCE Based on information contained in the study led by the General Dynamics Corp

reduced weight and lifecycle costs that it recommends. Some contractors identified standardization as contributing to cost containment; where no advance in technology appeared necessary, they suggested use of standard available equipment if practical, with space qualification as necessary.

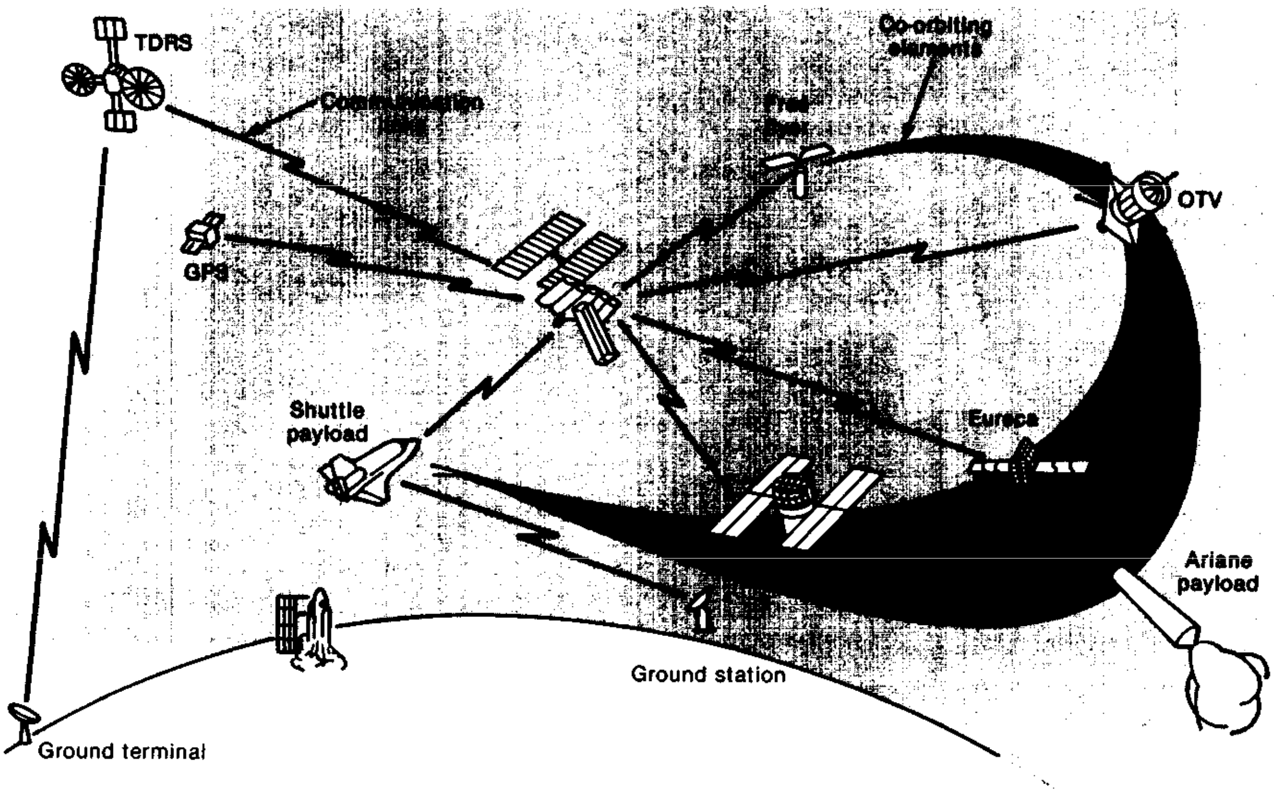
Evolution of the Initial Capability

All of the contractor groups provided plans for evolution from the initial operational capability (IOC) to expanded infrastructure expected to become available by the end of the century. One example of infrastructure located in the 28.50 orbit is shown in figures A-7 (IOC) and A-8 (Evolved). The crew would increase from three to nine, the power would triple, the number of pressurized core modules would increase from one to five, and the servicing facility would quadruple in size. A similar evolutionary plan including tended co-orbiting and polar platforms and an ROTV is shown in figure A-9. A possible co-orbiting industrial platform is illustrated in figure A-1 O, and an initial tended polar platform could appear as shown in figure A-1 1. Core module commonality was suggested by essentially all contractor groups in order to promote production cost economy.

Role of a Human Crew

All contractor groups emphasize the importance of having a human crew. All consider that "sophisticated machines" (robotics, artificial intelligence, etc.) will not be able to provide the desired capabilities that could be provided by a human crew through the early 1990s. The benefits of having a human crew are summarized by one contractor group in table A-4.

Figure A-4.—infrastructure/''Space Station”



SOURCE: Based on information contained in the study led by Grumman Aerospace Corp.

Costs and Benefits

The cost estimates of design, development, test and evaluation, and production, of a “space station” complex have been made by each contractor group according to parametric models following a “Work Breakdown Structure” developed by the joint Industry Government Space System Cost Analysis Group. Since detailed designs were not part of the study, predominantly weight-based parameter estimates were used to arrive at a rough order-of-magnitude estimate for the costs of designing, building and deploying a complex.

Inasmuch as individual contractor groups proposed different combinations of modules and systems, considerable care is necessary in making comparisons of costs among them. It will suffice here to note that a “core” IOC space station in a 28.50 inclination orbit (i.e., command/habitation capability for a crew of three or four, power unit, and resupply logistics modules) was estimated to cost $3.3 billion to $4 billion (1 984 dollars). With appropriate attached pallets and modules to provide further observation, experiment, and servicing capability, the cost would be $4.5 billion to $6 billion. With a crew of eight or nine, 60 kW of power to users, two or three laboratory modules and expanded servicing facilities, plus two tended platforms–one co-orbiting and one in polar orbit–the estimated acquisition cost would be $7.5 billion to $9 billion. This latter infrastructure array corresponds to the IOC suggested by the NASA Space Station Task Force (SSTF) in June 1983.

The above figures include those Shuttle launches required to place the elements in orbit, but generally do not include NASA support and program management expenses; OTA estimates that these latter costs would be another $1 billion to $2 billion if acquired by NASA in its usual fashion.

An additional ROTV capability cost has been estimated at $2 billion to $3 billion, including both the LEO basing facility and the operating vehicle. If a new fuel tanker vehicle were to be developed, it could cost approximately $1 billion.

