Chapter 3

SPACE INFRASTRUCTURE

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SUMMARY

Since 1957 various spacefaring nations have launched hundreds of spacecraft, many of which remain today in Earth orbit or on itineraries within the solar system or beyond. Many of these spacecraft, and some of those to be launched in the future including any "space station" elements and associated launch and transportation systems, are elements of space infrastructure, enabling humans at the surface and in space to carry out activities outside of Earth's atmosphere. This chapter begins with a discussion of the space environment, orbits, and the technical aspects of space infrastructure. NASA's specific aspirations for a "space station" and the functions that NASA expects it to provide are listed in detail. The projected uses of such a facility are summarized, taken from the response of a number of major aerospace contractors to NASA's Mission Analysis Studies. The reaction of the National Research Council's Space Science Board and the Space Applications Board to NASA's "space station" aspirations are then discussed. The remainder of chapter 3 lists and describes alternatives to NASA's aspirations for space infrastructure, including a number of currently existing platforms and other infrastructure elements, and some that are under development or in the planning stage.[1] A "USA Salyut" concept is presented as an option that could provide in-space infrastructure that is roughly comparable to the Soviet Union's current Salyut 7.

[1]Among the sources for the material presented in this chapter are background reports prepared for OTA by Dr. Jerry Grey, aerospace consultant (on space systems and transportation) and by Teledyne-Brown Engineering on alternatives to wholly new technology in-space infrastructure. Additional material on existing or proposed space platforms and spacecraft was furnished by individual aerospace companies. Also available were results of an OTA workshop on lower cost alternatives to a space station; workshop participants included aerospace industry and international representatives.

INTRODUCTION

The United States is currently pursuing a wide variety of civilian space activities. The argument is being forcefully advanced that additional in-space infrastructure would permit scientific, technology-development and commercial activities to be performed more easily or economically than at present, and might allow new types of activities in space. Plans for a civilian "space station, " i.e., space infrastructure, were included in the ambitious U.S. publicly supported space effort which commenced immediately after the launch of the first Sputnik over a quarter century ago. NASA undertook preliminary designs for such "space stations" in the early sixties.[2] In the early seventies, astronauts were successfully supported for *long* durations aboard Skylab, the first U.S. space laboratory. Now, at the beginning of the second-quarter century of the space age, U.S. space infrastructure that would support long-duration human activities in space is again under consideration.

[2]The first realistic design initiative for a space station appears to have been taken prior to the NASA efforts by the Lockheed Corp. Missiles and Space Division in the late 1950s (S. B. Kramer and R. A. Byers, "Assembly of a Multi-Manned Satellite, " LMSD Report No. 48347, December 1958).

CONSIDERATIONS FOR ANY SPACE INFRASTRUCTURE

The space environment is quite different from that on and near the Earth's surface. There are a number of orbital, environmental, and technical factors that must be considered to ensure safe and successful operations in space.

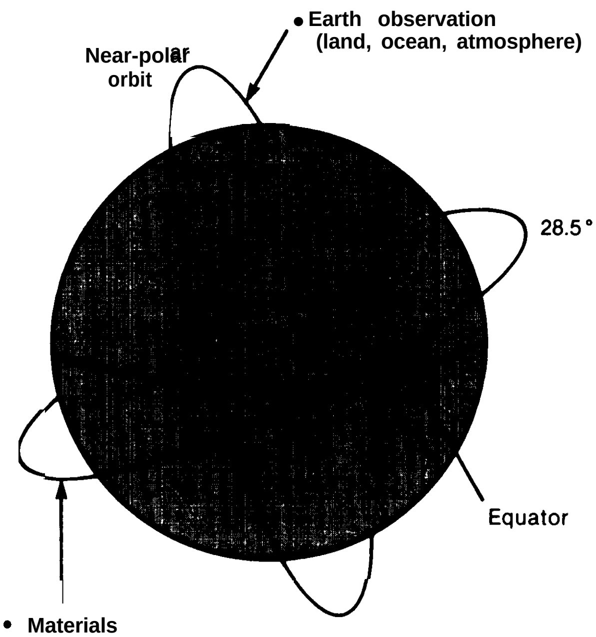
Orbits

Infrastructure elements could be located in one, or several, of a wide range of orbits. Most communications satellites and some meteorological and Earth observation satellites utilize locations in geostationary orbits, 35,800 km above the Equator, as fixed vantage points from which to transmit and receive signals or to observe the Earth's surface and its atmosphere. It has been frequently suggested that on-orbit servicing of geostationary satellites, their orbital transfer propulsion systems, and inter-orbit transportation vehicles, could be done more efficiently from infrastructure located in low-Earth-orbit (LEO) with a low inclination relative to the Equator. An orbital inclination of 28.5° (see fig. 1) would be reasonable for this infrastructure, because launches over the Atlantic Ocean from Cape Canaveral into orbits of this inclination consume the least energy.

These two functions–servicing geostationary satellites and launching into the lowest energy orbit from Cape Canaveral—are reasonably compatible, because the additional energy needed per unit mass at great altitudes to transfer a payload into geostationary orbit from 28.5° is relatively small.

However, full repetitive coverage of the Earth for low-altitude meteorological and other Earth-viewing satellites requires near-polar orbits (such as the near-900 inclination illustrated in fig. 1). Such satellites are therefore launched from the Vandenberg Air Force Base in California, which offers a safe launch trajectory to the south, over the Pacific Ocean. A Sun-synchronous near-polar orbit that follows the dawn-dusk line is possible; it avoids Earth shadowing of solar-powered or solar-viewing instruments, but does not accommodate Earth-viewing instruments that require illumination of the Earth's surface by the Sun.

Figure 1.—Orbital Inclinations and Representative Uses



When repetitive but not full coverage of the Earth is essential, a lower inclination can be used; an orbit inclination of **57°** is favored because it is the maximum practical inclination obtainable with a Cape Canaveral launch. It may be desirable to use infrastructure elements in several orbital planes, or perhaps to develop and employ a reusable orbital transfer vehicle (ROTV) for transportation between orbits having various inclinations, although this would be expensive.

Orbital altitudes are also related to several physical characteristics of space. One of these is the "solar wind," a radiation flux of high-energy particles from the Sun, that can present a threat to human beings and equipment. However, the region from 200 to 600 km in altitude (LEO) is shielded by the Earth's magnetosphere and the radiation there is almost negligible compared with the radiation in and beyond the Van Allen belts, which extend to 50,000 km in altitude. The magnetic field is less effective in shielding against ra-

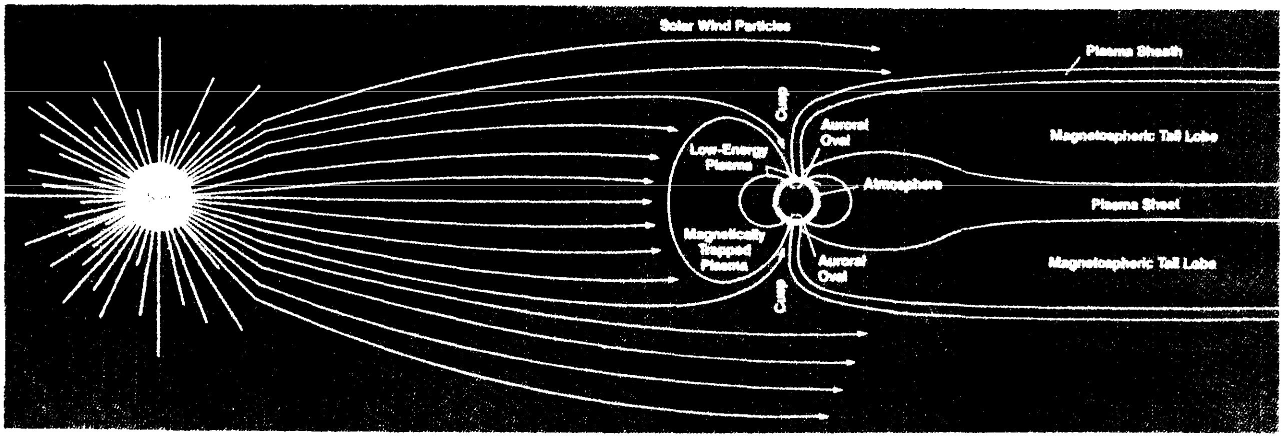


Photo credit: *National Aeronautics and Space Administration*

Diagram showing Earth's magnetosphere and other near-Earth phenomena.

diation approaching the Earth near its magnetic poles, including that associated with solar flares. Thus, high-altitude orbits and near-polar orbits are much less hospitable than low-Earth-orbits of low inclination.

Orbit altitude also affects the amount of global Earth coverage available to viewing instruments. If a sensor is required to provide daily global coverage, for example, the physical limitations on the angular swath width impose a minimum satellite altitude much higher than 500 km.

Aerodynamic drag becomes an important consideration for lower altitude orbits. Aerodynamic drag decreases for higher orbits; at 400 km, the drag is two orders of magnitude less than at 200 km. The minimum economical, long-term altitude for large semipermanent infrastructure elements that would be serviced using the Shuttle ordinarily would be above 300 km, and it will likely be below 600 km because of the rapid decrease in Shuttle payload capacity with greater altitude.

Since locations in LEO are above most of the atmosphere, astronomical observations of all sorts are favored there. As well, one revolution around the Earth in a typical circular LEO takes 90 minutes, allowing vast areas of Earth's surface to be observed in continuous succession and on a frequently repeated basis. However, higher orbits provide a broader field of view for remote sensing of Earth.

Another consideration is the energy that must be expended to take material to a sufficient altitude to obtain a relatively low drag, long-life orbit. To reach LEO requires more than half of the energy required either to reach geostationary orbit or to escape the Earth's gravitational field altogether. This is the physical basis for some of the projected cost savings of a permanently orbiting infrastructure base: large launch costs would be paid only once when infrastructure components are carried into orbit and left there, avoiding additional, repetitive, launch costs for heavy equipment that would be frequently used in space. Of course, resupply launches would still be needed and would offset some of this cost saving.[3]

Low-Earth-Orbit Environment

Four characteristics of the LEO physical environment are of particular interest: microgravity, high vacuum, periodic high-intensity sunlight, and the combination of solar exposure and shadowing that makes thermal control possible. For any infrastructure elements located beyond the Van Allen belts, a fifth environmental parameter is high-energy radiation,

[3]The number of resupply launches required would depend on the types and levels of activities carried out, the presence or absense of people, etc.

Above the minimum practical orbital altitude of a permanent space facility, the presence of microgravity and vacuum are essentially independent of orbital inclination and altitude. In particular, the exploitation of microgravity or near "weightlessness, " which occurs when gravitational and orbital acceleration counteract one another, shows promise for the processing of materials under such unique conditions. Energy generation depends on radiation from the Sun, and thermal control depends on radiating waste heat out into deep space. For most orbits, the Sun is eclipsed nearly half of the time by the Earth, but this effect can be tolerated if energy storage systems are used; batteries charged from solar photovoltaic arrays can be used to supply electric power during times that sunlight is blocked by the Earth.

Of course, for many human beings, simply being in orbit, and being able to view the Earth and heavens from this perspective, are the outstanding characteristics of space.

Technical Considerations

The design of infrastructure components and systems will depend heavily on a number of technical considerations. While a considerable amount of workable "space station" technology exists, as demonstrated by the success of Skylab, SPAS, MESA, and the Shuttle itself, the development of new technology may be desirable to obtain a long, and particularly useful and efficient lifetime for space infrastructure.

Data Management.–Space infrastructure elements would use an extensive data handling network both on-board and on the ground. The network would serve orbiting elements including the Shuttle, communication, navigation and remote sensing satellites, orbital transfer vehicles, crew members on spacewalks, tended free flyers, and support staff and scientific researchers on Earth. Cost, program control, and reliability prompt consideration of a wide variety of hardware and software technologies just now coming into being. For example, faster processors, laser disk storage, and flat display terminals will provide large increases in capacity at lower unit cost and weight.

Communications.—A number of communication links would be desirable using frequencies throughout the electromagnetic spectrum and encompassing a wide variety of distances, information content, and line-of-sight propagation directions. Space communications must be designed to avoid interference with established ground-based systems and to take privacy, cost, capacity, and reliability into account. Another consideration is the location of communications and data processing nodes. The various space infrastructure elements could require a large number of antennas and lenses (the Shuttle has 23) that, altogether, would cover a wide field of view. Phased-array antennas, whose radiation patterns can be "pointed" electronically rather than mechanically, could be widely used.

Systems for locating and tracking natural and manmade debris, loose tools, and approaching spacecraft is also necessary. System concepts for this purpose include radar with beacons or passive reflectors, radio transponders, interferometry, the Global Positioning System, ground-based radar, or lidar (laser radar),

Although space communications can rely initially on current technology, millimeter and optical wavelengths may be desirable for use in space. The development of systems in these parts of the spectrum would offer significant technological challenge.

Electromagnetic Interference (EMI).–This is a significant problem that can occur in space, particularly when high-power microwave sources and sensitive detectors are involved. It is difficult to protect some electronic circuits from this "pick-up" problem. In some cases EM I could force the use of a constellation of individual platforms separated rather widely from each other rather than a single large structure.

Attitude Control and Stabilization .–Although space infrastructure elements do not have to contend with gravity, wind, earthquakes, precipitation, and other problems encountered on Earth, they must deal with quite different problems such as the absence of both a "firm footing" and the ''stiffening" influence of gravity. Of particular concern is the control and stabilization of large, flexible, evolving, structural assemblies and modules. Elaborate control systems for each module (sensors, actuators, computers, , . .) that are coordinated by a single "supervisory" controller may have to be employed.

