ROLE OF SPACE STATION – THE HOW OF SPACE INDUSTRIALIZATION

by

William R. Marshall
NASA George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

ABSTRACT

An industrial revolution in space is underway with much of the required base for space industrialization currently available or in development. Logistics can be provided by the Space Shuttle. Launch facilities are in place. Ground mission and operations and an associated technological infrastructure are available. Business procedures and precedents can be modeled after or derived from the successful space communications industry. Industrial interest in all aspects of space, particularly materials processing in space, is growing. There is an increasing appreciation of the potential utility of space technology for both research and industrial purposes. Moreover, the President has proposed a national imperative which would place key defensive systems in space.

One vital element is yet to be provided — a permanent operating base in space. The space station, to which we are now committed, will provide the needed support for systematic exploration and exploitation.

This paper considers the roles of the Space Station, as an R&D facility, as part of an industrial system which supports space industrialization, and as a transportation node for space operations. Industrial opportunities relative to these roles are identified and space station concepts responsive to these roles are discussed in this presentation.

INTRODUCTION

For the past twenty-two months, following the successful flights of the Space Shuttle, NASA has conducted preliminary definition efforts in support of future decisions regarding a space station program. These efforts have been relatively modest in scope and coordinated by Mr. John Hodge, the Director of NASA's Space Station Task Force.

Earlier this year, President Reagan requested an interagency study to establish the basis for an Administration decision on whether to proceed with development by NASA of a permanently-based, manned space station. The study, which took place over the spring and summer, is now complete. The analysis addressed issues relating to leadership in space, fulfilling mission requirements, foreign policy and national security implications, and economic impacts. Participating in the study were NASA, the Department of Commerce, the Department of State, the Department of Defense, the Arms Control and Disarmament Agency, and the Office of Science and Technology Policy. Based on the results of these activities, President Reagan, in his State-of-the-Union Address on January 25, 1984, announced the commitment of the United States Government to establish a permanent manned presence in space: THE SPACE STATION. This major decision provides the impetus for space industrialization.

Up to now space program activities have been mainly directed at exploration. We have launched a number of probes, observatories, measurement devices, etc., to explore near Earth and deep space. These missions have been largely single point, discrete activities. With a few notable exceptions like the Apollo mission, data returned to Earth has been mostly in the form of electronic or photographic images.

The country has reaped huge rewards in scientific advancements, national prestige and technology spin-offs for our early space exploration activities. In addition, some overall applications with concrete economic benefits have resulted. These first order applications are primarily based on the new perspective achieved from the "high ground" of space.

Space provides a global perspective, thus Earth observations and weather satellites are readily evident applications. Space provides a very convenient way to relay line-of-sight communication signals. This latter application is now a full-fledged revenue producing industry. Again, these applications do not depend, but will be aided by routine, frequent access to space. Data to and from these space facilities are simple electronic signals. However, the operations of such facilities could be enhanced by routine frequent access to space simply by making user-shared launches. Moreover, a new permanent presence in space will make operations even more convenient and cost effective through resupply and repair activities.

Beyond these communication and observation applications there are a number of other scientific and economic applications of space. These applications, like Microgravity Materials Processing in Space (MMPS), are not as readily evident. For example, the theoretical basis for the effects of gravity-driven convection on processes like crystal growth lies in a differential equation on gravity driven convection. Unlike results from earlier space applications, the results of these processing experiments are contained in the sample, for example a crystal, which must be physically returned to Earth for subsequent analyses and use.

Therefore, these (and other) second order applications require not only frequent, convenient access to and from space, but they should profit greatly from a laboratory in space. After all, the type of science and technology encompassed by MMPS is high technology even on Earth. This kind of technology is constantly pushing the "state of the art."

On Earth, progress in advanced technology is made through sustained, systematic laboratory research. The same is true for space. The new working environment in space requires that we have a permanent presence there.

FUNCTIONS OF THE SPACE STATION

Based upon our analysis and that of our industry contractors, it is clear that the space station will serve a number of functions. As shown in Figure 1, the space station should provide:

- A laboratory in space, for the conduct of science and the development of new technologies;
- A permanent observatory to look down upon the Earth and out at the universe;
- A transportation node where payloads and vehicles are stationed, processed and propelled to their destinations;
- A servicing facility, where these payloads and vehicles are maintained and if necessary repaired;
- An assembly facility where, due to ample time on orbit and the presence of appropriate equipment, large structures are put together and checked out;
- A manufacturing facility where human intelligence and the servicing capability of the station combine to enhance commercial opportunities in space; and
- A storage depot where payloads and parts are kept on orbit for subsequent deployment.

For example, as traffic increases, more and more operations will be done in space. More payloads will be left in storage for later assembly or use. After all, the Shuttle can lift around 65,000 pounds, but can return (land) with only 32,000 pounds. This alone dictates the need for orbital storage and operations facility. Such an "orbital depot" or transportation node in space is clearly required to support industrial space operations. Industrial operations must be cost effective. Since transportation costs are a major part of any space endeavor, these costs must be shared whenever possible. The Space Station in its high traffic orbit will make this feasible. After the Space Station becomes operational, flights of the Shuttle need never go to orbit less than 100 percent loaded.

Perhaps more important than any of these individual points, however, the space station could also lead to important activities and functions that we can not predict today.

ARCHITECTURE

At this point, it is appropriate to comment conceptually on what NASA has in mind for the space station. The term "conceptually" is used because we do not have a space station design. There have been many illustrations of space stations, and while these are nice pictures, they do not represent a NASA configuration. The space station is conceived as a multi-purpose, permanent facility in low-Earth orbit, comprising both manned and unmanned elements, that significantly enhances the efficiency of our operations in space. The station could consist of a manned base and associated unmanned platforms as shown in Figure 2. These platforms (there might be only one to start with) would be discipline oriented and be tended from the base by an Orbital Maneuvering Vehicle (OMV) or by astronauts conducting Extra Vehicular Activity (EVA). A tether could also possibly be employed.

The base, as currently conceived, is a cluster of functionally oriented modules. The key elements, as presently defined, include a utility module to provide essential services, such as power and thermal management to the cluster, a berthing and assembly module, a module for living, a laboratory module for working, a logistics module for supply and replenishment, and pallets or platforms to which are attached scientific instruments and repair equipment for both the base and the platforms.

The concept of the Space Station encompasses both manned space flight and unmanned spacecraft activities. The Station will employ astronauts in tasks and jobs where the presence of man is uniquely valuable. Certain activities, particularly those of a routine nature or those that can be programmed in advance, are better suited for automated systems. The challenge for NASA is to design a space station that achieves the best of both modes.

BENEFITS

The Space Station Mission Analysis Studies, the concurrent Mission Requirements Working Group and panel activities, and the culminating Space Station Mission Requirements Workshop have all contributed to a better understanding of potential Space Station benefits. Just as the Space Station will support a diverse set of mission activities, the benefits will occur in many diverse ways. The potential benefits may be generally summarized as follows:

1) Mission enablement and enhancement due to resourceful manned presence;

2) Creation of a viable commercial activity, particularly in space materials processing;

3) Significant cost savings due to more efficient transportation and servicing operations; and

4) Tangible and intangible societal benefits related to mission results, space R&D applications, and national prestige.

The Space Station will contribute significantly to the goals of our national space policy to:

- Maintain United States leadership in space;
- Obtain economic and scientific benefits through the exploitation of space;

- Expand United States private sector investment and involvement in civil space and space related activities;
- Promote international cooperative activities in the national interest;
- Cooperate with other nations in maintaining the freedom of space for activities which enhance the security and welfare of mankind; and
- Strengthen the security of the United States.

Civil leadership in space means preeminence in space technology, preeminence in manned space operations and preeminence in space science and applications. At a time when U. S. leadership is at issue in certain disciplines of science and in a number of industries, the commitment to the Space Station is a welcome and reassuring reminder of our capacity to lead.

Already economic benefits accrue to the United States from the exploitation of space. The communications industry is in large part space-based, which is responsible for improved service at lower cost. This was made possible by federal research to develop the initial technology and to reduce the risk to an acceptable level, thus enabling private venture capital to launch a new highly successful business enterprise. The Space Station should do the same for the field of materials.