The programmatic approach assumed by a number of contractor groups is that of the use of “protoflight” construction. One group compared the new method

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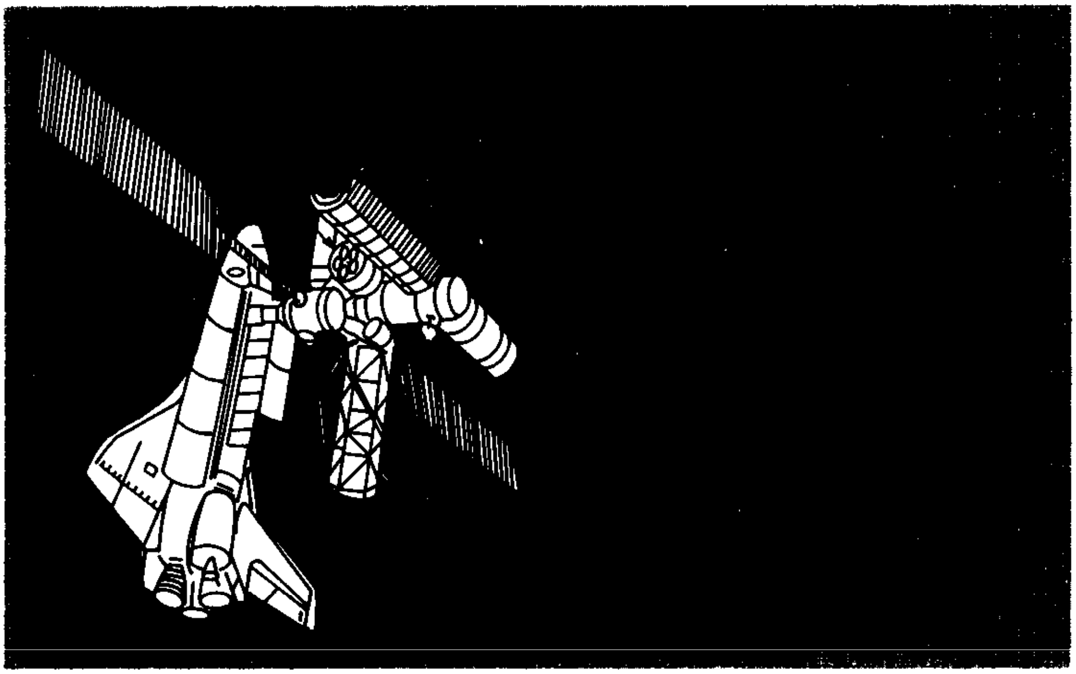
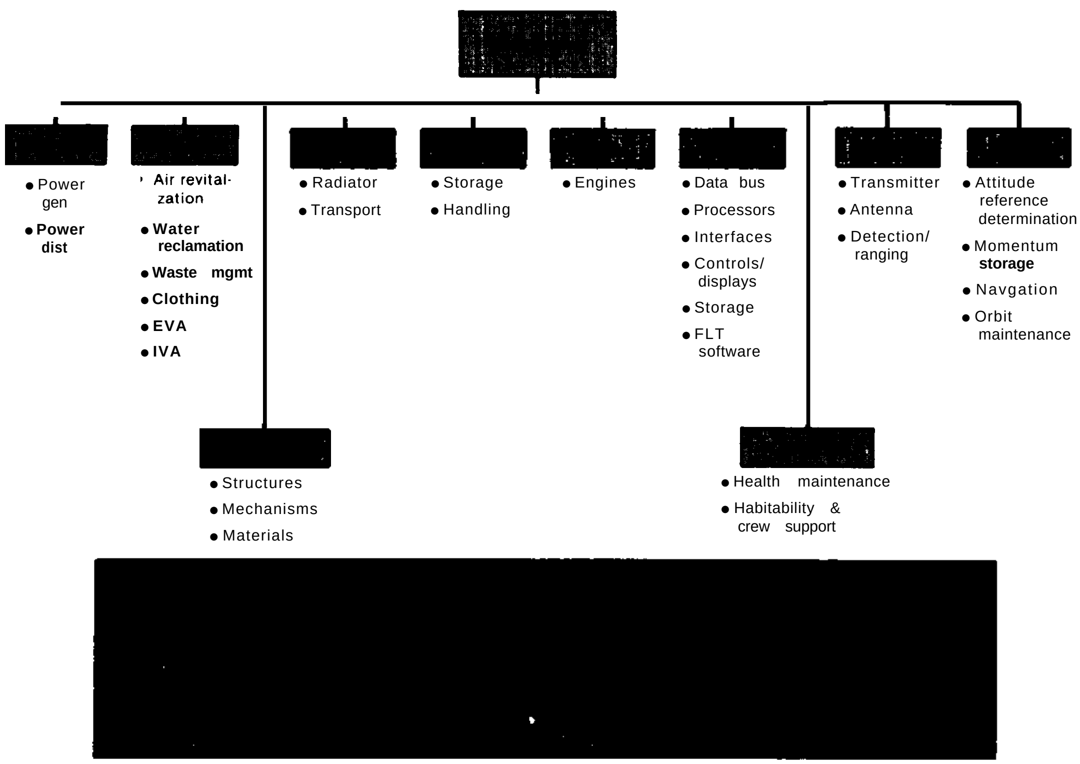
Figure A-5.—One Contractor's Suggested IOC Central Complex Architecture



SOURCE: Based on information contained in the study led by Rockwell International.