Power.–Solar photovoltaic power generators with nickel-cadmium battery storage are commonly used in space. Systems employing them today cost at least several thousands of dollars per watt and have useful lifetimes of 10 years or less in orbit. One alternative is a nuclear power reactor, perhaps of the type now being explored in the Space Power Advanced Reactor program, but development time and hazards to human beings (and perhaps cost) may well preclude the use of nuclear reactors for inhabited infrastructure in the near future.

Significant cost reduction in photovoltaic arrays has been achieved using optical focusing devices that concentrate sunlight on the photocells, but considerable effort would be needed to develop and demonstrate practical arrays of this type for use in space. Coupled with this technique could be the use of more efficient solar cells, such as gallium-arsenide, in place of silicon cells. Efforts to increase the lifetime and reduce the mass of batteries could also lead to cost reduction. One promising replacement for present nickel-cadmium devices is the nickel-hydrogen battery. Another, at an earlier stage of development, is the regenerative fuel cell/electrolysis method, in which a fuel cell produces electricity and water when in the Earth's shadow and splits water into hydrogen and oxygen when in sunlight.

Thermal Energy Management.–For infrastructure composed of connected modules, it may not be practical to use individual thermal control systems for each module. Although individual systems would offer maximum flexibility, such an approach would prevent heat thrown off from one module from being used by another, and each module's radiator, which is by far the biggest and most exposed component of the thermal system, would impose its own orientation and location constraints on the overall structure. Hence, a centralized, automated system may be needed both to minimize total mass and to optimize radiator orientation (i.e., edge to Sun). However, such a system would require both a large, massive single radiator and considerable transfer of energy among the various modules via a heat-transport medium. Therefore, the tradeoffs between centralized and modular thermal rejection systems need to be examined in detail. The centralized system might utilize a gimbaled radiator maintained in an edge-to-Sun orientation, not only maximizing heat dissipation and thereby requiring perhaps a 60-percent smaller area than a fixed radiator, but also minimizing solar-wind degradation of its thermal coating.

A conventional separate-tube radiator, similar to that used in the Shuttle, would be extremely complex and massive because of the need for redundant piping, valving, and other plumbing components. For a typical 100-kW heat rejection system, a Shuttle-type radiator would require almost 6,000 meters (almost 4 miles) of tubing in over 1,500 individual pumped fluid tubes, more than 50 fluid manifolds, and more than 75 isolation valves, fluid swivels or flexible line segments. Hence, a heat pipe radiator may be a better choice. Heat pipes transfer heat by boiling a fluid such as ammonia at one end of a sealed tube and condensing it at the other. The liquid is then returned to the hot end by capillary (surface-tension) forces in a specially designed wick which forms part of the tube. The heat pipe has no moving parts, and each pipe is self-contained. Single pipes have demonstrated heat rejection rates up to 2 kW; hence, as few as 50 could handle 100 kW of power in space, While the technology is relatively well known, considerable development is called for to evolve a practical, reliable, long-life, heat pipe radiator at this power level.

Another technological challenge would be an inter-module system that transfers thermal energy to a radiator. Shuttle-type pumped-loop systems using Freon 21 would consume large amounts of power (up to 5 kW for a 100-kW system), and would also require the development of large, costly, space-rated pumps and their attendant repair and maintenance. A two-phase heat transport system using the same principle as the heat pipe would consume only about one-tenth as much power. Hence, it may be worth the cost of its development.

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The use of passive cryogenic coolers for electro-optical detectors will present a difficult technical challenge. Active cryogenic systems are probably not satisfactory for long-term operation. Passive coolers require exposure to dark space and an environment that is free from effluents that would condense on the cooler's cold patch.

Propulsion.— Infrastructure elements require propulsion systems for attitude control, orbit change, station-keeping, and acceleration control. Propulsion systems currently use storable liquid mono- and bi-propellant pressure-fed thrusters. Near-future plans include cryogenic oxygen/hydrogen propulsion systems. Longer term prospects are electromagnetic thrusters including ion rocket (ions can be accelerated to much higher exhaust velocities than those provided by chemical rockets) and mass drivers ("buckets" of heavy materials can be accelerated, very rapidly by electrical motors rather than by conventional chemical combustion).

A principal challenge will be the creation of a storage and transfer system for handling liquid fuels in space. Specific needs are leak-proof fluid couplings and leak-detection techniques, fluid-quantity gauges that operate with acceptable accuracy in microgravity where conventional liquid-level sensors are not suitable, reusable, low-mass, nontoxic, long-life insulation for cryogenic storage and transport, and the liquefaction and refrigeration systems needed for long-term cryogenic storage. Improvements in cryogenic refueling procedures now used on the surface for Shuttle operations would be necessary—preferably procedures that would use automation—to obviate the need for a large technical staff that would be very expensive to accommodate in space.

Life Support Systems.–Some of the materials necessary for the support of humans in space would be supplied from Earth, others would be recovered in orbit from metabolic byproducts. With the exception of food, recovery technology demonstrated since 1967 can provide for oxygen, carbon dioxide scrubbing, and water for both drinking and washing. Such a "partially closed" system accommodating an eight-person crew, each drinking about 3.5 kg of water and using about a liter of wash water per day, would have to be resupplied every 90 days and would have a 30-day contingency supply. Compared with the Shuttle system, which does not use recovery, almost 7,000 kg per resupply launch could be saved. If reclaimed water were also used for showers, and for washing utensils and clothes, thereby replacing "wet wipes," disposable clothes, and disposable food service utensils, another **5,000** kg could be saved for each launch. Therefore, the development cost of such a system could be offset by associated transportation savings of over $100 million per year.

Food supply technology will also require some development, including improvements in packaging, preservation, bulk storage, reconstitution, and on-board preparation. Proper sanitation to reduce the incidence of debilitating illness in the completely closed environment of a "space station" will require waste disposal, contamination containment, disease-prevention measures, and heakh-maintenance facilities unique to microgravity environments to be developed and used. Some of this technology has already been developed for the long-duration Skylab project, but improvements are needed. Particular attention should be given to the proper design of residential, exercise, and recreational facilities if people are to remain in orbit for periods of much longer than several weeks.

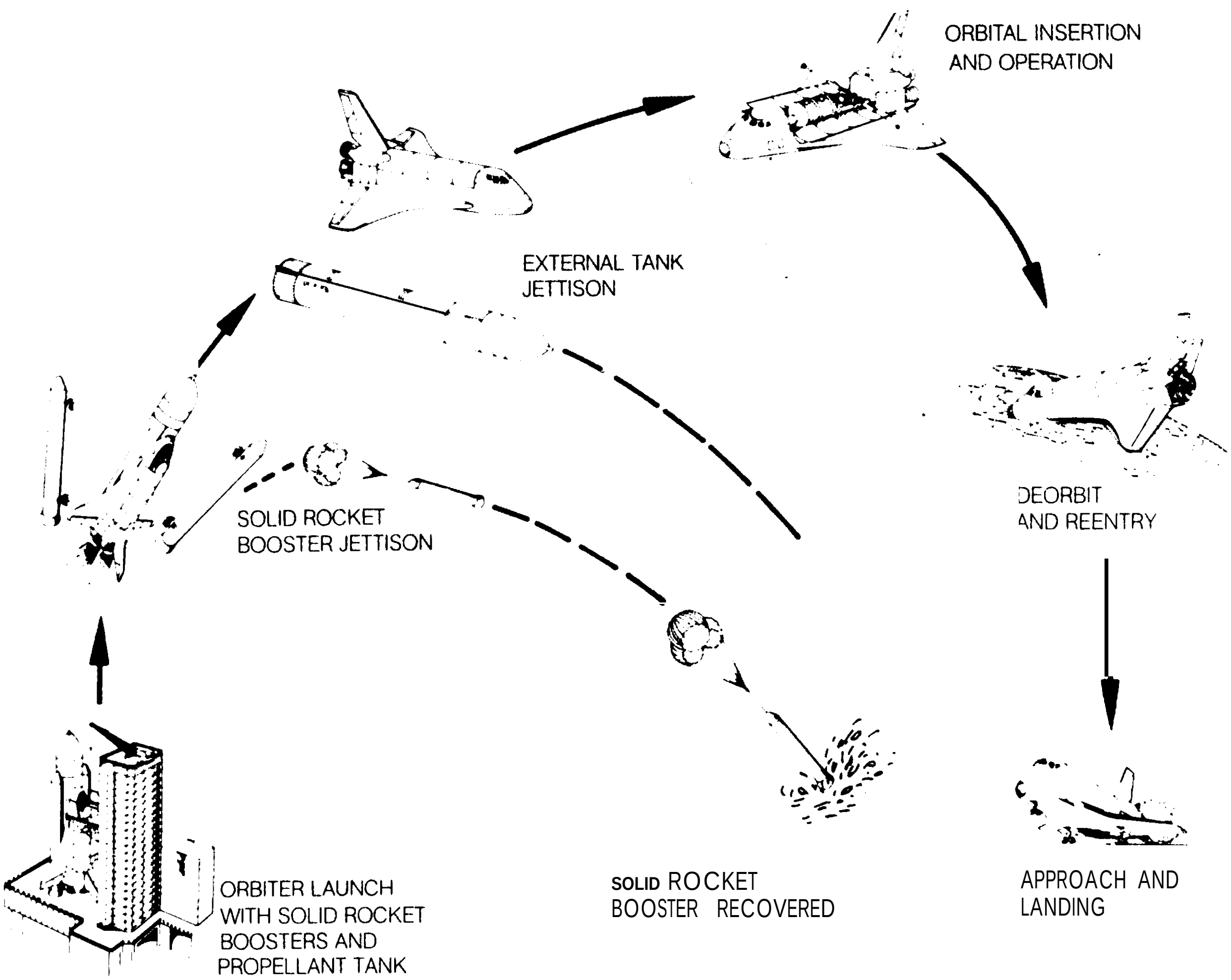
Space Transportation

Vehicles will be needed for transportation between Earth and LEO, between various LEO orbits, between LEO and higher, including geostationary, orbits, and beyond to the Moon and perhaps to other planets and some asteroids. In the near future, supply for a "space station" from Earth would rely primarily on the present Shuttle and possibly its derivatives. Local checkout and maintenance services requiring people working directly in space could be conducted by tethered or free-flying spacesuited astronauts, sometimes augmented by the existing manned maneuvering units (MMUs). Servicing of more distant spacecraft could be accomplished with a planned orbital maneuvering vehicle (OMV), possibly in combination with either the Shuttle or a planned space-based ROTV, or by an ROTV (or the Shuttle) carrying an astronaut equipped with an MMU.

Launching spacecraft into higher orbits or on Earth-escape trajectories requires the use of an upper stage rocket, which could be automatic, teleoperated, or used with a crew, plus kick stages or planetary landing stages, depending on the project. ROTVS, either teleoperated or employing crews, could be used to service satellites in orbits of significantly different altitude and somewhat different inclination.

Shuttle.-The Shuttle (fig. 2) meets most of the current needs for transportation between the Earth's surface and **LEO** at any Inclination. The Shuttle can deliver 30,000 kg to a 200-km (120-mile) orbit inclined at 28.5° to the Equator. Any increase in orbit altitude or change from this orbit inclination reduces the payload capacity. However, most payloads are volume-limited by the cargo bay's 18-meter length and 4.6-meter diameter rather than weight-limited. By the early 1990s, the earliest date considered practical for obtaining a "space station," NASA projects a total of some 24 to 30 Shuttle flights per year, and some 50 per year by the year 2000. The Shuttle's cargo bay could be used to carry infrastructure- elements nto orbit, and when there,

Figure 2.—Diagram of Shuttle Mission Profile



its crew of up to seven persons could be used to assist with any assembly and checkout. The Shuttle could also resupply expendable, ferry personnel, and serve for emergency rescue.

Manned Maneuvering Unit (MMU).–The MMU is a backpack equipped with a computer-operated propulsion system that permits an astronaut to "free fly," thereby projecting his senses, his strength and dexterity, and his judgment beyond the confines of the Shuttle or other habitable infrastructure out to a few hundred meters. It is a general-purpose device that can be used for inspection, servicing and deployment or retrieval of equipment, for construction and assembly operations, for crew rescue, for emergency repairs, etc. A Shuttle-based MMU was successfully demonstrated on two flights in early 1984.

Orbital Maneuvering Vehicle (OMV).-Local transportation in LEO would be provided by the OMV. It would be operated remotely from the Shuttle, other space infrastructure, or possibly from Earth. It would be designed to have a six-degree of freedom propulsion system that would allow satellite or platform servicing operations at distances well beyond the MMU'S few-hundred-meter limit. One version of the OMV would be able to make altitude changes of 1,000 km or more above its initial LEO and orbit plane changes of up to 8°, depending on payload weight.

Basic OMV equipment includes propulsion units and propellent tanks; television cameras and lights for inspection and operator guidance; communications; control systems for remote operations; electric power; thermal control; and various manipulators and docking attachments. Current NASA plans are to have such a new-technology vehicle developed and operating in time to be useful in the deployment and assembly of a "space station."

Expendable Launch Vehicle (ELV)-Up to November 1982, all payloads launched into space were carried there by ELVS. There are now three basic U.S. families of ELVS: the Delta, Atlas-Centaur, and Titan **III.** The European Space Agency has its Ariane family of boosters, Japan has its N-2 (derived from the U.S. Delta) and is developing others, the People's Republic of China has launched a geostationary satellite using its FB-3 "Long March" rocket, and the Soviet Union is offering to make its Proton launcher commercially available. In addition, several private corporations in the United States and Germany have announced plans to develop ELVS. Many of these vehicles and possibly others may be available commercially throughout the next decade. However, it is not likely that they will be suitable for launching spacecraft that carry people, although they could launch supply spacecraft as the Soviet Proton boosts the Progress into orbit.

Expendable launch vehicles that can launch to high orbits, or to Earth-escape trajectories, use either their own upper stages or uniquely compatible orbital transfer vehicles (OTVS). The payload itself carries the "kick stage" or other propulsion needed to move from high, inclined, elliptical orbits to geostationary orbits.