Benefits to the United States also accrue from the science conducted in space. Knowledge of the Earth and a greater understanding of our own solar system and the many galaxies of the universe has been gained from the scientific spacecraft we have placed in orbit and sent out to our sister planets. The Space Station will be a valuable addition to the nation's scientific assets.

In the future, NASA hopes to increase the benefits our many activities in space provide. These activities, in science and applications, in launch vehicles, in technology and in the area of commercial endeavors, offer tremendous potential for the years ahead.

In many instances, foreign aerospace capabilities are now fully mature and competitive with those of the United States. Thus, other nations can make genuinely significant contributions to the Space Station. These contributions, if determined to be appropriate, would have the effect of adding to the Station's capabilities at no additional cost to the U. S. Treasury.

THE SPACE STATION AND INDUSTRY

The Space Station will be the hub around which future space activities revolve. These capabilities relate to the broad categories of:

1) Space science and applications
2) Technology development
3) National security
4) Commercial endeavors

In the following sections, the foreseen roles of the Space Station for each of these categories are summarized and potential involvements for industry are identified.

SPACE SCIENCE AND APPLICATIONS

Space science and applications activities are those which are primarily planned, funded, and conducted by the government for the advancement of scientific understanding and its potential applications. These include activities in the areas of:

- Astrophysics — the study of the universe and of the sun as a star;
- Solar System Exploration — the study of the planets and their environment;
- Earth Science and Applications — the study of the planet Earth including the dynamics and interaction with the sun;
- Life Sciences — the study of life as it is affected by its environment in space and development of life support systems.
- Materials Sciences — the study of the production of special materials and processes in the absence of gravity; and
- Communications — R&D to exploit additional space-based communications techniques.

Together, these activities can make use of four classes of capabilities to be supplied by the Space Station. These are: (1) a pressurized laboratory (i.e., manned micro-gravity facilities); (2) a base for operating attached payloads (i.e., sensors); (3) a servicing station for associated free-flyers; and (4) a transportation node for a wide spectrum of R&D payload operations.

A number of science and application missions will be enabled by the Space Station. For example, some materials processing R&D and all pilot plant demonstrations require longer, man-tended mission durations, longer than those available on the Shuttle to demonstrate the viability of materials space processing for commercial use. The life sciences program (consisting of a health maintenance and clinical research facility, a human research laboratory, an animal and plant vivarium and laboratory, and controlled environment life support system (CELSS), experimental systems, pallet, and dedicated module) will require long duration, man-tended missions. The Light Detection and Ranging (LIDAR) facility will require frequent servicing and configuration changes for evolutionary development combined with an extended mission duration to be economically feasible. An experimental geosynchronous platform will be enabled in the sense that Space Station deployment and alignment will allow larger antennas than can be packaged in the Shuttle bay.

As will be later discussed, activities in this category, even though the government has prime responsibility for their planning and conduct, will require many support service functions which may be provided by the private sector.

TECHNOLOGY DEVELOPMENT

Technology development encompasses experimental activities for advancing space technology. The broad scope of these activities will enhance space science and applications, commercial uses, national defense, and overall capabilities in space. These activities, as categorized by NASA/Office of Aeronautics and Space Technology (OAST), encompass the following disciplines:

1) Materials and structures
2) Energy conversion
3) Computer science and electronics
4) Propulsion
5) Controls and human factors
6) Space Station systems
7) Fluid and thermal technology

Candidate technology development missions have been identified based on their need for elements of the space environment plus one or more of the operational conditions made available by the Space Station. Operating conditions offered by the Space Station will include:

- Space environment (low-gravity, low pressure, low temperature, plasma, radiation)
- Human interface/experiment accessibility
- Ability to handle large sizes (with EVA and manned maneuvering units (MMU))
- Long-term operations capabilities
  - Iterative adjustment/testing
  - Evolutionary development (e.g., optimal environmental control and life support system (ECLSS))
  - Long duration exposure, removal, inspection or replacement
  - Utilities and support systems

As with the space sciences and applications, current activities in the category of technology development are primarily planned, funded, and conducted by the government. As needs for such activities to support commercial ventures become more apparent, we should expect to see increasing involvement by the private sector in their planning, funding, and conduct. Such activities, whether sponsored by the government or the private sector, will also require many support services which may be provided by the private sector.

NATIONAL SECURITY

It is evident that space provides a global perspective and can be used for surveillance, navigation and other military operations. (However, to date, firm military needs and uses for the Space Station have not been identified.)

All of the missions in this category will most likely be planned, funded by and conducted under the direct auspices of the government. As with the other categories, however, there will be many areas in which the private sector may provide support.

COMMERCIAL ENDEAVORS

Commercial activities relate to products, processing and services in which elements of the private sector, anticipating a reasonable economic return, may be expected to directly participate in their initiation, planning, funding and conduct. These activities include:

1) Earth and ocean observations
2) Communications
3) Materials processing in space
4) Commercially provided support services

1. Earth and Ocean Observations

Satellite technologies have revolutionized our ability to monitor the Earth's environment and its resources. Meteorologists, oceanographers, hydrologists, geologists, farmers, foresters, and those in many other disciplines now look to space to learn more about the Earth.

Currently, meteorological satellites provide global meteorological data to support operational and experimental portions for world "weather watches" in addition to supporting international weather agencies and U. S. military requirements.

Capabilities from space for navigation and monitoring of sea states offer significant advantages. For example, a most important parameter in automated ship routing is sea state; however, winds, currents and hazards to navigation (fog, snow, ice) are also significant. Reliable sea state analysis and predictions can reduce transit time up to 10 percent resulting in savings of $15,000 to $40,000 for a typical Pacific voyage. Furthermore, the modern fisherman needs reliable and accurate marine weather information along with knowledge of oceanographic conditions affecting fish feeding such as water temperature and color/clarity structures. Weather influences all aspects of fishing operations. Wind and wave conditions affect vessel safety, the ability to deploy and secure gear, and travel time from the fishing grounds to processing plants.

Imagery of the Earth from space will provide a wide variety of such useful data applicable to polar region ice surveillance, agriculture, hydrology, geology, land use, environmental monitoring, and marine and ocean resources.

The Space Station (and future Space Stations in highly inclined and polar Earth orbits) will provide:

- An in-space laboratory for development and verification of remote sensing sensors and imaging techniques
- Manned platforms for targeting and selective control of the imaging processes
- Assurance of continuity of data
- Timely reaction to targets of opportunity

The high initial costs and undefined market potential will limit privately funded systems for Earth and ocean observations. With the advent of the Space Station (and associated platforms), investment costs may be substantially reduced and observations can be adapted to specific requirements. This will enhance involvement of the private sector. Furthermore, as the hardware evolution proceeds to space stations and platforms in polar and geosynchronous orbits, there should be increased impetus for involvement of the private sector.

Currently, the private sector is substantially involved in the processing and interpretation of Earth and ocean observation data. For this potential to be fully realized, the government should involve the private sector more in planning for such missions and provide for greater access to raw data. Further, the government should be prepared to relinquish some of its responsibilities in the data processing and interpretation field to the private sector.

2. Communications

Communications has been the major successful space commercialization activity to date. Communication satellites at geostationary altitudes have been used commercially for approximately 15 years. There has already been a significant involvement of the private sector in the ownership and operation of these satellites. Based on projected markets and on NASA's current plans for enhancement of in-space capabilities through continuing R&D of space transportation and on-orbit systems, private sector ownership and operation of commercial communication satellites should continue to increase as shown in Figure 3. Transportation costs to orbit should progressively decline with first, the expanded use of private sector commercially owned and operated expendable launch vehicles, then through the use of the Space Shuttle with government and commercially owned expendable orbital transfer vehicles, and ultimately, through use of the Reusable Orbital Transfer Vehicle in combination with multiple payload carriers and the spectrum of envisioned on-orbit capabilities to be provided by the Space Station, orbital Maneuvering Vehicles, etc. The capability for on-orbit servicing should further reduce the cost of ownership of these systems by allowing for lower cost designs, improved reliability, and longer overall lifetimes for the systems. Ease of replacement will allow for more continuity of the provided communication services.