Figure A-6.—A Suggested Central Complex Subsystem Organization



SOURCE Based on information contained in the study led by Rockwell International

Table A-3.—One Contractor's Suggested List of Subsystem Enabling Technology

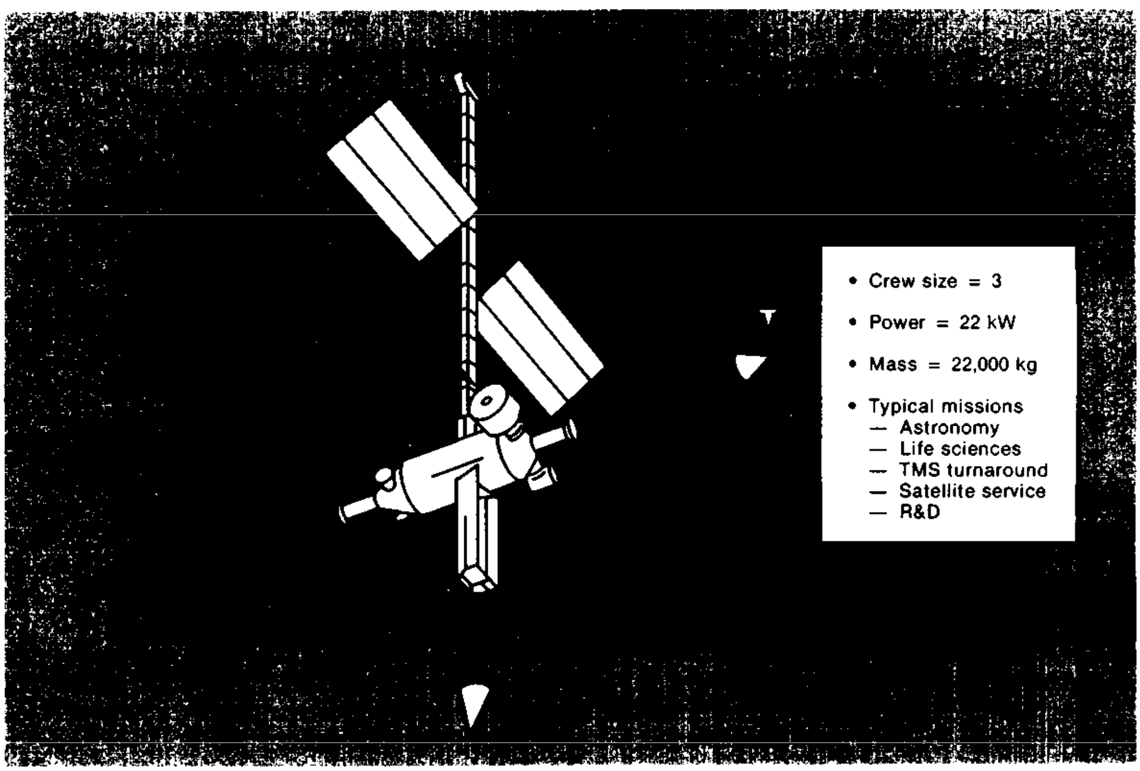
	Subsystem characteristics	Enabling technology
EPS	• Solar array	• Thin cell and higher efficiency
	• NiH, batteries	• Cell manufacturing processes
	• 180V dist.	• Battery development
		• High voltage component development
DMS	• Ada computer language	• Meeting existing Ada schedule[a]
	• Fibre optics	• Low loss couplers[a]
	• Advanced main memory with b/u battery	• Develop higher densities
	• Bubble auxiliary memory	• Space qualifications and higher densities
COMM & TRKNG	• S, K_u band subsystems	• Modulations/cod ing/bandw idth[a]
	• Dish, omni-antennas	• Design/develop for application
	• TDRS	• Acquisition/tracking/data rate[a]
	• Simultaneous operation	• Radio frequency interference protection
EC/LSS	• closed loop	• Existing hardware with modifications
GN&C	• Attitude control	• Existing hardware with modifications
	• Velocity control	• Existing hardware with modifications
	• Stabilization	• Existing hardware with modifications
	• Sensors	• Existing hardware with modifications

a 1983-86 technology and design techniques adequate
b Advance required for this technology

Key
EPS—Electrical Power Subsystem
DMS—Data Management Subsystem
COMM —Communication
TRKNG—Tracking
EC/LSS—Environmental Control and Life Support Subsystem
GN&C–Guidance, Navigation, and Control
TDRS—Tracking and Data Relay Satellite

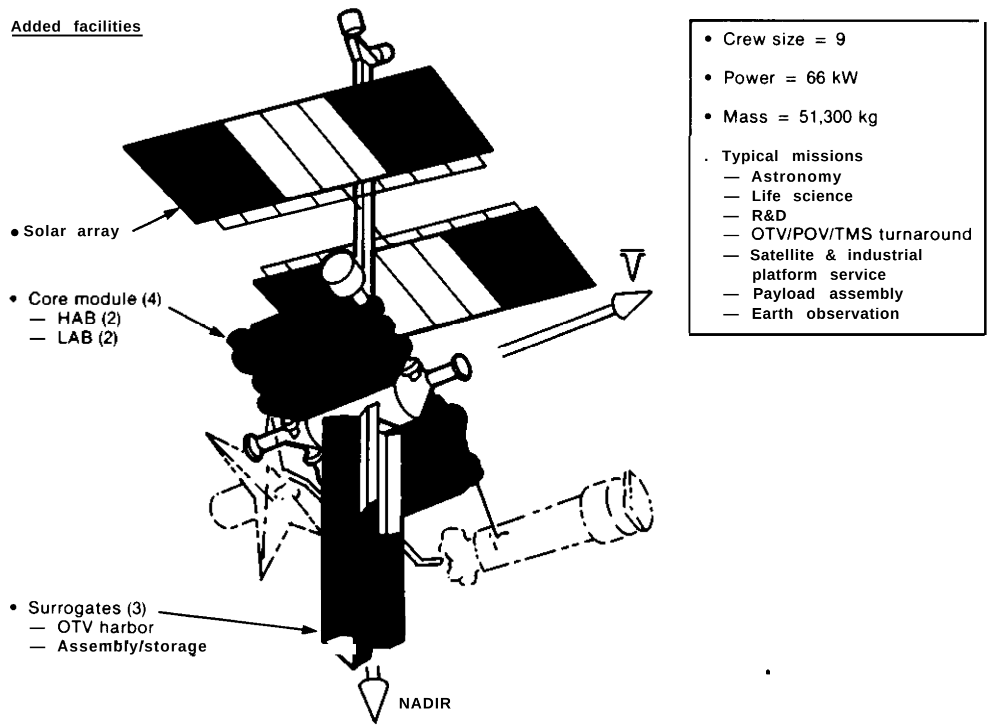
SOURCE Based on information contained in the study led by the Grumann Aerospace Corp

Figure A-7.—One Contractor's Suggested IOC Central Complex



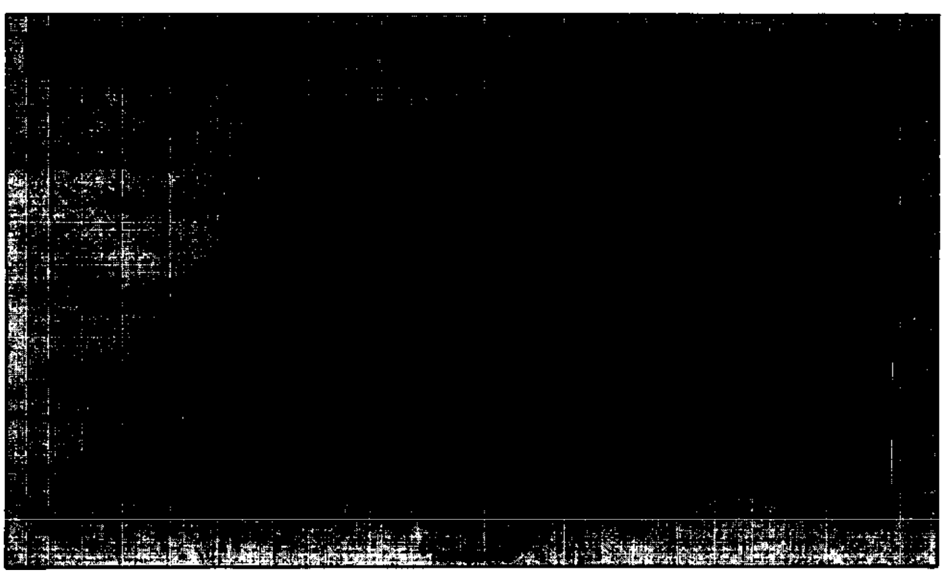
SOURCE Based on Information contained in the study led by Grumman Aerospace Corp