Reusable Orbital Transfer Vehicle (ROTV).-A reusable, high-performance, liquid propellant "space tug" could provide transportation between LEO and geostationary and lunar orbits, or between Earth orbits of various inclination and altitude. Reusability and space-basing give promise of economic benefit for the use of an ROTV in launching and servicing communications and other satellites that utilize the geostationary orbit. An ROTV could be piloted by a crew or remotely operated.

Development of an "Advanced Space Engine" suitable to power an ROTV has yet to be started. Space-basing implies reusability, of course, as well as flexibility of thrust and duration of rocket burn, and the ability to refuel and perform maintenance in space. Thus, space-basing requires some form of orbital logistics system, including tanks, pumps, controls, and other equipment for refueling, people or teleoperator devices to check out the ROTV, refurbish it as needed, and reset its operating systems for each new trip, and perhaps crew quarters.

Space-basing also requires docking, servicing, and storage facilities in space to make ROTV operation possible. Moreover, as fuel for the ROTV must always be brought from the surface to LEO, alternative ways of transporting it are under consideration. More efficient delivery systems than the Shuttle, such as a Shuttle-derived tanker vehi-

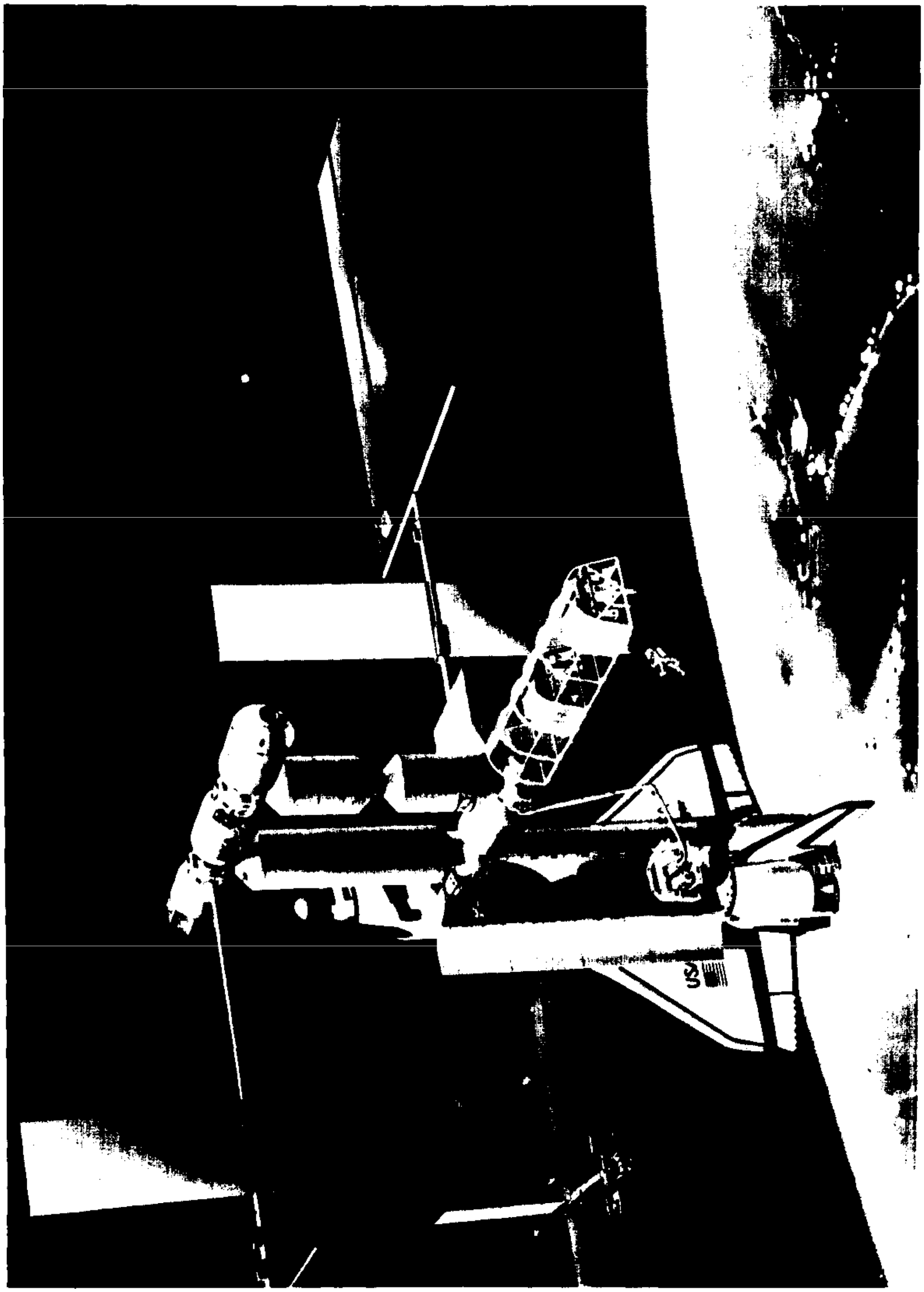


Figure 3.—A Possible Configuration for NASA's Initial Operational Capability Space Station Involving a Solar Power Array, Habitat Module, Logistics Module, Two Laboratory Modules, and Satellite Servicing Structure

cle, are being looked at. Scavenging left-over fuel from the Shuttle external tank is being given consideration. Considerable development time and expense would be involved in any of these efforts.

A prospect which offers an opportunity for considerable propellant savings is to dissipate the ROTV'S excess kinetic energy, on return from high altitudes to LEO, by allowing it to dip into the upper reaches of the Earth's atmosphere, a maneuver called "aerobraking." The return flight would consist of a brief de-orbit burn that would place the ROTV into an elliptical transfer orbit that intersects the top of the atmosphere. If the ROTV could dissipate enough energy to decrease its velocity by 2,400 meters per second, it would have just enough energy left to raise it to a "space station's" (typical) 300-km orbit. There, it could deliver its return payload (if any) and refuel for its next trip. This aerobraking concept promises a saving of over half of the propellant needed (compared to an all-propulsive ROTV) for a return trip with payload from geostationary Earth orbit.

NASA'S APPROACH TO SPACE INFRASTRUCTURE

"Mission Analysis Studies" Summary

In 1982, as part of NASA's planning to acquire long-term inhabited infrastructure, i.e., a civilian "space station, " the agency authorized "mission analysis studies" in the United States, and reached an agreement with foreign countries for parallel studies, of the desires or needs for, and characteristics of, such infrastructure. The results of these studies appear in appendix A.

The "mission analysis studies" started with the supposition that the United States would build a civilian "space station, " and did not require the potential user to address either justification of the basic "space station" concept or its funding. The studies were simply to identify uses that either would require or would materially benefit from the availability of a "space station" and to suggest some of its fundamental characteristics.

Of the several hundred potential activities in science, commercialization, and technology development identified by the U.S. companies (primarily aerospace) conducting the studies, the selection was narrowed by NASA to a set of about 100 time-phased missions for the first 10 years of "station" operation, 70 percent of which could be accomplished from a central base facility located in a 28,5° inclination in LEO. Free-flying platforms, either co-orbiting or in polar orbit, could accommodate most of the others.

The contractors viewed activities such as equipment servicing, research (especially in the life sciences and materials processing), and assembly and modification of large space systems as areas in which presence of a human crew would be particularly beneficial. They recommended architectural concepts involving several types of modules for the initial central complex: a command/habitability module with accommodations for a crew of four; an electrical power system providing about **25** kW to the users; logistics modules for periodic resupply; airlocks, docking ports, and pallets to enable mounting of equipment and laboratory modules. Subsequent development and growth of the facility over a 10-year period and incorporation of an ROTV and several free-flying platforms were anticipated.

Estimation of acquisition costs ranged from approximately $4 billion to $5 billion (1984$) for the initial facility, to about $12 billion for an evolved complex envisioned as being completed 6 to 8 years after the system first became operational. Other than the performance and social benefits of such a "space station," they estimated that economic benefits from servicing satellites in orbit, transfer of satellites to higher orbits by an ROTV, and human-tended long-term research activities would be considerable. The increased ability to launch planetary probes, establish a lunar settlement, and undertake human exploration of Mars was considered of great significance in terms of long-range goals.

The foreign mission analysis studies paralleled those of the U.S. contractors and defined a similar set of space activities appropriate for infrastructure use. All participating agencies from Europe, Canada, and Japan expressed great interest in taking part both in providing elements of space infrastructure and in actively participating as partners in its use. Many of them look upon it as fundamental to their future role in space and therefore want long-term understandings and agreements with the United States on participation.

NASA assembled the United States and foreign mission analysis reports and held a workshop in May 1983 to synthesize the results. The workshop established a minimum time-phased "mission set" (for the initial decade of use) of 107 specific space activities, plus four generic commercial-industrial service activities (e. g., satellite servicing). Of the total set, 48 were categorized under science and applications, 28 under commercial, and 31 under technology-development.

In parallel with the contractor studies, NASA hired two consulting firms to communicate with a variety of non-aerospace companies to identify and encourage interest in the use of in-space facilities for commercial purposes. The consultants discussed prospects with approximately sO companies, and more than 30 expressed active interest in using a "space station" if it were available. Most of the companies moving toward agreements with NASA to become active in space are well-known U.S. industrial firms (one with an announced agreement is the 3M Co.), but several are from the small business sector or Europe. Interest is concentrated on the possible production of particular chemicals, metals, glass, communications, and crystals. Among the half dozen companies now actively investigating the possi-

80X D.-NASA's Current Aspirations

The workshop recommendations led NASA to draw up, during the summer of 1983, a "first cut," both of the initial operational capability (IOC) and of a possible later extension, of NASA's desires for in-space infrastructure as follows:

	IOC (early 1990s)	Future (by 2000)
Central complex in 28.5° LEO:		
Average electrical power to users	60 kW	160 kW
Laboratory modules (60 m³ volume each)	2	5
Attached payload mounts	4-6	8-10
Crew	6-8	12-18
Data rate	300 Mbps	300 Mbps
Satellite servicing capability	Nearby orbits	Range increased
Orbital maneuvering vehicle	Available	Available
Free-flying platforms (each with 15 kW average electrical power):		
Co-orbiting in the 28.5° LEO plane	One	Several
In LEO polar orbit	One	One
Crew	None	None
Space-based reusable orbital transfer vehicle	None	One

A conceptual configuration of the IOC is shown in fig. 5.

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SOURCE: E. L. Tilton and E. B. Pritchard, "Overview of NASA Space Station Acitivites," presented to the 34th Congress of the International Astronautical Federation, Oct. 10, 1983, Budapest.

bility of sponsoring space experiments, most are more interested in crew-tended operations rather than automated procedures. Further details of the consulting firms' studies are discussed in the final section of appendix A.

Infrastructure Functions

The NASA planning process has depended heavily on the "Mission Analysis Studies" of U.S. and foreign aerospace contractors and foreign space agencies. From the views assembled therein, functions were identified for any space infrastructure ("space station") that could provide efficient and effective assets and services to support the projected space activities.

NASA's aspirations for a "space station" were most recently presented to the Senate Committee on Appropriations in March 1984. The infrastructure envisioned in their plans would provide the following:

1. an on-orbit laboratory supporting research on a wide range of life, materials, and other science topics, and the development of new technology (e.g., studies of biology, cosmic rays, processing methods for pharmaceuticals and semiconductors, testing of space materials, and advanced communications technology);
2. permanent observatories for astronomy and Earth remote sensing (e.g., a solar optical telescope to examine the surface of the Sun, a starlab to study the structure of galaxies, and lidar equipment to probe the atmosphere);
3. a facility for microgravity materials processing and manufacture of products (e.g., pharmaceuticals, semiconductors, glasses, and metals);
4. servicing of satellites and platforms (e.g., the maintenance or replacement of components, replenishment of consumables, and exchange of equipment);
5. a transportation hub to assemble, check out, and launch vehicles (e.g., those carrying communications satellites) to geostationary or other high orbits, and as automated interplanetary probes (e.g., a Mars orbiter or an asteroid rendezvous vehicle;
6. an assembly facility for large space structures **(e.g.,** antennas for advanced satellite communications systems);
7. a storage depot for spare parts, fuel, and supplies for use as needed by satellites, platforms, vehicles, and people; and
8. a staging base for more ambitious future projects-and travel (e.g., a lunar settlement or a human voyage to Mars).

Questions such as the following must be asked relative to the corresponding functions listed above:

1. How much of an investment do these (and other) capabilities warrant?
2. Is use of a "space station" the optimum way to accomplish these missions?
3. When will the need for a microgravity production facility be demonstrated, and how much of its cost should its users pay for?
4. What kinds of satellites will be repaired, why, and who will bear the cost?
5. When will the transportation hub be ready and why is it needed then?
6. What is the purpose of the assembly facility for the large space structures–and of the large space structures themselves?
7. What is the justification for a storage depot in space?
8. When will a staging base be required for a lunar settlement or a manned Mars expedition?

And, underlying all of these specific questions is the hazard that too great a commitment to the acquisition of in-space infrastructure, and the resulting long-term operations and management expenditures, might preempt the adequate support of other important civilian space activities.

REACTIONS OF NATIONAL RESEARCH COUNCIL BOARDS

Other science and engineering organizations have participated in the study of space infrastructure acquisition. NASA invited the National Research Council (NRC) to review its possible utilization for space science and applications. (The NRC is a private organization of distinguished scientists and engineers operating within the charter of the National Academy of Sciences to act as an advisor to the U.S. Government (and others) on science and technology issues. It works through its committees, boards, and institutes, two of which, the Space Science Board (SSB) and the Space Applications Board (SAB), studied these issues in workshops during the summer of 1982.)