Communication satellites, whether owned and operated by the government or the private sector, will utilize a wide range of Space Station provided support services, many of which may well be provided by the private sector. These include:

1) Communications tests — These will be accomplished on Earth and in space, and will involve basic and applied research and development, subsystem and system testing, and systems applications experiments. The in-space activities would include:

   a) Testing of large deployable antennas
   b) Testing of laser intersatellite links
   c) Development of spaceborne interferometry technology

   Such testing could involve the ownership and operation by the private sector of a communications test lab (attached to the Space Station) and free-flying platforms.

2) Communications satellite delivery and deployment (to include on-orbit assembly)

3) On-orbit servicing

3. Materials Processing in Space

There is the potential for large stable markets for high-value, low-mass items and materials (particularly for use by health, electronic, and defense related activities) which require the special environment of space for their processing. A cross section of MPS processes and typical experiments are identified in Figure 4. It should be emphasized that the majority of MPS research is being done for scientific reasons. However, some of this work has engaged industrial interest and participation. In-space laboratory testing for development of these processes has already begun. A current set of experiments aboard the Space Shuttle, i.e., those associated with a continuous-flow electrophoresis system for pharmaceutical products, are being conducted under a Joint Endeavor Agreement (JEA) between the McDonnell Douglas Corporation/Johnson and Johnson, and NASA. As is well documented from previous studies, the private sector has a strong interest in other similar in-space experiments and tests leading to commercialized in-space processing. Such activities can ultimately lead to private sector ownership and operation of Space Station modules or other on-orbit processing facilities.

An unexpected bonus was recently realized when the MMPS Program made its first sale. The Monodisperse Latex Reactor System (MLRS) was flown on the Space Transportation System (STS) -3, 4, 6, 7, and 11 and produced highly uniform latex spheres in sizes up to 30 micrometers. The quality of these spheres is considerably better than those produced on Earth. This experiment was conceived and developed for scientific studies of polymerization, yet has yielded both scientific data and potential applications. The National Bureau of Standards (NBS) has requested that NASA provide spheres of 10, 30 and 100 micrometers to be sold by the Bureau as "Standard Reference Materials." On the order of fifteen grams of the ten micrometer spheres produced on STS-6 are being turned over to the NBS. Plans call for these to be packaged into 3 milliliter vials and sold for $350.00 per vial. The MLRS will be reflown on at least three subsequent Shuttle flights to produce the 35, 60 and 100 micrometer spheres for the NBS. It is anticipated that this activity will become a commercial endeavor after this series of flights and will be implemented through a Joint Endeavor Agreement with industry.

The manufacture of high-quality metals, crystals, glasses, and chemicals requires high-temperature furnaces of various capabilities, chemical reaction chambers, levitation systems, and controlled chamber atmospheres and pressures. Presently on Earth, each manufacturing plant is tailored to the subject material. Overcoming practical problems of weightlessness will result in new designs and require demonstration and pilot plant activity. The repetitive nature and slow time constants of most high-temperature and vapor processes require long periods in orbit. The Space Station will be an attractive orbital vehicle to accomplish much of this activity because it will eliminate the requirement to re-orbit heavy support equipment and will allow continuous operation with technical risk kept to a minimum. Much technological development for levitating free-floating specimens of high-temperature melts is required prior to the operational phase.

Prior to the Space Station, we can expect further private sector involvement using the Shuttle accommodations and Shuttle dependent carriers for experimentation leading to in-space processing procedures and subsequent processing of small production quantities. The Space Station will provide for longer term experimentation and increased space for more complex investigations and larger production quantities as shown in Figure 5. With additional platforms and the advent of the Orbital Maneuvering Vehicle, separate processing and experimental and processing facilities could evolve.

Obviously, all in-space processing activities, both those of the government and the private sector, will require a broad spectrum of support services, many of which may be provided by the private sector.

4. Commercially Provided Support Services

It is expected that the government will have the primary role for the funding and conduct of missions in the areas of space science and applications and national security and will have a major role for funding and conduct of technology development activities. These missions, however, will require a complete spectrum of support services, both ground and space-based, many of which can be provided by the private sector. Similarly, government and commercial missions in the areas of Earth and ocean observations, communications, and materials processing will also require such support services.

Support services may be divided into five major categories as follows:

1) Support to program and project management

2) Transportation and logistics services

3) In-space testing and assembly/disassembly services

4) Payload servicing

5) Facility operations and support services

SUPPORT TO PROGRAM AND PROJECT MANAGEMENT

The private sector has historically provided and will continue to provide prime contractor support for the development, production, deployment, and operations of systems. As prime or support service contractors or subcontractors, elements of the private sector have also provided a myriad of program and project management support functions.

Such support to planning, research and development, production, and operational programs and projects will continue. With the emphasis on commercialization, the trend will be toward more delegation by the government of responsibilities in these areas to the private sector. This will be particularly true in the areas of planning wherein the private sector can be expected to exert more influence as its activities become a more integral part of the overall space activities.

TRANSPORTATION AND LOGISTICS SERVICES

The category of launch and logistics services encompasses:

1) The Earth/space and in-space transfer of personnel and cargo, for example:

    a) Launch
    b) Deployment (including initial orbit and/or trajectory adjustments)
    c) In-space transfers (including retrieval of payloads)
    d) Removal and disposal of space debris
    e) De-orbiting and Earth recovery of systems from space

2) Warehousing and provisioning of space consumables and spares

3) Operation, servicing, maintenance, and repair of all involved hardware systems

4) All support services related to the above.

Such services could involve private sector operation and/or ownership of transportation systems (ground and space) such as the Space Shuttle, the Space Shuttle Derived Launch Vehicle, the Aft Cargo Carrier of the External Tank, Expendable Launch Vehicles (ELV's), expendable and reusable Orbital Transfer Vehicles, Orbital Maneuvering Vehicles, attitude controlled platforms, deployment mechanisms, and Earth-based multiple payload carriers, and Earth-based recovery systems. Furthermore, they could involve operation and/or ownership of ground and space launch/communication and tracking/hangar/loading/fueling/warehousing facilities.

The private sector has already become involved in transportation and logistics services at both the primary and support levels. At the primary level, the private sector is currently planning to provide and launch expendable vehicles (for example, the General Dynamics Atlas Centaur and the McDonnell Douglas Thor Delta). Furthermore, NASA and the Orbital Systems Corporation have entered into a Joint Endeavor Agreement wherein Orbital Systems Corporation, with certain incentives and support provided by NASA, will develop and operate the Transfer Orbit Stage (an expendable stage primarily for interim transfer of payloads from Low Earth Orbit to Geostationary Orbit prior to the advent of the Reusable Orbital Transfer Vehicle.

Other than ownership, elements of the private sector could have the responsibility for operation of these primary systems. This could be accomplished under either of two arrangements: 1) contracts with the government for such operations, or 2) leasing by the government of transportation hardware to the private sector for private sector operation.

Considering the smaller elements of the Space Transportation System it is reasonable to assume that many could be operated, if not owned (if developed under suitable agreements with the government) by elements of the private sector. Those owned could be operated by their private sector owners or leased to the government and/or leased to other elements of the private sector for operation.

Short of ownership/operation of transportation and logistics systems, there is and will be a broad spectrum of opportunities for provision of support services by the private sector. The private sector is currently significantly involved in ground-based support services for transportation and logistics. It is logical to assume that private sector provision of such services will be extended into space as space-based transportation and logistics systems evolve.

IN-SPACE TESTING AND ASSEMBLY/DISASSEMBLY SERVICES

As capabilities for in-space operations increase, so will the requirements for specialized in-space services. In particular, large in-space testing activities (such as those associated with developing and verification of materials applications, processing methods, testing methods, designs, structural configurations, attitude controls and station keeping, communications, energy production, fuel transfer, and robotics) will require the weightless, vacuum, and/or high radiation environment of space. They will require specialized structures, equipment, instrumentation, procedures, and personnel for operation of large central test and staging areas or "in-the-field" operations. Planning and conduct of such operations will require large coordinated efforts both on Earth and in space. Many of the technology development and test requirements will be generated by members of the private sector to support their commercial interests.