Figure A-8. —The Same Contractor's Suggested Evolved Central Complex



SOURCE Based on information contained in the study led by Grumman Aerospace Corp

Figure A"9.—One Contractor's Suggested Evolution Plan; LEO, 28.5°

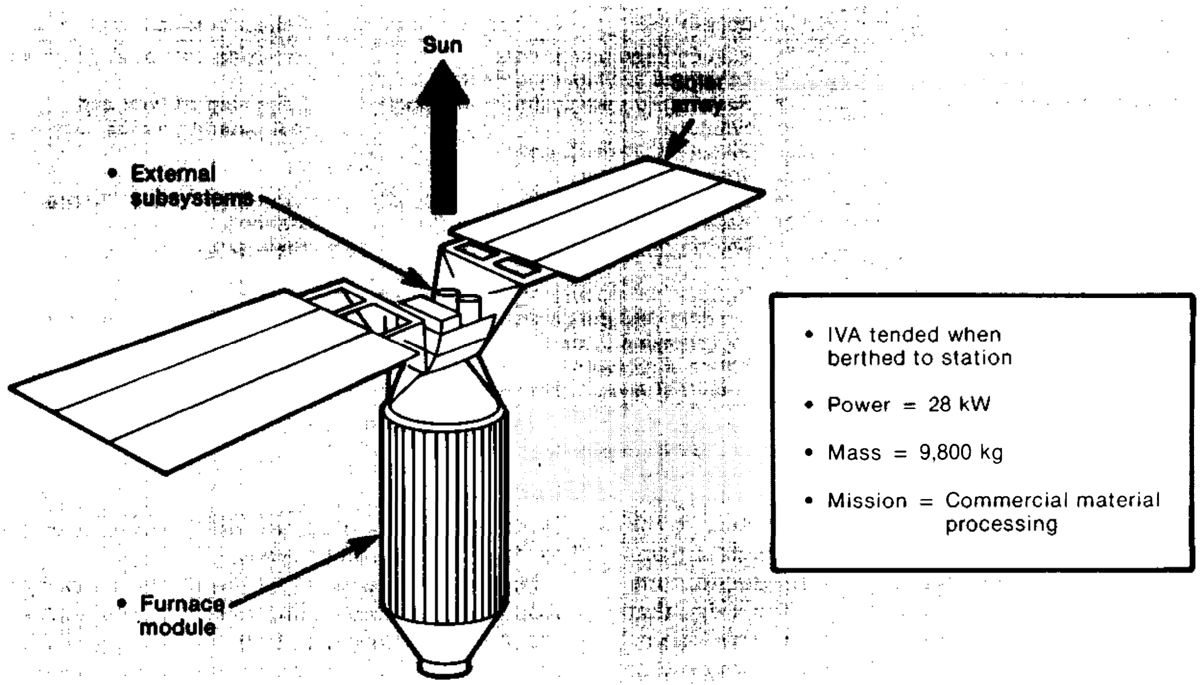


Key

TMS—Teleoperataor maneuvering system
MMU—Manned maneuvering unit
RMS– Remote manipulator system
OTV—Orbital transfer vehicle
ISTO—Initial solar terrestrial observatory
ASTO—Advanced solar terrestrial observatory
ASO—Advanced solar observatory
LSS — Large space structure

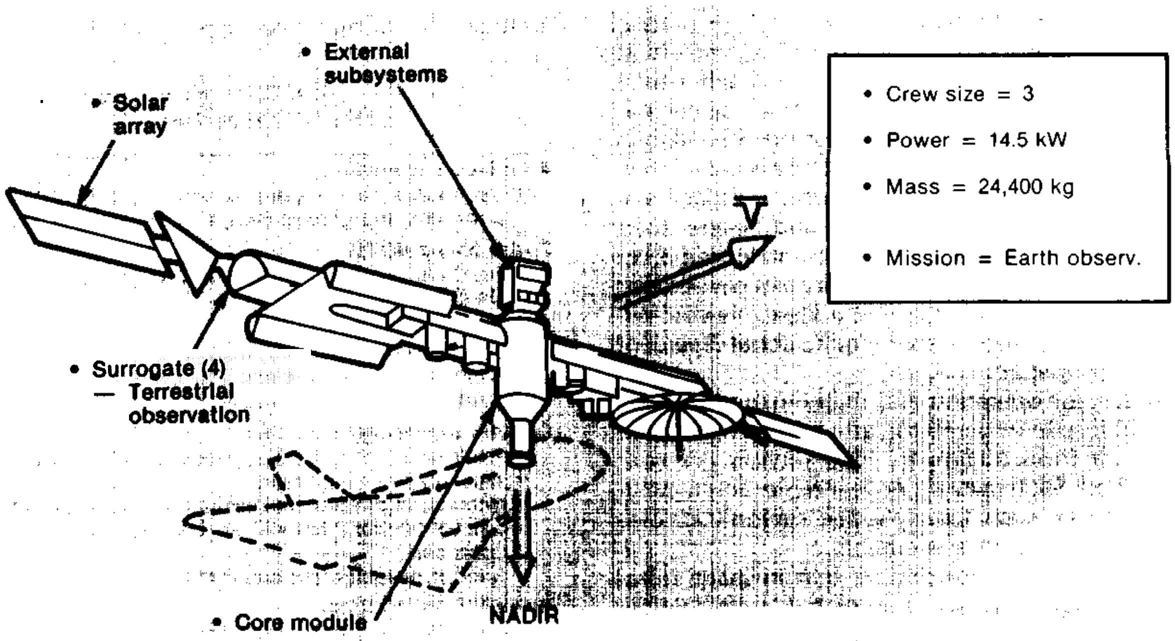
SOURCE Based on information contained in the study led by Martin Marietta Corp