The Space Science Board concluded that almost all of the space science research projects forecast for the next 20 years (a forecast made without giving great attention to the possible use of sophisticated in-space infrastructure) could be carried out without the use of a "space station" as then characterized by NASA. These projects could be carried out by using Shuttle/Spacelab, satellites, interplanetary probes launched with expendable launch vehicles, or contemplated upper stages compatible with the Shuttle. The SSB stated it was not opposed to a "space station, " that a decision on it should be made for reasons beyond science uses, and that some science interests would make use of it if it were available. But the SSB expressed concern that any delays in launching science payloads that might be imposed as a consequence of waiting for completion of any "space station" could harm science programs unnecessarily, as the SSB believes happened during the development of the Shuttle (when several programs used up funds for employee salaries and other program costs during such delays),

The Space Applications Board expressed guarded support for use of a "space station ." It indicated interest in applications made possible, or made more efficient, through use of appropriate infrastructure, such as servicing of free-flying platforms, launching of geostationary satellites, repairing LEO satellites, and serving as a materials processing laboratory. Communications experimentation, especially for large antennas, was another likely use in their estimation. The presence of a human crew was deemed desirable, particularly for materials science experiments and for modification and repair of instruments. The SAB also concluded that a platform in near-polar orbit would be an important infrastructure component, to be used for Earth remote sensing of resources, Earth environmental studies, and ocean observations. The capability of the platform to merge and process a variety of data prior to transmission to the ground would be an advantage compared to independent, unprocessed transmissions from individual satellites. The SAB cautioned that sufficient resources must be made available to develop instruments and payloads for use on any "space station. "

Another body examining the role of expanded space infrastructure was the NASA Solar System Exploration Committee (SSEC). The SSEC is a group of the Nation's outstanding planetary scientists directly advising NASA on planetary research. The SSEC, which spent 2 years defining a new U.S. planetary space strategy, looked at the usefulness of any new infrastructure for planetary exploration. It concluded that, in the near term, the facility could be used beneficially as an assembly and launch base for deep space probes with potentially important advantages for planetary spacecraft requiring large internal propulsion systems. In the longer term, this could greatly facilitate the return of samples from Mars by providing a fully loaded booster such as a Centaur rocket. A "space station" could also serve as a holding facility for returned samples to alleviate concerns of their possible contamination of the Earth.

In January 1984, NASA created a 15-member advisory panel of academic space scientists that, over a 2-year interval, is expected to give NASA advice on suitable research projects for long-term, habitable, space infrastructure.

Of related interest to NASA programs, the NRC's Aeronautics and Space Engineering Board (ASEB) conducted a workshop during 1983 on NASA's

Space Research and Technology Program. While not directly addressing "space station" issues, their report noted the high payoff uses of space in the communications and meteorology fields, the present speculative nature of manufacturing in space, the high cost of space transportation and systems as an inhibiting factor in the commercial use of space, and that, in the face of foreign competition, the United States should continue to explore and stimulate potential uses of space.

The ASEB urged NASA to provide access to space for experimental purposes as a natural extension of national aerospace facilities on the Earth's surface. Overall, the report recommended that NASA devote a significant portion of its efforts to develop technology that would reduce the cost of spacecraft subsystems, payloads, transportation, and operations.

ALTERNATIVE INFRASTRUCTURE

Because of the large public costs associated with the NASA plans for acquiring in-space infrastructure, and considering the view of the Space Science Board (and others) regarding the NASA plans, it is important to explore alternative approaches for providing the desired capabilities of such infrastructure. OTA has identified several alternatives that could provide various capabilities, at various times, and at various initial costs to the Government. These alternatives include system components that currently exist or are currently under development. OTA has also considered a gradual approach to infrastructure acquisition with various average annual funding rates; lower cost alternatives could be used as early steps in an evolutionary development leading to increasingly sophisticated and capable arrays of infrastructure. Each of these approaches has different implications for initial Government cost, life-cycle costs, pace of commercial development, and the pace for carrying out human activities in space.

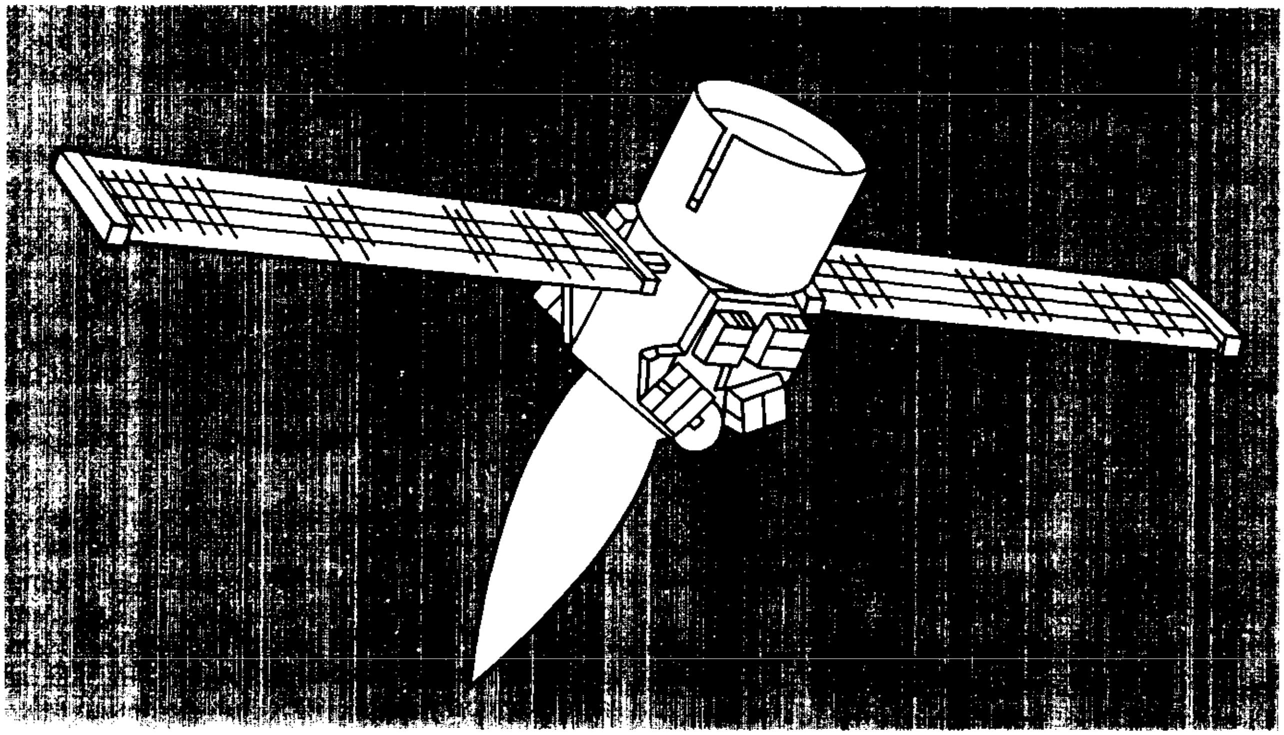
Uninhabitable Platforms

Regardless of the outcome of the debate over the need for infrastructure that includes and/or supports a long-term human presence in space, there is a significant community of users who would benefit from having uninhabited space facilities and services available to them. A number of so-called free-flying automated platform alternatives now exist, are in development, or have been conceived, that could take advantage of the Shuttle or expendable vehicles for launch and service.

The Shuttle can be used to launch to, and return equipment or other materials from, LEO. This ability allows for the use of space platforms offering electric power, heat rejection, communications, attitude control, and other services to a number of users. Some time after insertion into orbit (typically several months to a year), the Shuttle or an ROTV would rendezvous with such a platform, and servicing intervals for platform-mounted instruments would be coordinated with the rendezvous schedule, keeping costs in mind. Payloads could be exchanged, attitude control, fuel and other expendable replenished, batteries charged, or the platforms could be returned to an LEO base or to Earth. Platforms could avoid contamination and stability problems associated with inhabited infrastructure. The cost of the common platform facilities could be amortized over a long lifetime and a large number of activities.

Fairchild LEASECRAFT.-The Fairchild LEASECRAFT (fig. 4) is designed to support equipment that can be exchanged on orbit. This design approach anticipates that the costs (special equipment, crew training, etc.) and risks associated with performing maintenance and payload modifications and substitutions on orbit are outweighed by the saving in transportation cost and improvement in spacecraft utilization, which avoids frequent launch and return of the platform.

Figure 4.—An Artist's Conception of a LEASECRAFT Enroute to Orbital Altitude With Payload Attached



LEASECRAFT was inspired by the Multimission Modular Spacecraft (MMS) system on which the Landsat D and Solar Maximum Mission spacecraft are based. It can provide up to 6 kW of power and other services to user payloads, and is intended to serve LEO space projects that include data acquisition/transmission and materials processing.

Data acquisition activities generally require fine pointing and high data rates but relatively modest power levels. Materials processing projects, on the other hand, require high power but low data rates and relatively coarse pointing. The LEASECRAFT could be converted from one configuration to the other on orbit from the Shuttle or from other inhabited infrastructure.

The LEASECRAFT design includes a centrally mounted propulsion module that contains 2,700 kg of hydrazine for transfer from the standard Shuttle orbit of about 300 km to an operating altitude of 480 km. Later it can be returned to the Shuttle orbit for rendezvous. The total weight of the LEASECRAFT bus is expected to be 6,400 kg (including the initial charge of propellant).

The power and other services provided by the LEASECRAFT are dependent on the number and type of its modules. Details of how module and payload changes will be handled will depend on lessons learned from the Solar Max repair. Possibilities include the manipulation of tools by the Remote Manipulator System (RMS), spacewalking outside the Shuttle cargo bay by payload specialists, and retrieval of the LEASECRAFT by the RMS to a position in the cargo bay where payload specialists would perform the work needed.

An automated electrophoresis payload being developed by McDonnell Douglas is frequently mentioned in conjunction with the LEASECRAFT. It will consist of an electrophoretic processing facility and a separate supply module having a combined weight of some 10,000 kg. The processing unit will use 3.5 kW of power and will require an acceleration environment of less than 0.1 percent of gravity on Earth.

Another prospective payload for the LEASECRAFT system is NASA's Advanced X-Ray Astronomy Facility (AXAF). AXAF is a 9,000-kg telescope that will operate in a 500-km orbit, require 1.2 kW of power, and periodic change of imaging and spectrographic instruments.

The LEASECRAFT's ability to accommodate specific payloads is very similar to that of the high power version of EURECA (see below), with one important exception: the higher data handling ability of LEASECRAFT would allow it to accommodate most science and applications instruments. It would not accommodate some instrument projects that are very large, or those that require human involvement.

The initial LEASECRAFT reportedly will cost at least $150 million (1984$) apiece to purchase. Users may also purchase partial services of LEASECRAFT or lease an entire platform from Fairchild for $20 million to $40 million (1984$) per year. Transportation costs will include initial launch of the LEASECRAFT and its payload and other payloads that, subsequently, are taken to it for exchange.

Boeing MESA.–The Modular Experimental Platform for Science and Applications (MESA) is a low-cost satellite system designed by Boeing for launch on the Ariane. The MESA design follows from Boeing small spacecraft designs and production of the last decade. This includes three spacecraft known as S-3 for the Department of Defense, two Applications Explorer Modules (AEMs) for NASA, and the Viking Spacecraft being produced today for the Swedish Space Corp.

The MESA program utilizes existing hardware and previous experience to achieve a low-cost platform for modest payloads that do not require recovery, and for special cases that do require recovery.

An interesting feature of the MESA system in its Viking configuration is that it duplicates the Ariane structural interface on its top side, which enables it to share a launch by fitting between the Ariane and the primary payload. This use of residual launch capacity can reduce the cost of transportation to orbit.

The total mass of the MESA/Viking platform is some 500 kg. The design of the platform provides for attitude control and propulsion. Once the Viking separates from the main satellite after launch, the propulsion unit can boost the Viking into its operational orbit. The spacecraft is spin stabilized at 3 rpm, and Earth/Sun sensors and magnetic torquers are elements of the attitude control system. A combination of solar arrays and a battery provide 60 W of average power with a peak power of 120 W.

Limited changes can be made in solar array size and power output. The overall diameter of the MESA with payload cannot exceed the 2.95-meter internal diameter of the Ariane's payload compartment. The central core of the platform is designed to accommodate both platform (420 kg) and payload weights (0o kg for the design reference) and up to nearly 2,000 kg of host satellite weight during Ariane launch. The available volume for the payload is 1.6 cubic meters (m J). Should the solid-propellant rocket motor not be required, an additional internal volume of approximately 0.6 m^3 would be available for payload use.

MESA is limited in its applicability because of its small size, limited resources, the use of spin stabilization, and the intention to have the payload integrated within the structure. This makes it best suited to small, scanning or nonviewing, dedicated activities. While suited for some space plasma physics or cosmic ray investigations, the spin stabilization is not appropriate for microgravity activities. MESA will accommodate only a small fraction of the science and applications projects identified in NASA's Mission Analysis Studies.

MESA is reported to cost $10 million (1984$). Transportation charges on the Ariane are uncertain since it can share a launch with another payload. If it is carried in the Shuttle, it should qualify for the minimum charge of $12.5 million (1984$).