Many of the specialized and larger structures envisioned for space operation will require on-orbit assembly. There will also be continuing modifications to those previously provided structures and systems. Obsolete elements of the space stations, antennas, and other systems will require disassembly for replacement. These assembly/disassembly operations offer opportunities for involvement of the private sector in areas such as:

1) Development and provision of specialized tools

2) Training of personnel for specialized operations

3) In-space conduct of the operations

4) Support services to all of the above

Furthermore, there is a good potential for orbiting facilities to serve as an in-space test laboratory and testbeds for operations such as:

- Test and evaluation of advanced subsystems and testbeds needed for future space systems (energy storage, fluid transfer, thermal control, etc.)
- Evaluation and use of space-based solar furnaces, photovoltaic arrays and nuclear power systems
- Modal surveys and analysis of large-scale structural assemblies, masts, antennas, etc. (not feasible on surface due to size, gravity effects, etc.)
- Long-term duration testing of materials, components, and rotating machinery
- Performance evaluation of teleoperator systems and devices
- Development of procedures and equipment for in-space assembly/disassembly operations
- Large-scale thermal/vacuum testing using the readily available space environment

Such facilities, whether owned/operated by the government or the private sector, should be accessible for private sector sponsored as well as government-sponsored testing.

SATELLITE SERVICING

Satellite servicing includes pre-launch and post-launch activities such as repair, refurbishment, refueling and, in some cases, reconfiguration of spares (such as Direct Broadcast System satellites, stored Low Earth Orbit for rapid deployment with the Reusable Orbital Transfer Vehicle).

The objectives of on-orbit servicing include:

- Reducing life-cycle costs
- Improving overall system reliability
- Reducing risks, particularly for larger, more complex and more costly satellites

The capability to service and repair satellites in situ or to retrieve satellites for servicing in space or on the ground should, therefore, provide lower cost, more reliable satellite payload systems. The Space Shuttle currently provides such capability for satellites in lower inclination low Earth orbits. As a result, more and more satellites are being configured to take advantage of these initial capabilities.

These capabilities, as initially provided by the Space Shuttle, will be further enhanced and extended with the advent of the Space Station, Orbital Maneuvering Vehicles, and associated teleoperators and robotics. These capabilities will be extended into highly inclined and polar low Earth orbits. With the advent of the Reusable Orbital Transfer Vehicle, these capabilities will be further extended to all Earth orbits. Furthermore, these capabilities will be increasingly enhanced with the deployment of additional Space Stations, Orbital Maneuvering Vehicles, and remotely operated hardware. Means of exploiting these capabilities will challenge the designers of satellite systems, and on-orbit operational hardware. The broad spectrum of systems that will be deployed will require a diversity of specialized skills and supporting hardware, and many types of extra-vehicular activities. These requirements will provide many opportunities for involvement of the private sector.

The Space Station will function as a way-station, providing access for servicing of satellites in non-space station orbits, and as an in-space service facility for retrieved satellites.

Potential opportunities for involvement of the private sector in the servicing of satellites include the following:

1) Operation of on-orbit service facilities

2) Provision of teleoperators, robotics, and other specialized service equipment

3) In situ servicing operations

4) Training and provision of personnel having the required specialized skills for such service operations including the required extra vehicular activities

5) Provision of transportation services for access to and recovery of satellites

FACILITY OPERATIONS AND SUPPORT SERVICES

This category encompasses in-space facilities for R&D activities, manufacturing, launch, docking, loading, maintenance and repair, servicing, and communications and navigation.

The initial basic Space Station will be primarily funded and owned by the government. Certain internal equipment and attached modules (and their internal equipment) may, however, be developed and owned by elements of the private sector. NASA is making every effort to assure maximum participation and support of the private sector for Space Station development and operations. As additional capabilities are added to the Space Station through attached modules, etc., there will be impetus and opportunity for private sector involvement, e.g., private sector owned and operated equipment or attached modules for materials processing labs, an in-space communications test facility, an in-space Earth and ocean sensor test facility, etc.

Ultimately, the operation of the Space Station could revert from the government to an element of the private sector. This could be accomplished under a lease arrangement or under a contract let by the government. In most likelihood, initial operations by an element of the private sector would be accomplished under the latter. As the number and capabilities of space stations increase, private ownership and/or operations under lease agreements could become more distinct probabilities.

Even with government ownership and operation of the basic Space Station, there will be many opportunities to the private sector for support services. These could include the following:

- Administrative services
- Command, control, and communications
- Data collection, analysis, and dissemination
- Instrumentation and calibration support
- Photographic services
- Facility engineering services
- Provision of energy
- Other utilities and services
- Maintenance and repair services
- Minor modification services
- Logistics support
- Extra vehicular activities
- Provisioning, maintenance, and repair of equipment and tools
- Ownership and leasing of special items of equipment and tooling
- Fuel supply
- Servicing and fueling of docked transportation systems

The many activities projected for accomplishment within or at the Space Station will require a broad range of highly specialized services which must be performed in the rigorous environment of space. These will require extensive training programs covering a variety of disciplines. Such training could well involve the private sector in the provision and operation of Earth and space-based facilities to train government and private sector personnel.

As the Space Station is established as an operational facility in space, adjacent facility elements will evolve. These will include satellite service modules; manned observatories; expanded power systems; detached test facilities; large deployed antenna; facilities for docking, fueling, servicing, and storage of space-based transportation systems; detached facilities for materials processing; facilities for processing of space debris; facilities for in-space fabrication of large structures; and (ultimately) large arrays for collection of solar energy and its conversion to RF energy for supply to ground systems.

While many of the above facilities will be owned and operated by the government for support of their continuing roles for research and development and enhancement of in-space capabilities, others may be ultimately owned and operated by the elements of the private sector as part of their commercial enterprises. Whether owned by the government or the private sector, all of these facilities will require support operations, such as identified above for the Space Station.

SPACE STATION DESIGN CONSIDERATIONS

Space Station and Platform designs are inherently modular in that multiple flights of the Space Transportation System are necessary to provide the required capability. This implies a building block approach. Configurations are determined by defining and arranging modules in a manner that meets operational requirements and is compatible with the delivery system (STS). The process of defining these module functions and their arrangement in a configuration are determined by such things as: (1) The element(s) delivered on the first launch must have the capability to remain on orbit and serve as a base for additional elements (implies power, attitude control, communications capability, etc.); (2) Separation of functional activities such as habitability/operations; (3) Safety (safe haven, etc.); (4) Determination of pressurized and non-pressurized accommodations necessary (internal volume, external mounting provisions, etc.); (5) Compatibility with the Orbiter berthing and proximity operations at each stage of build-up; (6) Controllability at each stage of build-up and operation; (7) Achievement of commonality of modules where possible for cost saving considerations; (8) Compatibility with operational requirements at stages of growth and with growth to increased capability; and (9) Compatibility with cost limitations.

Studies of station concepts have led to the following element (module) functions: (1) Utility Module for power, attitude control, etc. (first launch); (2) Habitability Module; (3) Logistics Module (resupply of expendables); (4) Berthing Module; (5) Laboratory Modules; and (6) External Mission Accommodation Structure. Attitude control has been found to be a very strong driver in configuration studies due to the variations in the mass properties as the Orbiter and mission accommodation items come and go and the station evolves. These changing masses must be accommodated in such a manner that control authority requirements do not become unmanageable.

CONFIGURATION CONCEPTS

Figure 6 illustrates one concept for the 75 kW station. The configuration consists basically of resource provisions (power, attitude control, communications, etc.), habitability, logistics, and mission accommodation. Mission accommodation is broken into two areas which are pressurized laboratory modules and an unpressurized area. A berthing module is used for element interfaces and contains an internal EVA airlock and controls for the station. Reboost and backup attitude control system thrusters are located in two modules as shown and are designed for orbital changeout as units. Antenna locations for this configuration have not been determined. Two locations are available for Orbiter berthing with the primary one being on the habitability module and an alternate one on the laboratory module in line with the berthing module.