Figure A-10.—One Contractor's Suggested Free-Flying Industrial Platform



SOURCE Based on information contained in the study led by Grumman Aerospace Corp

Figure A-11.–One Contractor's Suggested Tended Polar Platform (IOC)



SOURCE Based on information contained in the study led by Grumman Aerospace Corp

Table A4.—One Contractor's Summary of Benefits of infrastructure Work Crew Presence

Function	Benefit	Related issues
Maintenance and repair	• Reduced equipment cost • Enhanced availability and life	• Realizing cost savings potentials
Real-time mission involvement	• Reacting to unexpected or transient events • Discovery, insight, and understanding	• Designing activity and instruments to take advantage
Lab operations	• Difficult or impossible to automate[a] • Research progress not paced by Shuttle reflight schedule	• Lab equipment at "space station" • Crew skills
Construction, assembly, test checkout, modification of large systems	• Difficult or impossible to automate[a] • Simplify designs compared to complex deployment • Stiffen structures • Final test and correction in space	• Role of EVA • Design to realize benefits • Low-thrust transfer to final destination

[a]Within the predictable future.

SOURCE: Based on information contained in the study lad by the Boeing Aerospace Co.

with that used in the Skylab project. In contrast to the multiple qualification test, backup, and flight articles used then, they assume that the first production unit will be a flight article. Furthermore, they judge that the large size of modules permitted by the space transportation system (STS) would promote economy of scale. Finally, they judge that autonomous operation of the infrastructure would allow significant reduction in ground support compared to that of Skylab. These factors lead them to conclude that a "space station" could be acquired for significantly less cost per pound than was Skylab. Although it is unclear which precise spacecraft elements are included, their estimate was **$77,000/kg ($35,000/lb)** for Skylab (1984), while they projected $44,()()0/kg ($20,000/lb) for a "space station." Their estimate of the cost of the Spacelab is $220,000/kg ($100,0O0/lb), although this is higher than that of European **sources.** (Of course, a "space station" could be many times larger and heavier than either Skylab or Spacelab.) They estimate that it required 10 percent of the acquisition costs per year for Skylab O&M, and estimate that a life-cycle-cost designed "space station" would require about 3 percent per year to operate.

Estimates for operation and maintenance costs of all the aerospace contractor groups fall within the range from $150 million to $600 million per year (1984); about $400 million per year represents a mean value of these costs for a "space station" accommodating 8 to 10 crew members.

All contractor groups foresee that in-space infrastructure could provide operational performance, sociopolitical, and economic benefits. The first two are essentially qualitative in nature: appropriate activities would enable scientific and commercial communities to expand and improve their activities in space. Some of the technology advances would be expected to "spin off" to other areas.

Further, they expect that the performance benefits would accrue from an improved ability to perform in-space tasks, resulting in both an increase of quantity and improved quality of output. A number of these are listed in table A-5. In the research and technology areas, the cost of development programs could be reduced by large factors–some project it to be as much as 50 percent. Free-flying platforms could enable and promote many commercial projects. A base for maintenance and repair of in-space equipment on

Table A.5.—One Contractor's Summary of Performance Benefits

All mission operatlons:
- Decoupled from Shuttle launch schedule, payload priorities, and ground delays

Space based ROTV:
- 10,000 kg + useful payload into GEO
- On-demand capability

On-orblt assembly:
- Work crew can inspect, work around, and complement robotics and automation
- Shuttle size limits surmounted

On-orbit technology and R&D:
- Work crew can calibrate, operate, and modify
- True space environment
- Interaction of multiple disciplines and capabilities in a novel environment will produce synergistic advances
- Shorter development programs

Sclentific observations:
- Short lived experiments extended
- Work crew can monitor, intervene, replenish, and update

SOURCE: Based on information contained in the study led by the Grumman Aerospace Corp.

an as-needed basis, and scheduled activities such as resupply and/or removal of manufactured products, would be provided. The useful life of observation modules would similarly be enhanced by replenishment of consumables, change of experimental equipment items and their unscheduled repair.

As scientific knowledge is gained there is greater potential to enhance the quality of life. Basic research results provide some of the background to applied research, where economic and social benefits prospects become more visible. Improved space-based ocean, weather, and atmospheric research eventually could assist in our ability to locate and manage Earth resources, and monitor and control the physical environment. New pharmaceuticals as well as semiconductors and metal products could become available through space research and processing. Other social benefits envisioned by one of the contractors are indicated in table A-6.

"Space station' '-related economic benefits are hoped for in at least three ways: research, development, and production activities generally; satellite servicing; and orbital transfer vehicle operations. The contractor groups judge that the greatest benefits should flow from the latter.

Research and development cost reduction through use of infrastructure support is the most difficult to estimate, but most of the contractor groups concluded it could amount to hundreds of millions of dollars per year. One example is that of a lengthy science research project such as that involving the Shuttle Infrared Celestial Telescope Facility that anticipates some 250 days of use in space. If done in a series of 30-day extended-duration orbiter (EDO) trips, the associated operating expense is estimated to be about $3.6 million/day, while if accomplished in a continuous interval in a laboratory there, the cost is expected to decrease sharply, to $0.4 million/day. Materials science experiments done in space using a 30-day EDO might cost $2.9 million per experiment, compared with an estimated **$0.6** million per experiment if done in a long-term laboratory there. One estimate of the cost of pharmaceutical production, where a large portion of the expense is in the materials, is that of some $33 million/kg ($15 million/lb) if done in an EDO, compared to $18 million/kg ($8 million/lb) if done at a "space station." These kinds of cost benefits could be expected to continue throughout the complete "space station" life of some two decades and, if realized, could be a significant factor in encouraging the commercialization of space.

Table A-6.—Some Social Benefits Suggested by One Contractor

- **High-technology—a national goal**
- **Focus for engineering/science education**
- **Lunar and beyond exploration**
- **International cooperation**
- **Unique, sophisticated development facility**
- **New communication services**
- **New commercial products and industries — medical, semiconductor**
- **New therapeutic, diagnostic techniques**
- **Enhanced national security**

SOURCE: Based on information contained in the study led by the Grumman Aerospace Corp.

Were a Shuttle used to service an LEO satellite, the price per flight would approach some **$20** million, which is comparable to the value of the servicing for many such satellites. Using permanent space infrastructure services offers the possibility, in principle, of reducing this operational cost by perhaps one half.