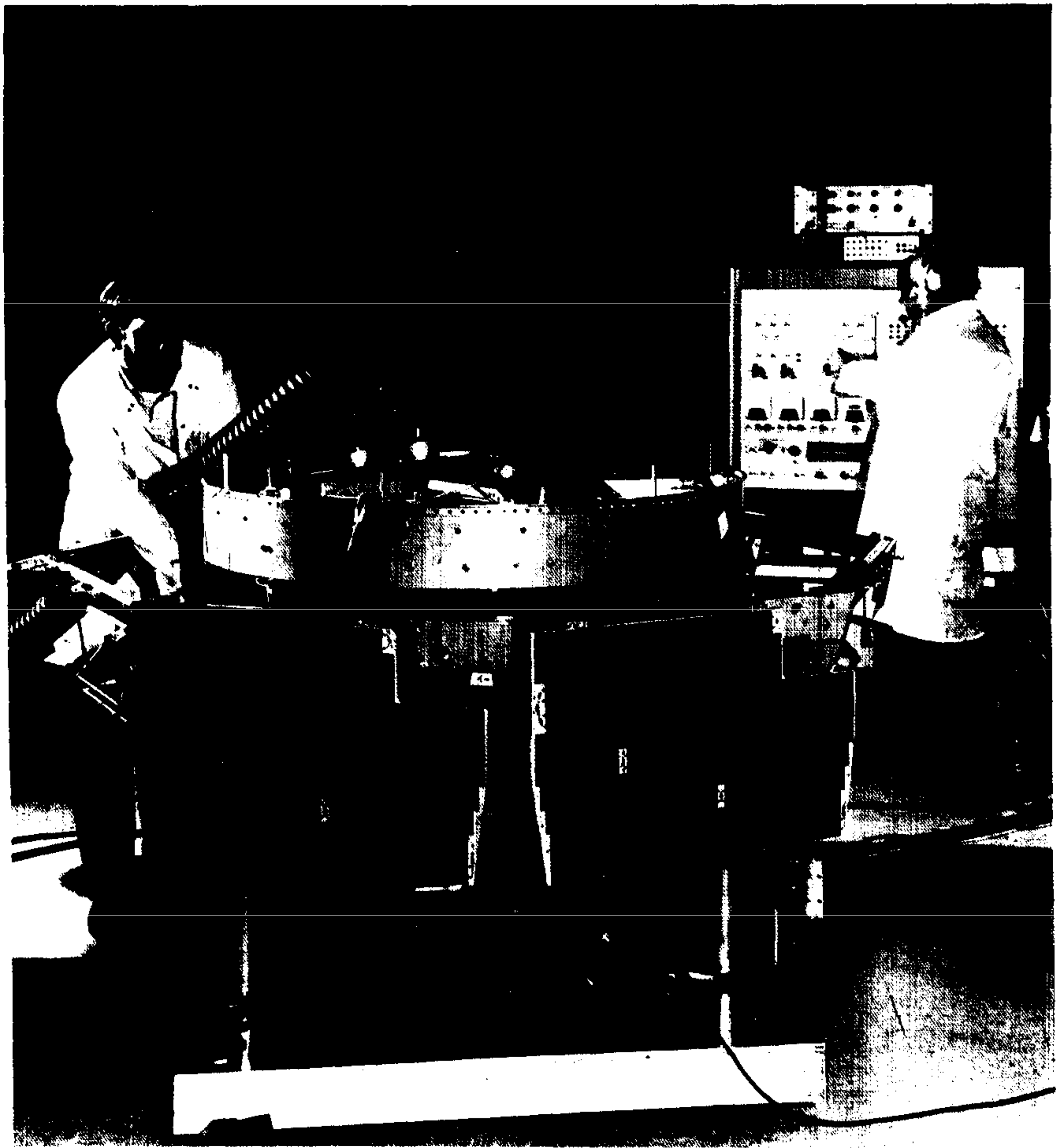


Photo credit " Boeing Aerospace Corp

The Boeing MESA spacecraft undergoing ground processing.

Shuttle Payload Support Structure (SPSS).–An example of a structure supporting payloads that remain attached within the Shuttle cargo bay is the SPSS that has been developed for NASA. Teledyne Brown expects to commercialize SPSS during 1985. It will provide a mount, electrical power, data handling, and environmental control for payloads weighing up to 1,400 kg.

Long Duration Exposure Facility (LDEF).–A platform housing 57 experiments, many of them seeking to record how manmade materials hold up in the LEO environment, was released from the Shuttle in April 1984. The 10,000 kg-satellite, called the Long Duration Exposure Facility (LDEF), will be retrieved by the Shuttle in 1985. The LDEF, basically a free-flying support structure for scientific experiments, cost $14 million (1 984$), not including launch and retrieval.

Pleiades Concept.–A concept to expand the use of platforms for space science research has been proposed by students in a 1983 systems engineering course at Stanford University. In this concept (called "pleiades"), a platform located in the Shuttle cargo bay would provide data processing and other support for several co-orbiting free flyers equipped for long-term astrophysics research. Periodic servicing would be feasible from the Shuttle. If developed, it might become a permanent space infrastructure element.

Space Industries' Platform.-A free-flying permanent industrial space facility (ISF), designed primarily for materials processing, has been proposed by a new commercial space company, Space Industries, Inc. (fig. 5). An automated platform suited for production purposes, it could be placed in LEO by the Shuttle and serviced several times a year by it and/or any eventual long-term space infrastructure. The ISF would include a pressurized volume where equipment could be serviced by a crew during resupply periods; the facility, however, would provide no life support functions when occupied other than a suitable atmosphere compatible with the Shuttle or ROTV, to which it is expected to be attached during these periods.

Assuming successful financing, the facility could be placed in operation in the late 1980s. No cost figures have been made public, but some industry sources estimate that it would cost some hundreds of millions of dollars to develop and construct.

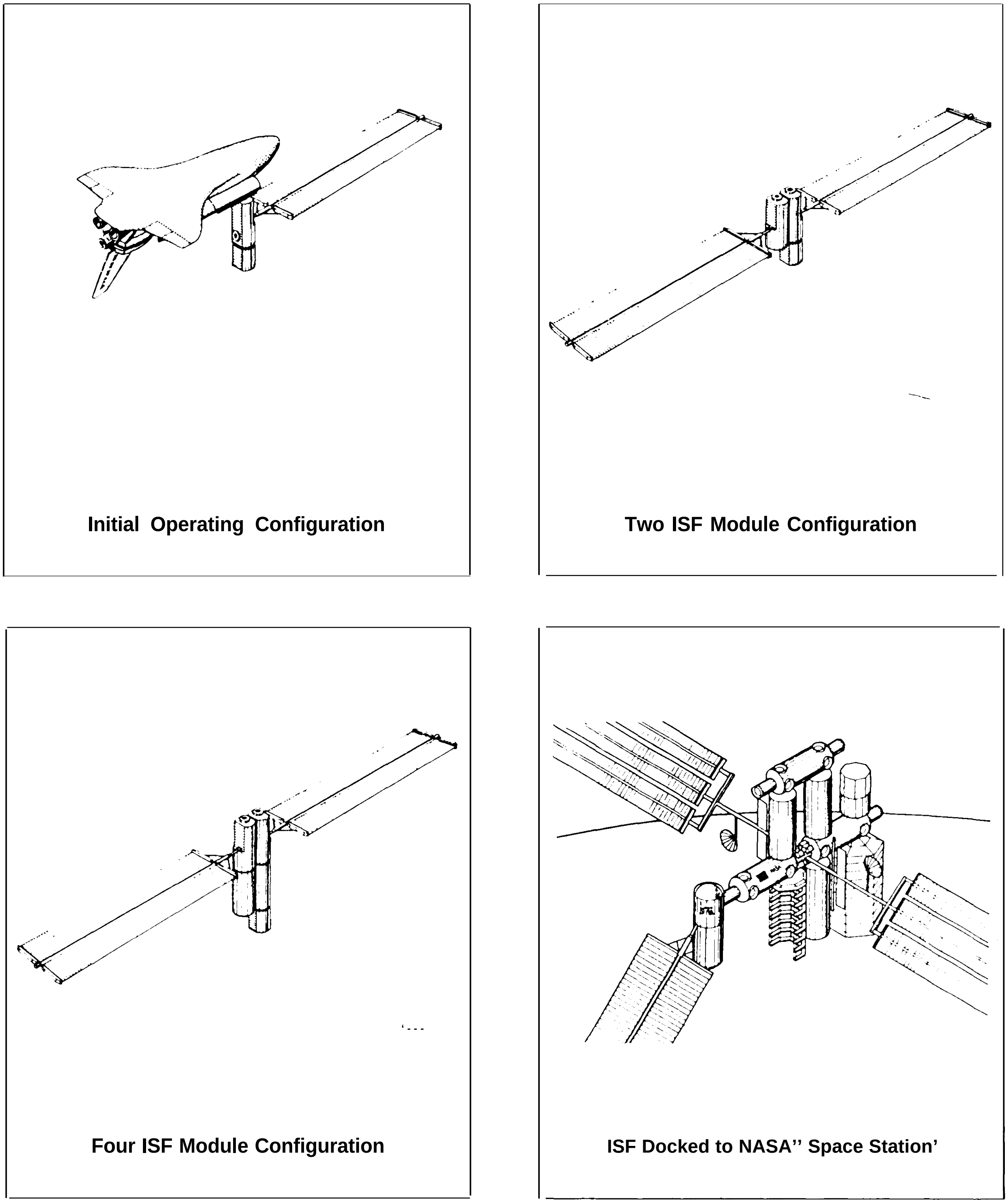
MBB SPAS.–The concept of a Shuttle-tended platform was tested, to a limited degree, with the Space Pallet Satellite (SPAS) payloads during two Shuttle flights. SPAS was developed at the initiative of the German company Messerschmitt-Bolkow-Blohm (MBB). Its structure is constructed out of graphite epoxy tubes to form a modular truss bridge that spans the Shuttle cargo bay in width and fits that length dimension for which a minimum launch charge is made by NASA. The structure provides mounting points for subsystem and experiment hardware and includes a grapple fixture for handling by the Remote Manipulator System, i.e., the Shuttle arm. The SPAS is designed to operate in either a Shuttle-attached mode or as a free-flying platform, and it was released during the seventh Shuttle flight to operate in the latter mode for about 10 hours before retrieval. In that operation it provided the first opportunity to demonstrate the Shuttle's ability both to deploy and retrieve a satellite. The SPAS payload remained in the cargo bay during the 10th Shuttle flight, where it successfully handled equipment for several commercial users.

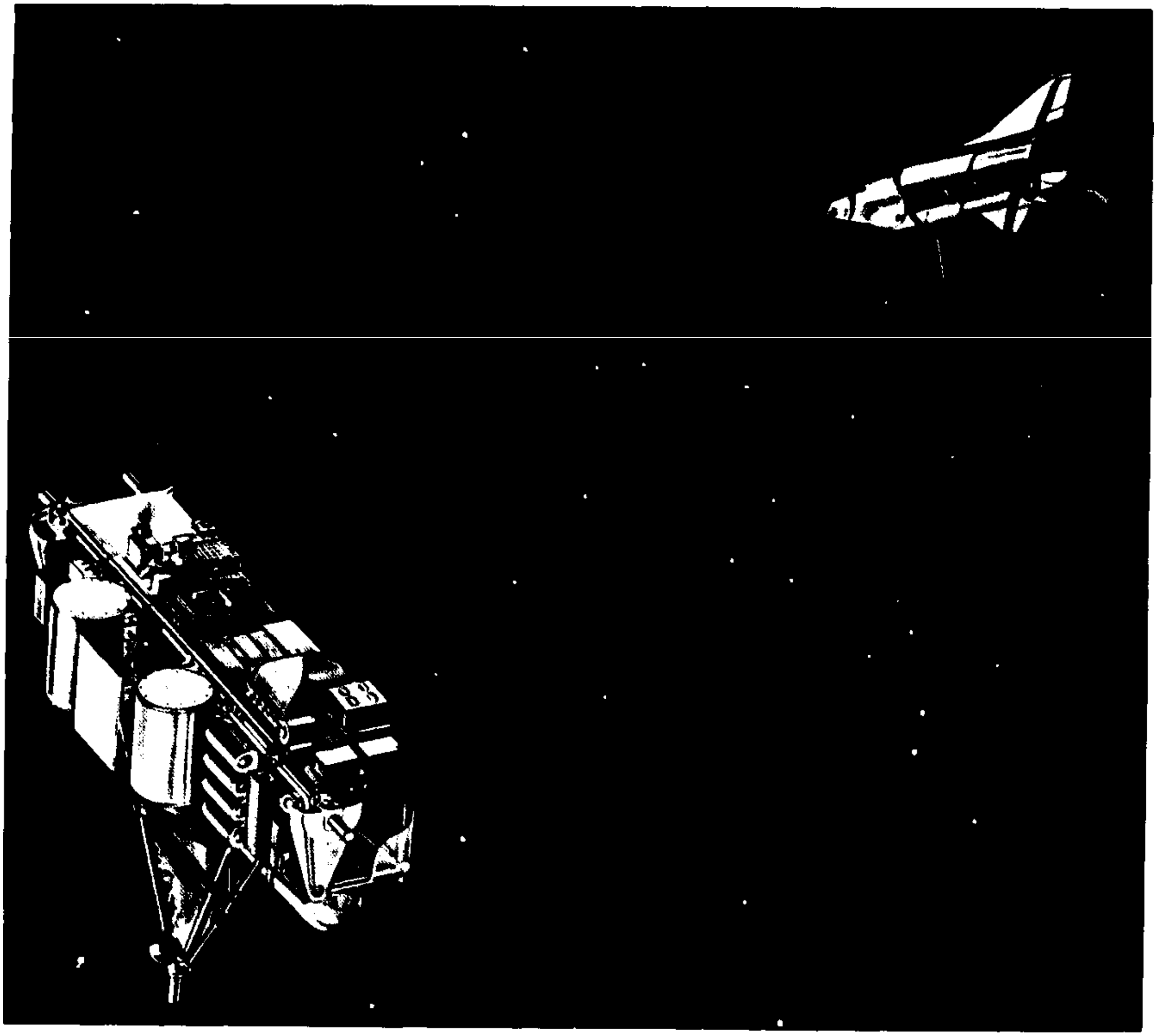
Having only battery power and compressed gas thrusters, the initial SPAS is designed for short-lifetime projects (7 to 15 days), but subsequent versions could undoubtedly extend the lifetime by incorporating solar photovoltaic arrays and propellant-type thrusters, and maybe even a kick motor to achieve a wider range of orbits and/or to be able to return to a Shuttle-compatible orbit for rendezvous. In its present form, SPAS will only accommodate relatively small, low-power instruments used for short periods of time.