Attitude control considerations were given high priority in configuring this station concept. Previous evaluation had led to the objective of creating a configuration which is balanced aerodynamically, minimizes secular torques (accumulative) and minimizes principal axis shift as large masses are added to and removed from the station. The concept which appears best to accomplish these objectives has the solar arrays located within an area centrally located between the arrays for mission and module accommodation. It is desirable to balance masses within this centrally located plane as much as possible, but compromises result in obtaining this. The configuration separates areas within this plane into a pressurized module location and an unpressurized location. This approach seems more compatible with separation of functions and allows for growth of both areas which must still occur primarily in this plane for consistency with the control approach. The Orbiter (which is a significant mass to the station) is also berthed to the station in this plane and gravity gradient effects may be used to keep the Orbiter on the Earth side to minimize control requirements.

The configuration is designed to operate in either an Earth-fixed or inertial orientation. In either case, the X-axis of the configuration is maintained perpendicular to the orbit plane and the solar arrays and radiators remain inertially fixed. For Earth-fixed capability, the central portion of the station (inboard of radiator attachment structure) rotates relative to the arrays and is Earth-fixed (axis toward Earth variable). The deployable booms for solar array positioning are provided to clear the Orbiter as it is berthed to the station and the solar arrays rotate at Earth rate relative to the Orbiter. Separate rotation capability is provided for the radiator modules so that in the Earth-fixed orientation they may remain edge-on to the Sun and be rewound on the dark side of the orbit as the solar arrays remain inertially fixed. This allows fluid transfer to the radiators by flex hoses rather than less reliable rotating seals. Another option for the radiators may be to fix them to the Resources Module without rotation capability and allow some solar illumination. This would require oversizing of the radiators. (Radiator sizing shown is consistent with no solar illumination and use of pressurized module sidewall radiators for heat dissipation.)

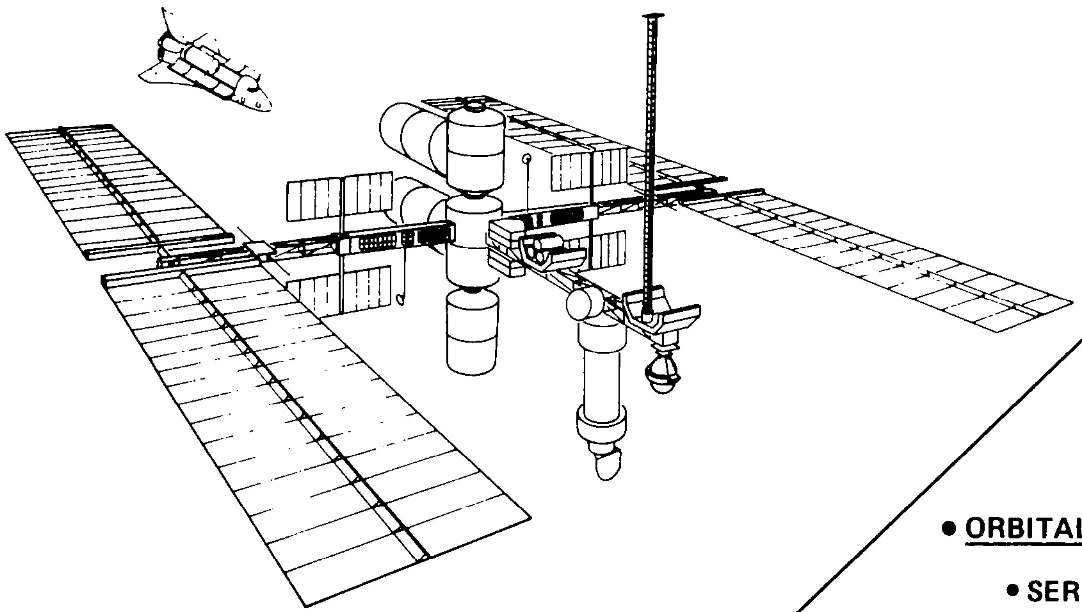
In order to grow beyond the 75 kW power level it is necessary to add solar array blankets, radiator elements, energy storage provision, etc. to the configuration. This would still need to be accomplished in a balanced manner with additional mission accommodation occurring in the central area. The current planning schedule for the Space Station is shown in Figure 7.

CONCLUSIONS

What is required for space industrialization? For the answer we can look at Earth analogs. Facilities, transportation, business organization, capital, markets, and process technology are items that logically spring to mind.

Of these, several are already available for Space Industrialization. Transportation via the Space Shuttle is becoming more and more frequent and reliable. Process technology is being developed by both ground and space experiments and will become even more prolific with the advent of a permanent R&D laboratory on the Space Station. Business procedures like the current Joint Endeavor Agreements are in place now. New policies and incentives to augment and encourage business have been formulated by the NASA Space Industrialization Task Force. Now, the final key piece, a permanent base in space (Space Station), is coming to fruition. Figure 8 depicts the relationship between these various elements needed for full-scale space industrialization.

FUNCTIONS OF SPACE STATION



- **PERMANENT R&D BASE**
  - SCIENCE R&D
  - TECHNOLOGY DEVELOPMENT
  - IN SITU ANALYSES
- **ORBITAL DEPOT**
  - SERVICING FACILITY
  - ASSEMBLY FACILITY
  - TRANSPORTATION NODE
  - STEPPING STONE FOR SPACE EXPLORATION
- **INDUSTRIAL BASE**
  - LONG DURATION MISSIONS
  - UTILITIES, POWER, COMMUNICATION, ETC.
  - COST EFFECTIVE LOGISTICS
  - PROCESS DEVELOPMENT
  - LOGISTICS
  - STORAGE