Benefits expected of an ROTV are related primarily to its being based in space and its reusability. One of the study contractor groups estimated that a fully amortized ROTV service could be provided at a total cost of about $60 million for a 4,500 kg (10,000-lb) payload delivered from LEO to GEO. In contrast, a large expendable upper stage costs some $100 million or more, delivered with its payload to LEO. Thus, net economic benefit for the ROTV would be some $4o million to $5o million per flight, and 20 launches per year could provide a total savings of $1 billion/year.

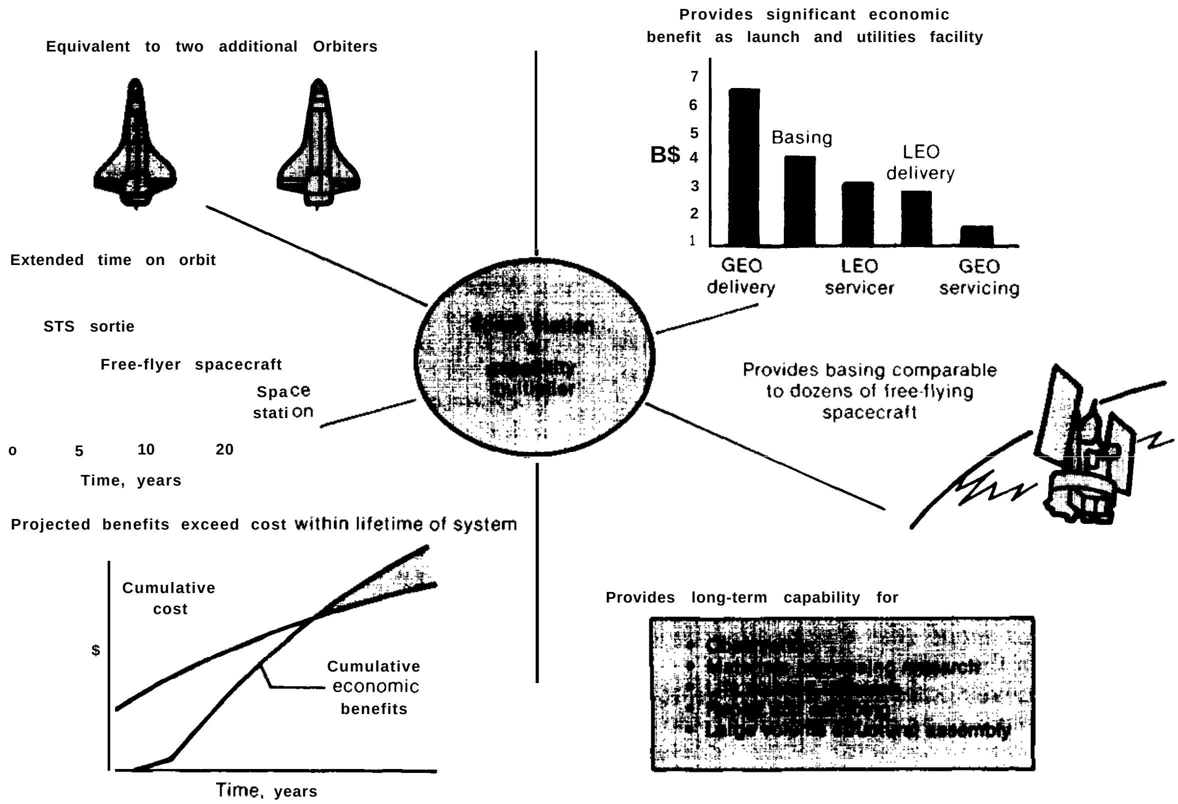
Figure A-1 2 illustrates the judgment of one contractor group regarding the various kinds of benefits expected of the use of a "space station."

Regardless of when a positive economic payoff might commence—always assuming that it does—a "space station" could be a powerful capability multiplier. Of course, one of the most important benefits would arise from the conduct of activities which would be impossible to conduct without it, and activities that we cannot conceive of now.

Conclusions

The aerospace contractor groups that studied potential needs and desires for new infrastructure identified hundreds of activities in the areas of space science and applications, commercialization, and technology development that could be carried out utilizing long lifetime infrastructure with accommodation for a crew to live and work in space. The vast majority are activities that are possible only with a crew supported by the infrastructure, or ones that would be enhanced by their presence: they would maximize R&D performance, especially in the life and materials sciences, and contribute to economic benefits. No single activity, or even a few, would be sufficient to justify its establishment, but the large total number

Figure A-12.–One Contractor's Summary of Infrastructure ("Space Station") Payoffs



SOURCE Based on Information contained in the study led by Martin Marietta Corp

contributing in all functional areas, in the judgment of the contractor groups, provide reasons to acquire an extensive permanently inhabited space infrastructure.

All study participants see significant benefits—including such intangibles as national prestige, leadership in space, and economic, performance, and social benefits connected with scientific research, commercialization, and new technology. Reflecting the broad range of advantages projected, contractors differed as to which aspect would be most significant. Planetary probes, a Lunar settlement, and human exploration of Mars are considered of great significance in terms of longer range goals.

It was the unanimous recommendation that the first infrastructure units should be placed in a 28.50 inclination low-Earth-orbit. All were envisioned as new technology designs and were projected as allowing evolutionary growth with increased size and capability phased in over an initial assembly period of about 5 years. The smallest unit with adequate volume to house a crew of three for extended stays and with minimum experimental and research facilities would consist of a command/habitat module connected to a solar-array energy module, plus two logistics modules (for resupply by Shuttle flight). They estimated such an initial unit's acquisition cost to be from $3.3 billion to $4 billion (1984). A later complex accommodating eight crew members, 60 kW of power to users, two laboratory modules, several external payload attachment points and satellite service pallets, and two tended platforms (co-orbiting and polar) were estimated to cost $7.5 billion to $9 billion. An ROTV capability could cost as much as $3 billion more. And further expansion of "space station" components and capabilities were contemplated into the 21st century.

These contractor costs accumulate to $10 billion to $12 billion for the development of the contractor-suggested evolved complex over an approximately 9-year period to the mid-1990s; NASA support and program integration expense could be another $2 billion to $3 billion. The contractor "evolved" system is roughly comparable to the summer 1983 NASA IOC but with the addition of full ROTV capability. (Further additions that enter, generally, in NASA's future plans to the year 2000 would add another $6 billion.)

The contractors point out that, although quite large, these expenditures may be compared with the approximately $60 billion (1 984) invested in the Apollo program and the estimated equivalent $56 billion spent for the Salyut-Soyuz project (reported by *Interavia* for February 1982), each over a somewhat comparable period of time. While the study contractor groups concluded that these estimated costs could be contained within a NASA budget projection that maintained today's level of appropriation over a 10-year period, they recognize that some cost-offsetting economic return on this public investment is necessary.