The basic SPAS platforms costs less than $1 million (1984$); subsystem equipment required by specific payloads is not included. SPAS is designed to qualify for the minimum Shuttle launch charge of $12.5 million (1984$) but, with a large payload, it may exceed this qualification.

EURECA.–The European Space Agency (ESA) is developing a small unmanned platform carrier that would be released from the Shuttle and retrieved after free flights in space of 6 to 9 months.

Figure 5.—A Free-Flying Permanent Industrial Space Facility





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Shuttle. The ability to fly from the Shuttle to a useful orbit and back for rendezvous with the Shuttle is typical of most space platform concepts.

The EURECA will have a payload capacity of about 1,100 kg with the combined carrier and payload weighing approximately 3,500 kg. The total length of the carrier/platform, plus its payloads, in the Shuttle's cargo bay will be 2.3 meters, with an option for a shorter length of 1.6 meters if desired.

Energy for EURECA will be provided by deployable and retractable solar arrays that will initially deliver **5.4** kW of power at 28 volts. Of this output, 1 kW will be available to the payload on a continuous basis, while much of the balance will be required to charge the batteries that supply power when sunlight is not available.[4] The power supply for EURECA and its payload will be cooled using a fluid loop connected to a radiator.

EURECA payload and housekeeping data will be relayed to Europe via circuits employing the L-Sat communications satellite as a test. The telemetry system will normally use ground stations in Europe, but it will also be compatible with the Shuttle. The maximum data rate that can be processed on the ground by the proposed system is 2.5 kbps, although the on board system will be capable of transmitting up to 1 Mbps.

Size, mass, capacity, and data handling ability are the most stringent EURECA design constraints. If the data rate is restricted to 2.5 kbps, only film cameras can be accommodated. But if the full 1 Mbps data rate can be utilized, many science and applications instruments can be accommodated. However, large, high power, or high data rate payloads, such as telescopes, radars, lidars, multispectral scanners, or a combination of these or other instrument payloads cannot be accommodated. Increasing the available power level alone does not significantly improve the ability to accommodate such payloads, since science and applications instruments that require high power (e.g., remote sensing radars) also tend to have high data rate requirements (tens to hundreds of Mbps).

[4] **More power would be available for payload use if it proves possible to operate the platform in a Sun-synchronous dawn-dusk orbit where it does not enter the Earth's shadow.**

The cost of EURECA has not been clearly stated, although ESA has referred to a program cost of $170 million (1984$) that appears to include some payload costs.

Plans are also being developed for EURECA 11, an advanced version having increased power and payload capacity. The new design will allow space-basing and equipment exchange on-orbit, using the Shuttle or a yet-to-be-developed Ariane automatic docking system.

SOLARIS.-This French concept includes preliminary designs for an automated platform. It would be unmanned, located in LEO, and would use furnaces, a robot manipulator arm, solar power, and other subsystems. Ariane 4 would launch a transfer and supply stage, and a ballistic reentry capsule will bring processed materials back to Earth.

The first generation facility would have the following major elements:

- The Orbital Service Module (OSM), which is a user-shared platform with docking ports for payloads and transport vehicles.
- An in-orbit Transport Modular Vehicle (TMV) for resupply, transport, and servicing of space payloads.
- A Data Relay Satellite Communications System for control and high data rate transmissions.
- The Ariane *4* launcher.

The intent is to fly the OSM in a circular "Sun-synchronous" orbit following a path over the twilight line, thus avoiding the Earth's shadow and thereby achieving a relatively high 10 kW of continuous power output for its users. Activities such as materials processing, microwave Earth observation, and assembly and check-out of large vehicles in orbit are envisioned. The orbit altitude could be adjusted from 600 to 1,000 km. Two docking ports would be available for TMV berthing, with five ports for payloads. Data transmission rates would not exceed 400 Mbps. The entire OSM weight would be 4,500 kg (excluding propellant).

The function of the TMV is to provide transportation service between the Ariane delivery orbit and the OSM, and to permit the return of a lim-

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ited amount of equipment and products to Earth. The TMV will consist of an expendable module with propulsion, attitude and trajectory control, and the ability to rendezvous and dock.

The TMV can be used in either one-way or round-trip service. For one-way service the payload would be attached directly to the TMV module, and both would be placed inside the fairing of the Ariane 4 for launch. A 5,000-kg payload could be accommodated in this manner.

Round-trip service requires the use of a reentry vehicle similar to the Apollo reentry module. The TMV module is attached to the reentry body for launch in a manner similar to the arrangement for a one-way payload, and the two are separated during reentry. About 2,500 kg and 15 m^3 of payload could be accommodated within the reentry vehicle; it could touch down on either land or water and is designed for reuse.

The first generation SOLARIS concept is functionally similar to the science and applications space platform studied by NASA, except that SOLARIS specifies a dawn-dusk Sun-synchronous orbit. This orbit restricts its usefulness for many Earth-viewing projects that require lighting from the Sun. However, radars, lidars, and some microwave instruments can "see" in the dark and would not be affected, while solar-viewing instruments would gain the advantage of continuous visibility of the Sun. The ability of SOLARIS to support large, multiple instrument facilities should allow for accommodation of most of the solar physics payloads. However, a continuous full Sun orbit would be a problem for many celestial-viewing instruments that depend on Earth shadow to eliminate scattered light from the Sun. All automated life science activities and all materials processing, except for those requiring human presence, could be accommodated.

The orbit of SOLARIS is not suited to launch, retrieval, or servicing of low inclination satellites (including geostationary satellites), since a large orbit plane change is required. And, since most Sun-synchronous satellites are not in dawn-dusk orbits, a "latitude drift" would be required to service them. Some studies consider satellite assembly and service to be a major role for a "space station"; SOLARIS would be able to accommodate only a small fraction of this market.

Costs of the evolutionary SOLARIS program have not been defined, but they likely would be several billions of dollars (1984$) if the entire concept is developed.

Habitable Infrastructure

Although uninhabited platforms can be used to support many experiments and commercial processes that do not require human presence, and some activities require a stability that would be difficult to achieve if humans were present, other activities require or can be greatly aided by human presence. These include life science studies of humans in space, which are necessary to prepare for long duration human travel in space, and interactive experimentation in materials processing (e.g., pharmaceuticals, semiconductors, crystals), which is required in order to explore the commercial potential of materials processing.

A number of infrastructure elements other than the proposed NASA "space station" are available that can support humans in space.

Extended Duration Orbiter (EDO).–A major constraint on the duration of the on-orbit time for the Shuttle is the availability of electrical power. The current Shuttle power system uses three fuel cell powerplants fed by cryogenically stored hydrogen and oxygen, and delivers 21 kW on a continuous basis, of which 14 kW is allocated to the Shuttle itself and 7 kW is available for payloads. The fuel cells are fed from tank sets (one hydrogen and one oxygen tank in each set) located under the floor lining in the Shuttle cargo bay. Three tank sets are considered standard equipment. Two additional sets (for a total of five) can be installed with no volume penalty to payloads, but with a combined weight penalty (fully fueled) of 1,500 kg. The full complement of five tanks will provide a stay time of 8 days if the full 7-kW payload allocation is drawn upon continuously. Where little payload power is drawn, as might be the case for satellite repair or remote sensing activities, the stay time could be as much as 12 days.

One obvious approach to extending the stay time is to add more tank sets. One such concept results in a stay time of 15 to **22** days, again depending on power consumption, by loading a four-tank-set carrier into the cargo bay. Such a carrier would shorten the usable length of the cargo bay by some 2 meters out of 18, and result in a 3,700-kg decrease in payload capacity. Extension of this approach to even longer durations has a practical limit because of the volume and weight capacity lost, and the limited storage lifetime of cryogens.

A 20-day stay time with 7 kW of power consumed by the payload, or up to 26 days if less power is consumed, can be achieved by using a solar array in conjunction with the five standard cryogenic tank sets. In one concept, the solar array would deliver 18 kW in sunlight, and the fuel cells would deliver 3 kW makeup power for a total 21 kW. During orbital eclipse of the solar array, the fuel cells would supply the full 21 kw. The RMS could deploy the array underneath the Shuttle, to avoid interference with the power system heat radiator and the field of view from the cargo bay. A previously proposed Power Extension Package (PEP) was identical in concept but was sized to provide 15 kw, instead of the normal 7 kw to payloads. The payload weight penalty for these concepts, including tank sets, is estimated at 2,300 to 2,700 kg. The cost to modify one Shuttle was estimated to be $100 million to **$200 million (1984$).** Spacelab would have been the principal beneficiary of the PEP, but the planned flights of Spacelab were judged to be not frequent enough to justify the expenditure.

To achieve stay times well beyond 20 days requires some radical changes in the power system, but the Shuttle could be designed for essentially limitless duration as far as power is concerned. Batteries would be used for power during Shuttle eclipse, and operation of the existing fuel cells would be limited to launch, reentry, or emergencies. The fuel cell reactants would be stored at ambient temperature and high pressure, thereby eliminating the storage lifetime constraint associated with cryogens. A 48-kW solar array would be required to provide power to recharge the batteries in sunlight; this power would be in addition to the basic 21 kW needed for Shuttle and payload power. The weight penalty for such a power subsystem is estimated to be about 3,200 kg.

Modifications are required in other areas as well. Flash evaporators that are currently used to supplement radiator heat rejection require large amounts of water in some attitudes, and to minimize reliance on them it would be necessary to increase the capacity of the radiators. With regard to habitability, water tanks must be added to compensate for water that is no longer generated by fuel cells and a regenerative CO_2 system would be required. Furthermore, for 15- to 30-day durations, the Shuttle habitable volume is only adequate to marginal for a crew of four. A reconfiguration of the mid-deck, recommended for 30- to 60-day durations on orbit, includes moving the airlock to the cargo bay. A Spacelab module would also be added to provide such crew amenities as a shower and an exercise and off-duty area as well as increased work area.

Among the activities which an EDO would be expected to support is satellite servicing. The Shuttle can reach a wide range of orbit inclinations and LEO altitudes, and the cargo bay, with its RMS and space for supplies and other support equipment, seems well suited for this type of activity. The technical feasibility of repairing satellites from the Shuttle was demonstrated on the Solar Maximum Mission Satellite in April 1984. With the Shuttle launch charges alone projected to be as much as $100 million for a dedicated flight before the end of the decade, the prospect of sharing a launch for this purpose along with other payloads and/or activities is a significant factor in the economic viability of such an operation.

In theory, with on-orbit infrastructure serving as an operations and distribution center, a Shuttle destined for it could carry not only supplies and equipment for the operation at hand but could be loaded with payloads and supplies to be left in space. Subsequent transfers to free-flyers, for instance, could then be accomplished with a lighter, more energy-efficient proximity-operations vehicle in contrast to the relatively massive Shuttle. The premise is that the saving to be realized by utilizing the launch capacity of the Shuttle more effectively would, over time, more than offset the cost of the on-orbit infrastructure specifically designed to handle equipment and supplies. It is not clear to what extent the on-orbit infrastructure operations costs (both on-orbit and ground-support) are included in analyses of such operations. It is also not clear how total costs (facilities and operations) would be allocated among all users of a shared "space station" to establish the economic viability of any particular activity such as satellite repair and servicing.

Finally, an EDO could function as an observatory and a laboratory. There are adequate accommodations in the aft flight deck to control and monitor an observing payload such as one containing a large telescope. The Shuttle has no provision for laboratory operations beyond the accommodations available in the mid-deck lockers and, on some early flights, the main galley area. However, a Spacelab module, discussed in the following section, could be added to provide a shirt-sleeve working environment in the cargo bay. One drawback is that Spacelab consumes nearly half of the available 7 kW of payload power. Thus, electrical power for experiments would require careful management, and a more capable power system would be desirable for an EDO.

An EDO is estimated to cost about $2 billion (1984$) for the basic Shuttle, $300 million (1984$) for an upgraded habitation module similar to Spacelab, and $200 million (1984$) for the PEP. The full Shuttle launch cost would be incurred for each flight.

Spacelab.–The Shuttle carried Spacelab into orbit for its maiden flight in November 1983. Spacelab is a set of hardware that converts the cargo bay into a general-purpose laboratory for conducting science, applications, and technology investigations. It was financed and built jointly by ESA in close cooperation with NASA, providing a convenient means for working with a collection of experiments in a shirt-sleeve LEO laboratory environment. It augments the Shuttle services for powering, pointing, cooling, and controlling experiment hardware and for data handling and transmission to Earth.