Figure 1

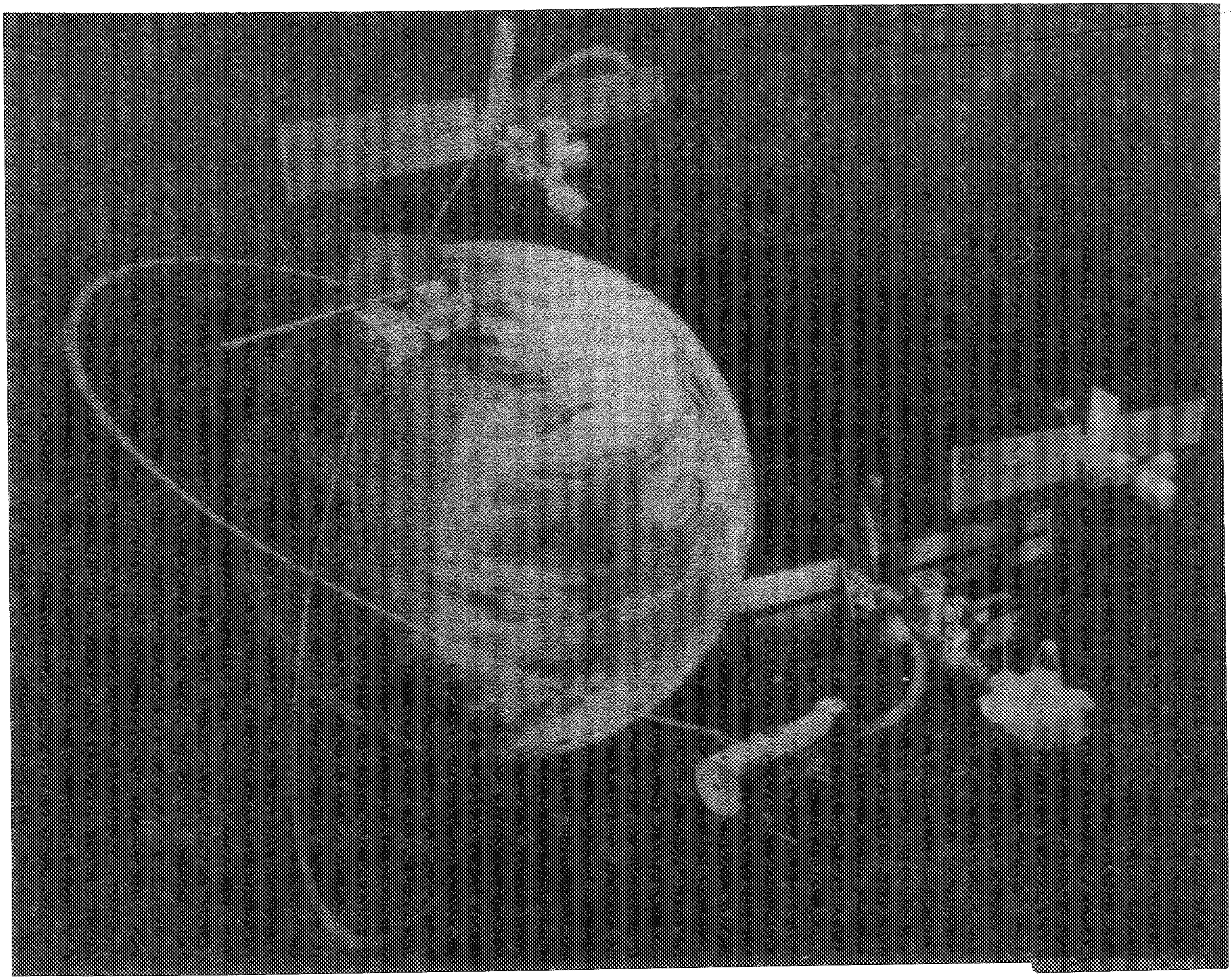


Figure 2

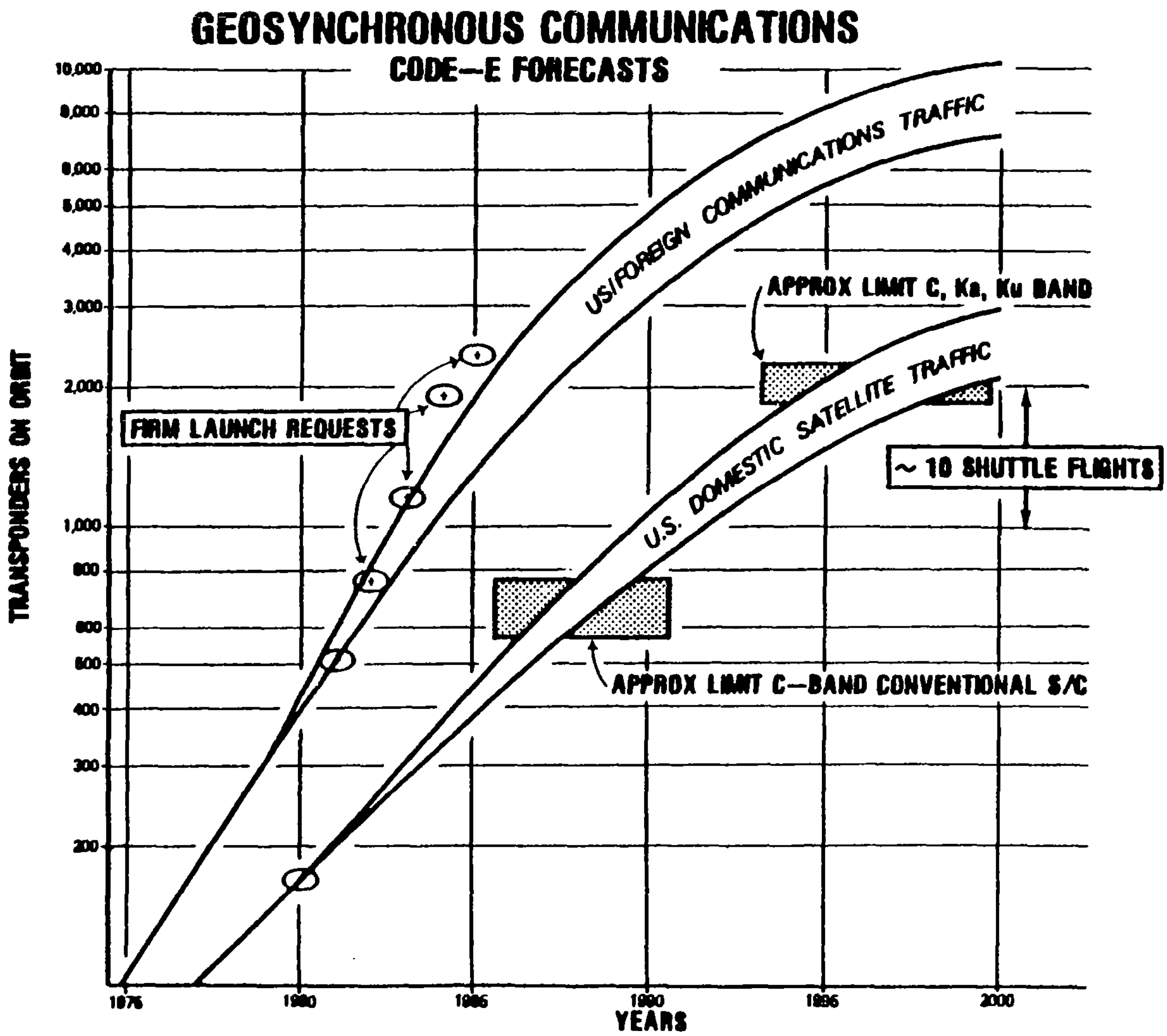

GEOSYNCHRONOUS COMMUNICATIONS
CODE—E FORECASTS
TRANSPONDERS ON ORBIT
YEARS
US/FOREIGN COMMUNICATIONS TRAFFIC
U.S. DOMESTIC SATELLITE TRAFFIC
APPROX LIMIT C, Ka, Ku BAND
FIRM LAUNCH REQUESTS
~ 10 SHUTTLE FLIGHTS
APPROX LIMIT C—BAND CONVENTIONAL S/C