While the prospects for cost containment and other intangible benefits are considered to be promising, two operational factors are pointed out as the main sources of large, quantifiable economic benefits. One is the use of an LEO-based ROTV system to transport equipments between LEO and higher orbits, including GEO. The other relates to the fact that appropriate infrastructure would result in maximizing the STS load factor for each flight. The contractors project a reduction in costs for these activities of up to $10 billion over the system lifetime. Income could result from increased commercial space development fostered by the lower cost of space activities and faster conduct of research activities generally.

A final comparison may be made regarding other long-duration "space stations" of the past and present: Skylab and Salyut. As orbiting spacecraft accommodating crews, at first glance they appear to be fundamentally similar. But, while all three could function as space test and laboratory facilities, the contractors note that the proposed "space station" is the only one providing for satellite servicing. And neither Skylab nor Salyut offered the assembly and transport harbor envisioned for a new "space station. "

Major Findings of "Mission Analysis Studies" of Other Countries

Related studies were also requested of potential foreign participants in any "space station" program. In terms similar to the eight U.S. aerospace contractor group studies, the European Space Agency (ESA), the National Research Council of Canada, and a Japanese Space Station Task Team (representing numerous organizations in Japan interested in aerospace activities) prepared studies. In addition, individual companies or groups of companies from these regions presented reports of elements or subsystems of special interest to them. Among these were Dornier of Germany, Aerospatiale of France, Spar Aerospace of Canada, and a group of European companies consisting of AEG, British Aerospace, Fokker, and CIR.

European Space Agency

The member nations of the European Space Agency (ESA) authorized a study team which was directed by MBB/ERNO and included Aeritalia, Matra, British Aerospace, Dornier System, SABCA, BTM, and KAMPSAX. It examined European interest in providing elements and the likely consequences of utilizing a "space station" having crew capabilities.

Especially emphasized was ESA's desire to participate actively in the program, both in the design and construction of components (e.g., logistics modules, free-flying platforms, laboratory modules, and equipment and servicing pallets) and in the later operations (e.g., access on a continuing basis for experiments, identification of payloads and operational requirements, and provision of crew members).

The study assessed participation as offering potential benefits to European nations in scientific, technological, industrial, economic, operational, and political areas. European contributions were seen as based upon their own set of potential user interests, on systems with clean interfaces with other infrastructure components, and on the utilization of developed European technologies (specifically Spacelab). Perhaps ESA could provide "dedicated modules" with preferential conditions for European users to compensate for European investment. Participation would be particularly cost effective to ESA if all of the infrastructure were available to it without a major program on their part to obtain it, so that it would be complementary with rather than competitive with European unmanned systems.

The study team identified about 130 activities that, conceptually, European countries desire to carry out in space. Similar to the projections of the U.S. contractor groups, they included materials processing, life sciences and bioprocessing studies, space science and applications, and technology development. An innovative use was that of entertainment, such as filming of space movies and creation of new artistic forms in space.

ESA recognized the possibility of free-flyers as a supplement to a "space station" for Earth observation and space science, but noted the advantages (over an expendable booster) of the Shuttle and additional in-orbit infrastructure; this combination would involve less costly hardware, provide return transportation as needed, and obviate the necessity of bringing a complete spacecraft back to the surface for servicing.

The need or benefit from human involvement in about 70 percent of the proposed activities was stressed. Among these were life sciences experiments and the servicing of satellites such as the EURECA vehicles that are under design in Europe. Power needs identified for users were in the range of 20 to 30 kW.

Canada

The National Research Council of Canada expressed a high degree of interest. The Canadian report identified about 37 potential uses and desires, largely in the areas of remote sensing and technology development. Most could be carried out at an orbit inclination of 28.5° with 5 kW of power. Many uses would benefit from having a human crew, and a Canadian astronaut as a payload specialist was proposed.

Continued development of the SPAR Remote Manipulator System is anticipated along with new work on associated construction and servicing subsystems. Also, Canada would develop a space vision system to facilitate ranging and docking, and consideration is being given to advanced remote sensing subsystems.

In a separate report, Spar Aerospace Limited outlined its capabilities in high-power solar arrays and indicated interest in building one of a modular type; various concepts were given but no cost estimates.

Japan

The Japanese Space Station Task Team reported long-term, across-the-board interest. While few specifics regarding individual experiments were given, they anticipated uses for astronomy, life sciences, materials processing, technology development, Earth observation, space energy research, and large communications satellite assembly. The majority of these would require or benefit from human presence, with long time on orbit and human judgment and/or operating capability as important factors. They anticipate that space activities would involve two general phases—one up to the middle 1990s to develop methods to be capitalized on thereafter.

The Japanese would be interested in developing almost any or all elements of the space infrastructure, from attached modules to the ROTV. They suggest starting with simple standard modules and enlarging the capabilities for various additional needs.

Individual Foreign Company Interests

Extensive studies were made by several European companies or industrial groups to augment the reports discussed in the previous sections of this chapter. A submission of Spar Aerospace Limited has already been discussed in the section on Canada; others are presented here.

DORNIER

Dornier of Germany investigated several conceptual infrastructure elements for ESA which have an obvious relation to a potential later participation of Europe in a U.S. program. The conceptual elements analyses included:

1. ‘requirements and technology aspects for space pointing systems;
2. designs and capabilities of heat pipe radiators; and
3. life sciences experiments and development of life support systems.

AEROSPATIALE

Aerospatiale of France studied the following areas:

1. General infrastructure concepts, along with their evaluation of the eight U.S. contractor group architectural designs. The contractor group studies were noted as having numerous advantageous design features, but in each case several difficulties are foreseen.
2. Concepts for a Reusable Orbital Transfer Vehicle were studied with special consideration of its fuel storage arrangements.
3. Designs of a Teleoperator Maneuvering System were-studied. It would incorporate solar arrays to provide electrical power.

AEG, BRITISH AEROSPACE, FOKKER, CIR

This group of European companies analyzed power sources employing solar energy arrays, comparing planar and concentrator designs and various supporting structure arrangements. A flexible-blanket, retractable, fold-out array was favored for further study. This approach also lends itself to stepwise growth to power levels as great as 250 kW.

MBB/ERNO, AERITALIA, BRITISH AEROSPACE, DORNIER SYSTEM, SABCA, BTM, KAMPSAX

MBB/ERNO, the leader of this group of companies, was also the principal contractor for the general ESA “space station” study. Thus, much duplication occurs in this report of the summary appearing earlier in this chapter.

Considerable emphasis was put upon the possibility of the Spacelab and EURECA spacecraft being used as infrastructure elements.