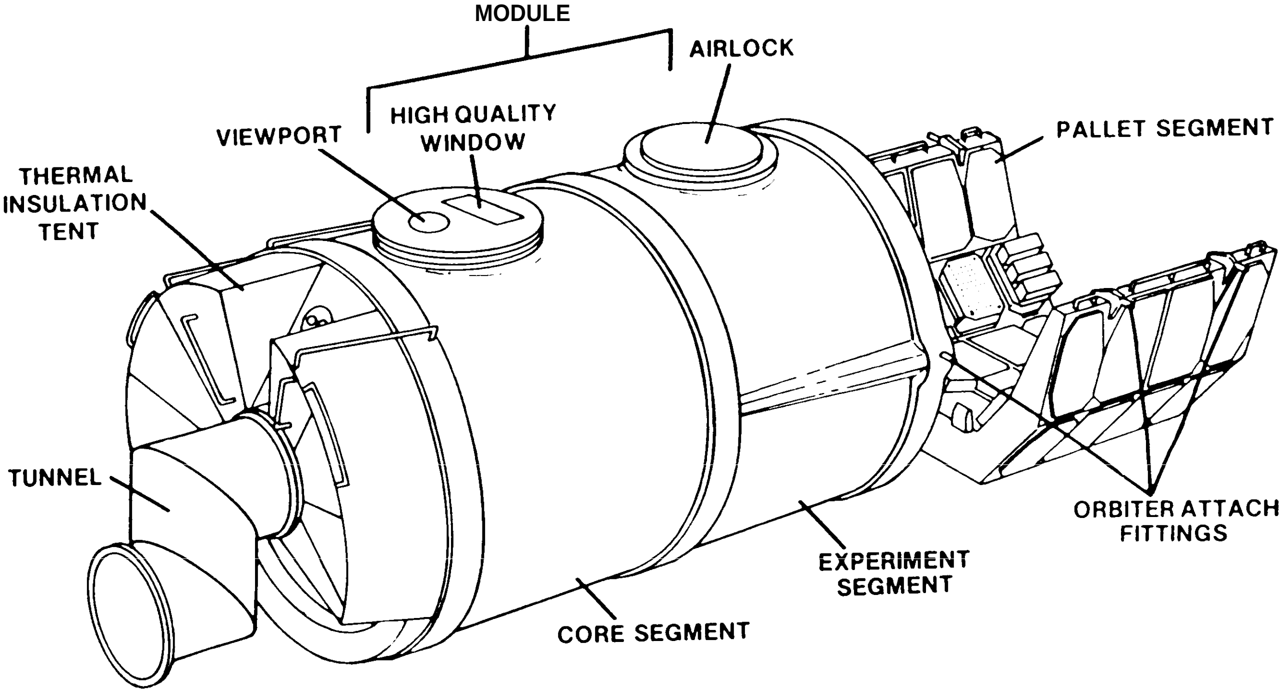
Spaceiab is composed of two primary building blocks: modules and pallets. The module is a can-like pressure vessel approximately 4 meters in diameter that provides a shirt-sleeve working environment for the crew and rack accommodations for experiment hardware. The module consists of two end cones and one or two center sections (each 2.7 meters long). It may be used in either its long form (7.0 meters) or short form (4.3 meters) and may be flown alone or in combination with one or more pallets. The pallets are U-shaped structures 3 meters long that span the cargo bay and provide mounting for instruments that are to be exposed to the space environment. pallets may be flown individually or tied together in trains. For pallet-only projects, the computers and other subsystem elements normally carried in the module are housed in an "igloo" that can be attached to the forward pallet, The Spacelab hardware set also includes an Instrument Pointing Subsystem (IPS) capable of high-accuracy pointing for clusters of small instruments or a large telescope.

While both pallets and modules can be considered for use as independent space infrastructure, in its present form Spacelab is totally dependent on the Shuttle for its resources. Specifically, the Shuttle provides 7 to 12 kW of electrical power, 8 to 12 kW of cooling, data handling and data communication at rates of up to 50 megabits per second. Further, the Shuttle provides oxygen replenishment, and serves as both a crew residence and a safe haven under emergency conditions. Spacelab depends on these resources to provide a safe, stable laboratory environment.

Several stages in the evolution of the Spacelab module beyond the current generation have been studied, moving from complete dependence on, and attachment to, outside support elements, to relatively independent operation as a free-flyer that is resupplied every 6 months or so by the Shuttle or an OMV.

Spacelab With an EDO.–One version of the Spacelab that would be carried by an EDO utilizing a PEP, was studied by ESA in collaboration with NASA, The electrical and heat rejection sys-

Figure 6.— Major Spacelab Elements



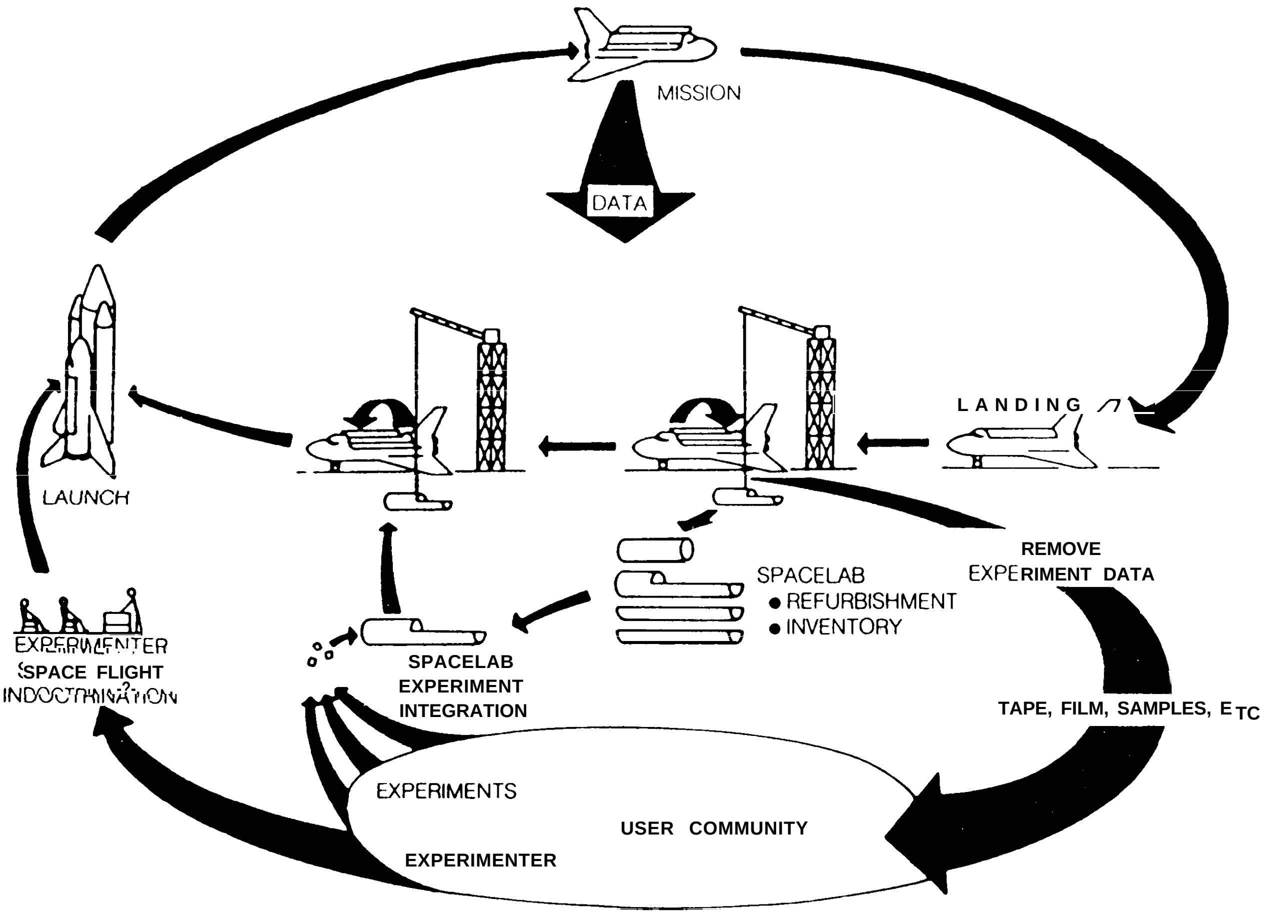
terns would be modified to handle increased power, and the command and data management system would be modernized. Since two Spacelab modules are now owned by NASA, additional costs would involve only the modifications and launch costs.

Spacelab as an Attached Module.–Another version would see the Spacelab used as a laboratory component of a "space station." The module would be lengthened to provide a greater shirt-sleeve volume for more experiments and people, but in this case other connected infrastructure elements would replace the Shuttle as a support system. Either an existing NASA Spacelab module could be used for this purpose, or an additional module could be provided at a cost of $300 million (1984$).

Spacelab as a Free-Flyer.–A third version is that of Spacelab as an inhabited free-flyer. This would require the development of a dedicated service module that would provide the types of resources currently provided by the Shuttle.

For attitude control, there are a number of possible candidate systems which could be adopted. In Europe, for example, there is the ESA Modular Attitude Control (MAC) system, which is designed for general satellite application. This subsystem is in prototype form, and hardware tests are u rider way at present. Electrical power and cooling provisions would be required, as part of the dedicated services module, in the form of solar arrays, batteries, and a heat radiator with a cooling fluid loop. It is possible that the increased-capacity (12 kW) solar arrays under development by ESA, together with the ESA radiator, would be suitable. Command and data handling could be satisfied by commercial computer technology. Oxygen supply for the free-flying Spacelab could be handled by using the nitrogen tanks that are already available in Spacelab. However, for long durations on orbit, additional provision for oxygen supply would be necessary, which might possibly take the form of a water electrolysis system (as yet undeveloped). For crew habitation, the developed Spacelab free-flying module would

Figure 7.–Shuttle-Spacelab Flight Profile



need to be based on a two-segment-long module as a minimum (7.0 meters), or preferably a three-segment-long module (1 O meters), in order to provide the necessary volume for sleeping, food preparation and consumption, waste disposal, exercise and recreational equipment, and commodity stowage. Crew-supported experiment and laboratory activities could be accommodated in a Spacelab-derived two-segment module, connected to the habitation module by an airlock; it would contain the necessary laboratory equipment and Spacelab-derived racks. The use of two modules connected via an airlock would provide the basis for a necessary safe haven in the event of a major failure in, or of, either module.

The use of two Spacelab-derived modules, combined with the associated dedicated service module, could provide long-duration infrastructure for human and automatic operations in space. An intermediate step in this direction would be the development of a two-segment Spacelab-derived module, coupled with a dedicated service module. The cost of such a development (designed for Shuttle resupply every 90 days) could be some $400 million (1984$). The two-module development costs would be considerably greater than for a one-module configuration, perhaps approaching $800 million (1984$).

To put the size of a Spacelab-derived free-flyer into perspective, it is interesting to compare the facilities described above to the Skylab facility which was orbited 10 years ago. A three-segment Spacelab module has roughly the same external dimensions as the Apollo Command and Service Module's propulsion/resource system plus reentry vehicle, that part of the Apollo transportation system that rendezvoused with Skylab. The Skylab Orbital Workshop (OWS) provided primary habitation and work space 6.7 meters in diameter by 8.2 meters long or about **280** m^3 of volume. Thus, the volumes enclosed by the two- and three-segment-long modules contain 25 and 40 percent, respectively, of the habitable volume of the OWS, and together would total just 70 percent of the OWS volume. In addition to the OWS, some Skylab control and utility functions were housed in the airlock module and the Multiple Docking Adapter. Because of the dimensions of the Shuttle cargo bay, a number of Shuttle Launches would be required to build up a Spacelab-based infrastructure on a scale equal to Skylab.

The free-flying Spacelab could accommodate any payload currently envisaged for the Space lab module on the Shuttle. Some life science facility concepts now being studied use a dedicated Spacelab module as their basic structure. All life sciences studies could probably be performed; high-temperature furnaces for material processing may require higher power and cooling that could, if necessary, be provided by additional power modules. Commercial production facilities are not yet clearly defined, but if such production proves to be desirable, additional power and Spacelab modules could be added, if necessary, to accommodate it. A small fraction of the Earth or celestial-viewing instruments could utilize the scientific airlock or window of Spacelab, but this is a cumbersome way to handle such instruments. The only advantage of the Spacelab window or scientific airlock over a permanent external mounting position is easier access to the instrument, while the disadvantages include limited space, restricted field of view, and the necessity to handle the instrument whenever it is installed. However, viewing instruments could be installed and operated on one or more co-orbiting platforms.

Spacelab could serve as an operations control center for other space activities. Properly equipped, it could accommodate 100 percent of this function, although, depending on the number of activities conducted, more than one Spacelab module might be needed. The characteristics of, and the problems associated with, exchanging equipment in the Spacelab module indicate that its best use might be as a dedicated life and/or materials science laboratory, or as an in-space control center.