Figure 3

COMMERCIAL MPS PROCESSES AND POTENTIAL APPLICATIONS

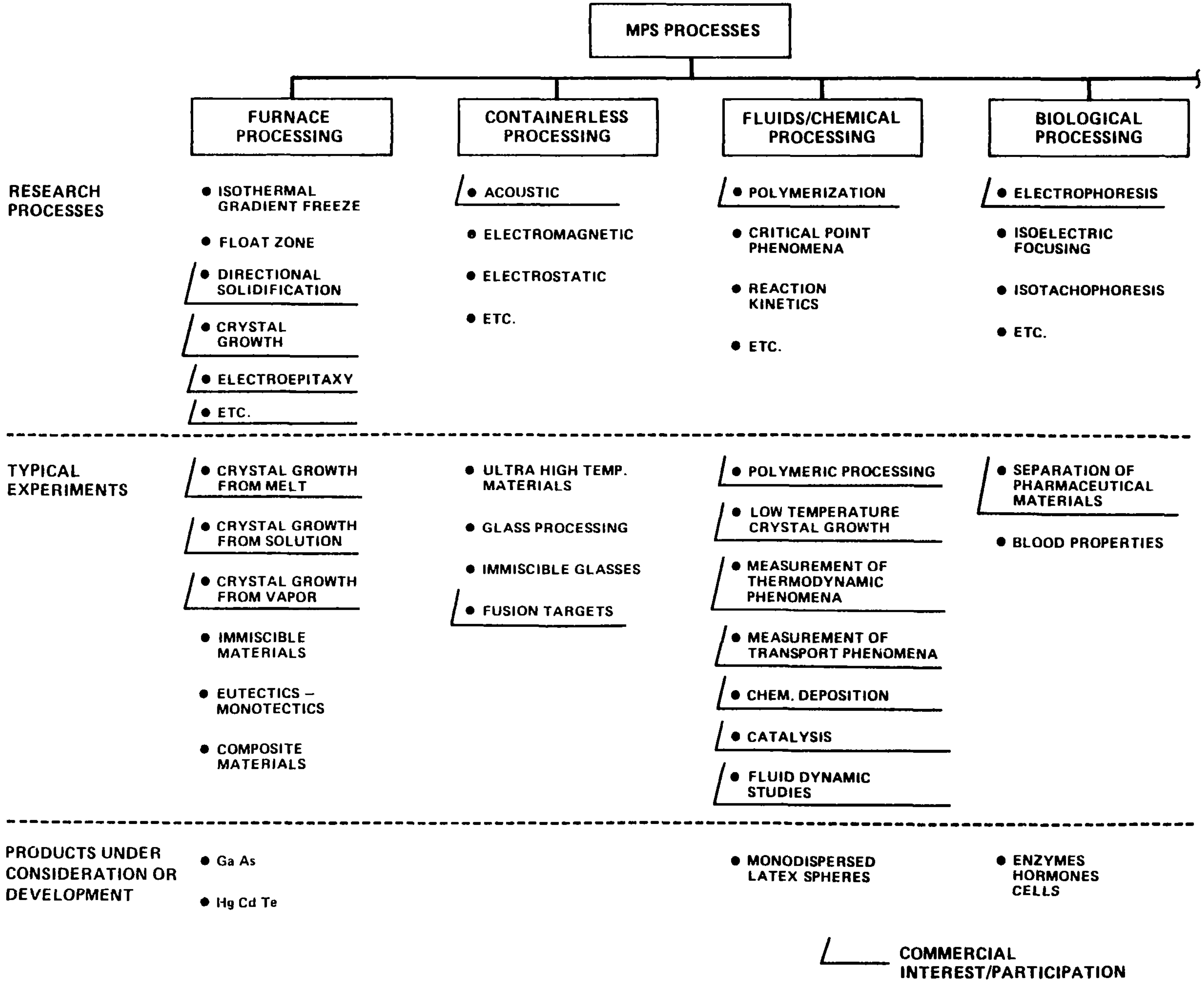
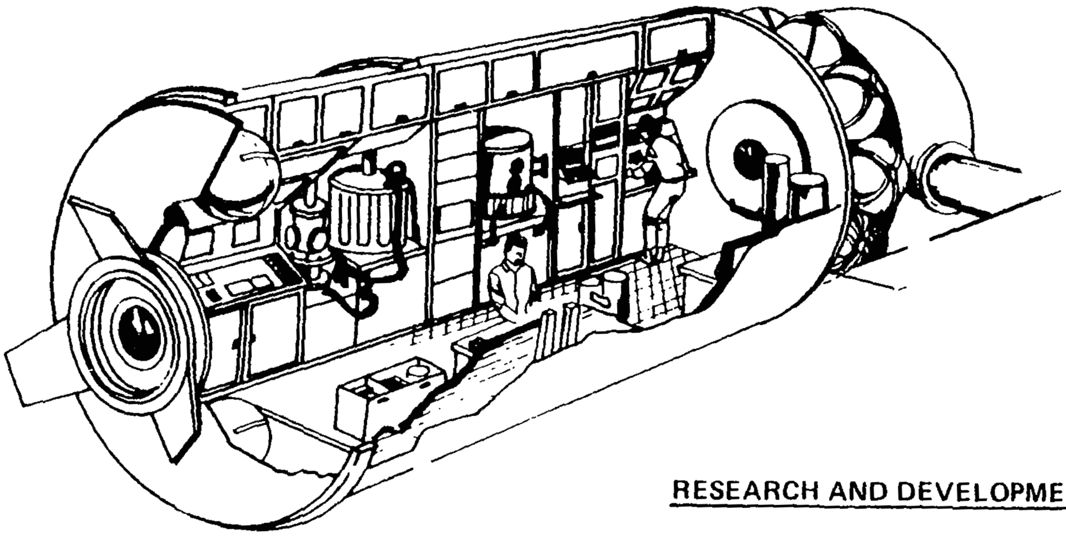


Figure 4

MICROGRAVITY MATERIALS R&D MODULE



RESEARCH AND DEVELOPMENT STUDIES

- CRYSTAL GROWTH
- ALLOY SOLIDIFICATION
- BIOLOGICAL SEPARATION
- UNIQUE GLASS COMPOSITION
- FLUID AND CHEMICAL PROCESSES

Figure 5

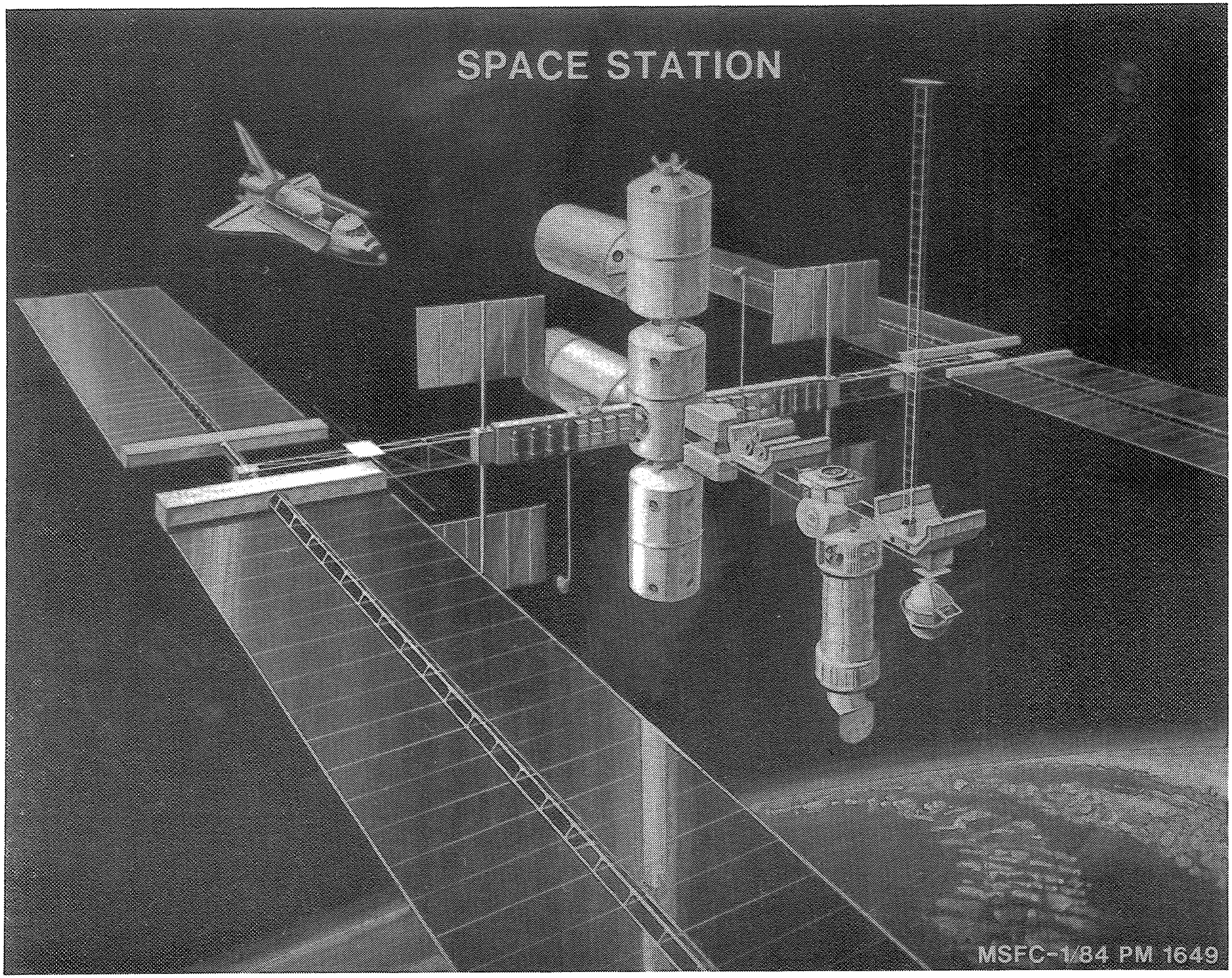
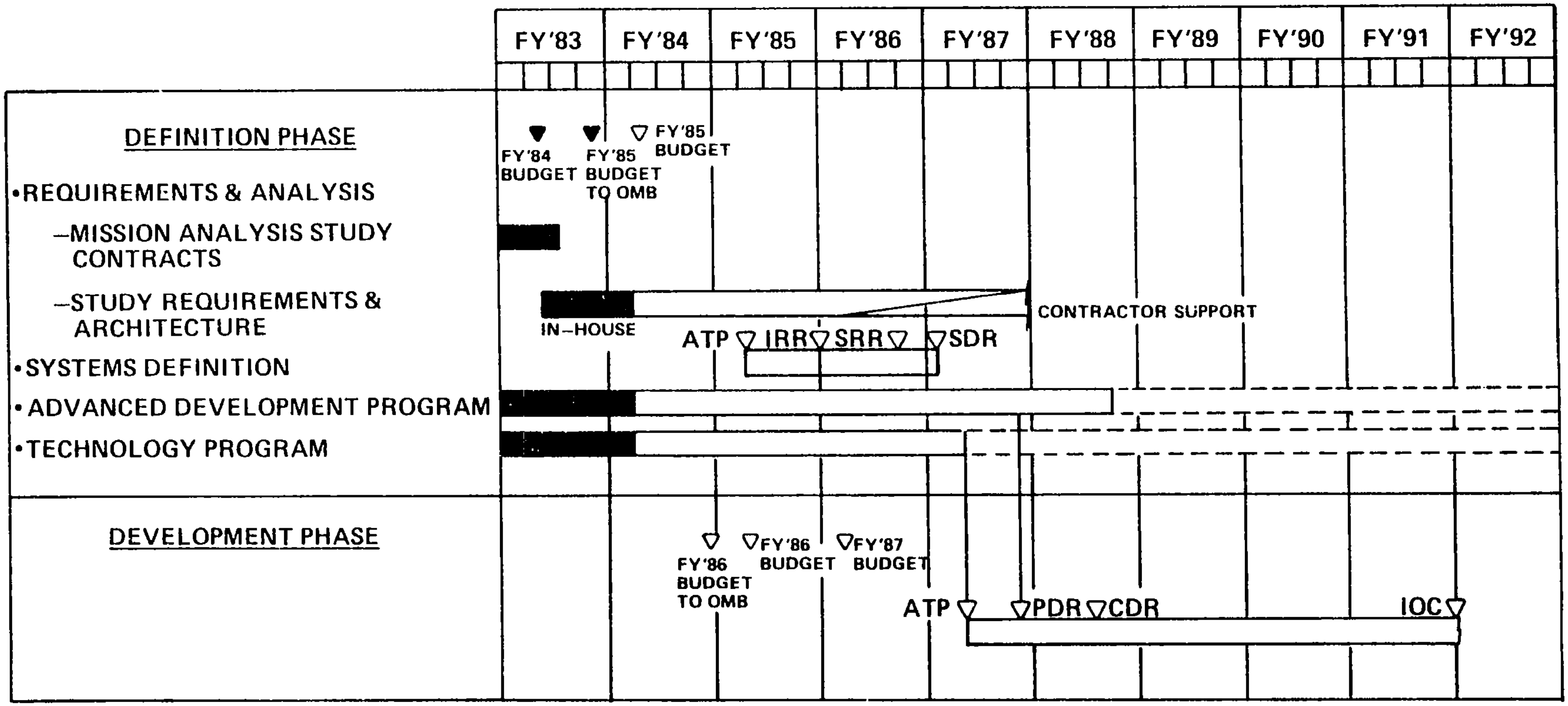