Modifications of Spacelab could provide combined habitation/laboratory functions in conjunction with an EDO vehicle. A crew of three could be accommodated, but this would result in a decrease in laboratory space compared to the present Spacelab design. EURECA would first be used as a Shuttle-tended unpressurized free-flying platform. Later development of a resource/service module incorporating solar electrical power, environmental control, and life support systems would enable an increased capability in association with the developed Spacelab and the EURECA platform. Ultimately these elements could, with others, become components of a larger, more permanent space infrastructure.

Also, a Spacelab with its own solar array could be a free-flying experiment module which could be tended by a crew that would visit for a few hours at a time.

They also indicated a European consortium was prepared to develop and produce an ROTV and its hangar facility, a Teleoperator Maneuvering System (labeled by Matra as a Teleoperated Service Vehicle), and the satellite service and assembly infrastructure segments.

No specific estimated costs were given. However, six items (a free-flying, tended, experiment module, a logistics module, a free-flying platform, an unpressurized logistics resupply carrier, a teleoperator maneuvering system, and a thermal control technology development program) could be achieved over a 1s year period at funding levels aggregating about $1.6 billion (1984). While direct comparison with estimates made by U.S. aerospace companies is difficult because of numerous design and capability differences, this cost could be lower than, but of the same order of magnitude as, the estimate for a corresponding set of modules by the American contractors.

The study observed that pressurized modules would sometimes be needed for experimental reasons even if human habitation were not a consideration, and this would affect not only the design but also the operation of such modules.

The study team recommended that development should proceed in phases with the initial phase using proven existing elements. Automated processes should be preferred for routine work, but cost effectiveness must always be considered, inasmuch as automation can be costly.

This study, representing companies from many European countries, was oriented to identifying potentially produceable infrastructure elements, not overall concepts. This emphasized Europe's intention to play an active role in development and operation, not simply provide hardware. The candidate elements would satisfy their user needs and have clean interfaces with the other elements of space infrastructure. This would not only put Europe in a position to operate their facilities, but also enable them to be offered to the United States, thus allowing a sharing of resources and reducing the financial involvement of participating nations,

Summary

The universal attitude of all non-United States organizations is one of enthusiasm to participate in a space infrastructure program, not just to develop and build elements of it, but to be active as partners in the operation and use of its facilities, especially the elements that they would produce. Many of them look upon it as fundamental to their future role in space and therefore want long-term understandings or agreements with the United States. The characteristic note is one of desired international cooperation in which there is true participation throughout rather than simply shared eventual utilization.

NASA Synthesis of the "Mission Analysis Studies"

NASA assembled the United States and foreign mission analysis reports relating to a civilian "space station" and held a workshop during May 1983, to synthesize the results. Of the hundreds of projects and experiments proposed by potential users, the workshop of the Requirements Working Group and the SSTF Concept Development Group established a minimum time-phased "mission set" (for the decade from 1991 to 2000) of 107 specific space activities, plus four generic industrial service activities (e.g., satellite servicing).

Of the 107, 48 were categorized under science and applications, 28 under commercial, and 31 under technology development. The four additional commercial opportunity activities would be continuously available as needed for industrial servicing.

The NASA working groups judged the list of activities to be realistic in terms of maturity of experimental and program planning, scientific need, and progress of technology development. The programs identified for the first 3 years were particularly well validated in their **view.** At the end of the workshop, their recommendations of the minimum capabilities required at IOC were as follows:

1. Space station central complex at 28.50:
   - 55 kW of **average electrical power** to users;
   - Two 60 m^3 laboratory modules (for materials processing in space and life sciences);
   - 5 person crew (4 for payload operations);
   - 300 MBPS data rate; and
   - 4 to 6 payload attachment mounts,

2. Polar platform (unpressurized):
   - 12.5 kW of average power;
   - 300 MBPS data rate; and
   - 4 payload attachment mounts.

Nonaerospace Industry Interest in Space Use

NASA contracted with the Booz-Allen & Hamilton and Coopers and Lybrand consultant firms to communicate with a variety of nonaerospace companies to ascertain (and at the same time stimulate) interest in the use of space facilities for commercial purposes. Up to March 1984, they discussed prospects with upwards of so companies of which more than 30 expressed active interest. To most of these firms the concept of doing business in space is utterly foreign; a great deal of exploring with them is necessary to surface possibilities of products or services that might be compatible with their commercial activities and offer promising opportunity of eventual financial success.

Booz-Allen & Hamilton reported to a conference in mid-1 983 that most of the companies moving toward negotiation of Joint Endeavor Agreements with NASA are well-known U.S. industrial firms (one with an announced agreement is the 3M Corp.) but several are from the small business sector or Europe. Interest is concentrated in such fields as chemicals, metals, glasses, communications, and crystals. Another type of enterprise being actively pursued is a fee-for-service laboratory in space. Among the half-dozen companies actively investigating space experiments, most are interested in crew-tended operations rather than remote or automated procedures.

Since the administration's authorization of a "space station" program, interest among several companies has become more firm, according to those involved in the study; the 3M Corp. has recently announced a Memorandum of Understanding with NASA to begin space experiments on inorganic chemical materials and on thin films. An executive with one company with experience in aerospace has indicated that the Government's funding toward eventual acquisition of permanently inhabited space infrastructure is a necessary (but not sufficient) condition to convince industries that the United States is serious about space commercialization. He considers that, in addition, a long-term commitment to supporting the commercialization effort is what will suffice to bring the private sector into full participation.

Some industry observers point out that the often-mentioned example of how communications satellites became a commercial success is not necessarily relevant to today's efforts at space commercialization in other areas. First, there was already a clear market for the improved communications services which a private organization was created to provide, something which is not clearly evident today is such areas as materials processing in space or remote sensing. Second, the enabling legislation to move it forward to reality was motivated by the need to create an international system, while today's commercialization issues concern primarily U.S. domestic businesses.

The barriers that Booz-Allen & Hamilton found to wider interest in commercial space enterprises were technical, economic, and government-related. First, technical knowledge of the space environment by many industries is very scanty, while in general there are too few answers as yet to the behavior of many kinds of materials in space. Second, economic risks associated with timing and cost of space experiments are looked at by private enterprise from the standpoint of the expected long payback period (1 O or more years). Third, the maze of government bureaucracy to be faced to obtain approval on such things as Joint Endeavor Agreements is deterring some, especially small companies, from entering into space business. Booz-Allen & Hamilton is recommending establishment of some form of permanent intermediary to assist nonaerospace companies in contacts with NASA and other Government agencies.