Figure 6

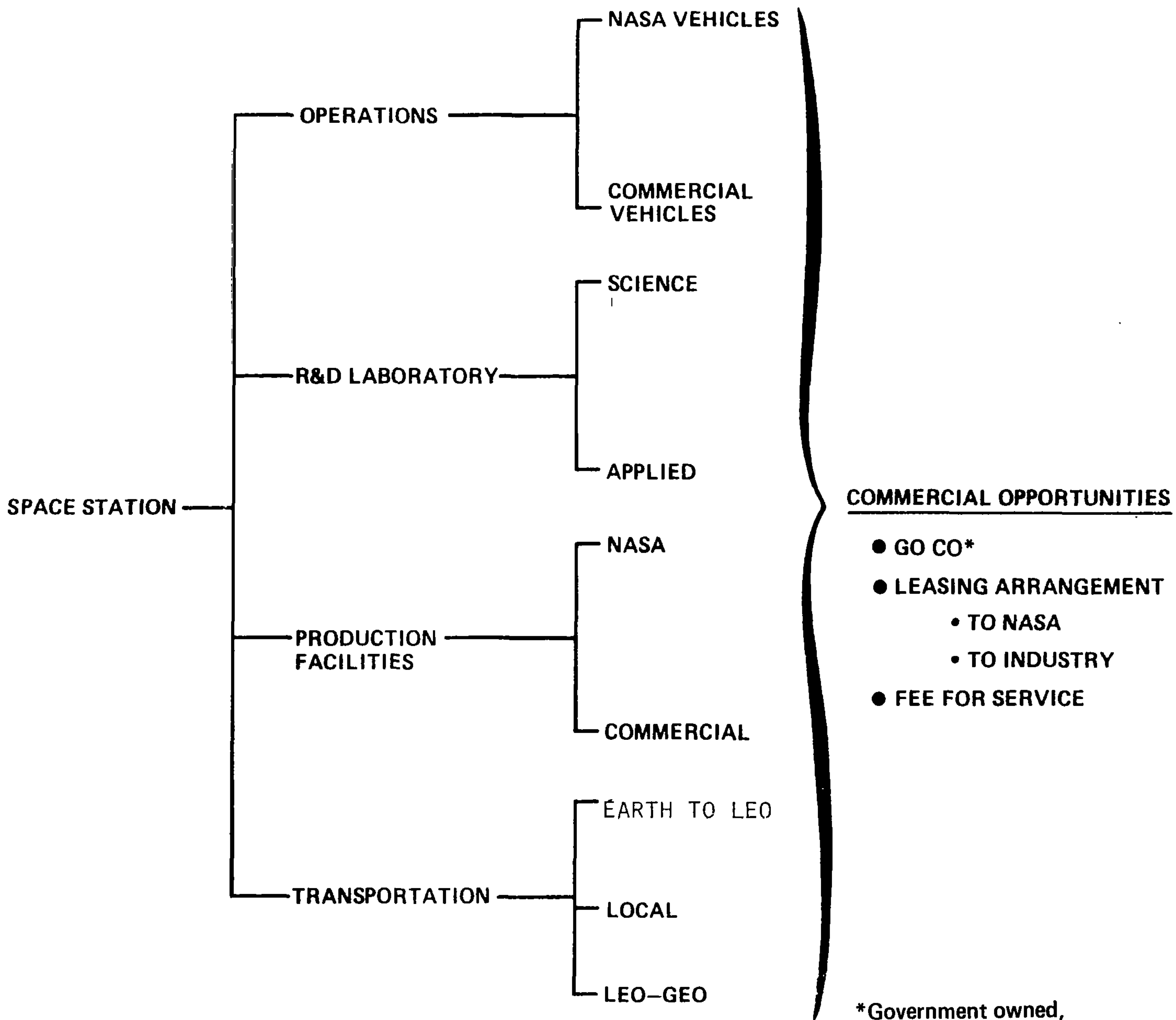
SPACE STATION PLANNING SCHEDULE



ATP – AUTHORITY TO PROCEED
CDR – CRITICAL DESIGN REVIEW
IOC – INITIAL OPERATIONAL CAPABILITY
IRR – INTERFACE REQUIREMENTS REVIEW
PDR – PRELIMINARY DESIGN REVIEW
SDR – SYSTEM DESIGN REVIEW
SRR – SYSTEM REQUIREMENTS REVIEW

Figure 7

POTENTIAL COMMERCIAL OPPORTUNITIES IN SPACE STATION ERA



*Government owned, contractor operated.

Figure 8