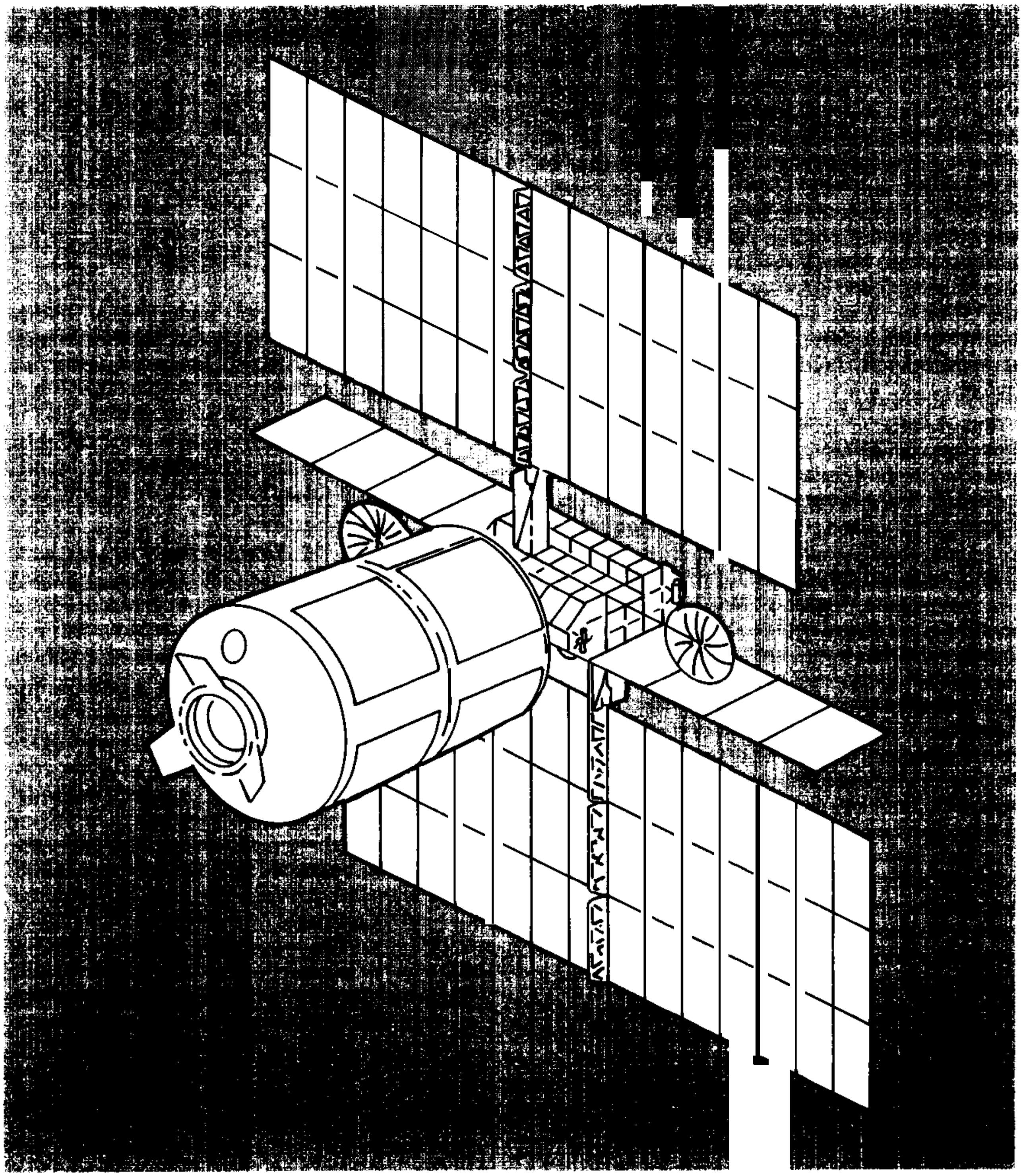
The idea of developing and using. existing Spacelab hardware for long duration human activities in space remains attractive in view of the maturity of the system building blocks. Limitations of the free-flying Spacelab concept, however, may be significant. As an example, it would be difficult to develop an efficient closed-loop life support system.

Spacelab as free-flyer, including a utilities module based on EURECA, has been estimated to cost $1 billion (1984$). Transportation costs would include an initial full Shuttle launch and subsequent supply and transport services via the Shuttle. An automatic docking service could be developed for resupply by expendable launch vehicles, but the cost of such a development is uncertain.

Columbus.–The Germans and Italians have proposed to ESA that the Columbus project, using Spacelab modules as components of a more extensive infrastructure, should become the ESA contribution to the U.S. "space station" program.

The plan, including three steps or phases, begins with a Spacelab module attached to a U.S. "space station, " providing laboratory workspace and deriving life support, power, attitude control, and other services from the parent "station. " A second step (fig. **8)** is an independent free-flying Spacelab with power, attitude control, and modest life support supplied by a service module fashioned after the EURECA platform. It would require direct resupply by the Shuttle or an OMV, provide laboratory workspace, and allow tending by a crew for up to **8** hours at a time. A third step would add another Spacelab one-segment module, with propulsion, to be used as a crew transport and servicing vehicle which might also be able to accommodate a small crew for short periods at the laboratory. By servicing the free-flyer, it would enable the Columbus module to operate autonomously for a few months at a time. This last phase is projected in Columbus program literature for possible implementation near the end

Figure 8.—An Artist's Conception of a Free-Flying Pressurized Module With an Attached Resource Module (second phase of Columbus concept)



of this century. Cost estimates for a Columbus project are not yet available.

NASA Minimum Cost "Space Station. "-A study regarding a "space station" that would minimize costs by using Spacelab modules was performed at the NASA Marshall Space Center and was reported in 1982. It would provide sound and useful infrastructure, but would be of relatively modest dimensions in comparison with NASA's present aspirations. It would include a habitat module, a separate safe haven for emergencies, and a support systems module. It would be launched by the Shuttle and would have 1 kw of power and a scientific workspace. Later, another support system module and a docking adaptor would be attached, providing for the long-term support of three persons, an experiment module, pressurized and unpressurized experiment ports, gyroscopic attitude control, communications and data handling, and 6 kw of nominal user power. According to the NASA study, the cost of this facility would be $2 billion to $2.5 billion (1984$), assuming the use of an existing Spacelab module already in the inventory.

Shuttle as permanent Infrastructure. -In the discussion of the EDO, it was shown how relatively modest changes to the existing Shuttle vehicle could result in 20- to 25-day on-orbit stay times while more extensive modifications could make 30- to 60-day stay times attainable. A concept has been proposed by one Mission Analysis Study contractor group that would have major Shuttle and its external tank assemblies carried into orbit together to form permanent infrastructure. The basic Shuttle would be stretched to add 30 feet to the cargo bay and would be utilized without the wings, tail, and thermal protection subsystem. The main engines and the OMS engines would remain in place. The crew compartment would be stripped to make room for a control module. A command module would be located in the cargo bay. Major external tank modifications would include a power module with solar arrays which would mount on the nose, and a wraparound radiator for thermal control.

The Shuttle and its external tank also would use the Shuttle solid rocket boosters for launching as is the case for the conventional Shuttle. Upon its reaching orbit, the solar arrays would be deployed, the cargo bay doors would be opened, and the command module would be rotated into an upright position, thereby freeing the cargo bay for use in servicing and staging operations. A subsequent Shuttle launch could deliver a habitability module, logistics module, and crew.

The use of a basic Shuttle in this fashion would allow the very rapid acquisition of infrastructure able to serve as a habitable "space station" for a relatively low development cost.

Shuttle External Tank (ET) .-Application of the ET as an infrastructure element is intriguing because of its large size, because it achieves a near-orbital velocity during normal Shuttle launch operations, and because it "comes free of extra cost" to orbit. As a result, several aerospace companies have studied the ET for possible use on orbit.

The ET has an interior pressurized volume of some 2,000 m^3 in the form of two separate tanks—one for hydrogen, the other for oxygen.

In present Shuttle launch operations, the ET separates from the Shuttle and reenters the atmosphere after main engine cutoff. On average, at separation from the Shuttle, the ET still contains about 4,500 kg of liquid O_2 and H_2. The challenge is to identify practical methods of salvaging the tank and scavenging these residual propellants.

The ET in orbit, initially viewed as a construction shed and distribution center, might serve as a mounting structure for telescopes, large antennas, large solar power collectors, and experiment pallets, or it could be used as a component of inhabited infrastructure, in which case it would need windows and entry hatches. The most obvious use for the ET is for on-orbit fuel storage. This requires the least on-orbit modification, but assumes that the techniques and equipment needed to scavenge leftover fuel from the Shuttle and to store it for long periods in space are

The addition of a free-flying SPAS platform, at a cost of $0.005 billion (1984$) would increase the science/applications uses by three. Other platforms such as MESA, LEASECRAFT or EURECA could also be added. For example, the use of three EURECAs, which could be purchased at a cost of $0.6 billion (1984$) or leased annually at a fraction of this cost, would increase science/applications uses by 10. (In addition, while the system as described here would not serve as an assembly/launch platform, 9 out of 10 projected solar system probes could be designed to be launched with upper stages from the Shuttle.)

In summary, a "USA Salyut" that approximates the, Soviet Salyut 7 could be assembled using essentially existing or currently under-development technology, i.e., Spacelab modules and a service module composed of EURECA or LEASECRAFT-type power and attitude controls. With the added cost of several free-flying platforms, it could support most of the science and applications experiments and about one-third of the commercial and technology development activities now described by NASA as requiring long-term space infrastructure. Among the science a@@@ it could not support are what NASA describes as the Large Deployable Reflector, Mars Sample Return, Earth Sciences Research Platform, and Experimental Geosynchronous Communications Platform. Operationally, the size, power, and port capabilities of the infrastructure would mean the pace@ research and development work would necessarily be less than half as rapid as with the NASA-proposed IOC space infrastructure. If started in 1985, it could be operational by about 1990 at a cost of roughly $2 billion (1984$).

Of course, any design aimed specifically toward current rough equivalence with the Salyut 7 may miss the mark by the time it becomes operational, because Soviet space infrastructure could be quite different by 1990. However, the general comparison of capability and cost is illuminating.

'Described in detail in the OTA Technical Memorandum *Salyut—Soviet Steps Toward Permanent Human Presence in Space,* December 1983.

developed. Use as an uninhabited warehouse or unpressurized, sheltered workshop in space only requires that the tank be purged of residual fuel, since several access openings (larger than 1 meter diameter) already exist.

A concept to use ETs as components of habitable infrastructure has been developed by the Hughes Aircraft Co. In this concept, four ETs would be taken separately into orbit and then joined to form the spokes of a large wheel-like structure. Solar panels would be mounted on a rim connected to the outer ends of the ET spokes, providing 150 kW of power. The wheel would rotate, and a "despun" module at the hub of the wheel would provide zero gravity workspace. The basic feasibility of this "dual-spin" system has been demonstrated on a much smaller scale in over 100 successful communications satellites built by Hughes. Modules attached to the outer ends of the ETs, carried into space as aft cargo carriers, would be available for habitation and pressurized workspace. Rotation of the wheel would provide artificial gravity in the spinning part of the facility and gyroscopic action for attitude control.

This innovative concept has several obvious advantages. There is no doubt that many human activities, such as eating, drinking, food preparation, showering, and dealing with human waste, would be much easier to carry on in the artificial gravity environment provided by this system. And possible health problems associated with long-term living in microgravity, such as decalcification of bones and atrophy of muscle and connective tissue, could be avoided. In general, the presence of spin and a choice of gravity regimes, ranging from microgravity to artificial gravity simulating what we are used to on Earth, should prove to be useful in solving a number of human, scientific, and engineering problems.

Figure 9.—External Tank Structure

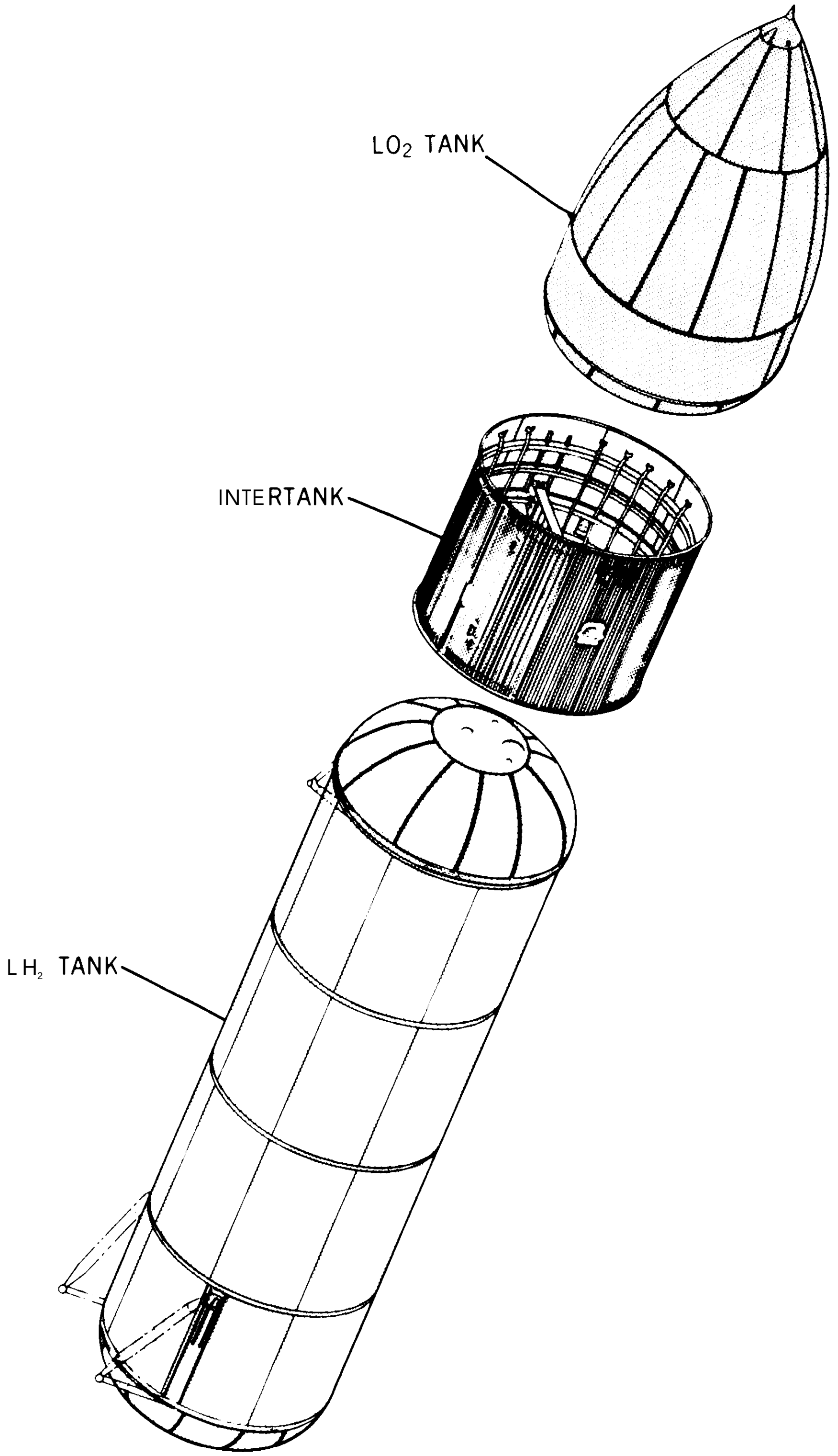


Figure IO.— Possible Uses of External Tank

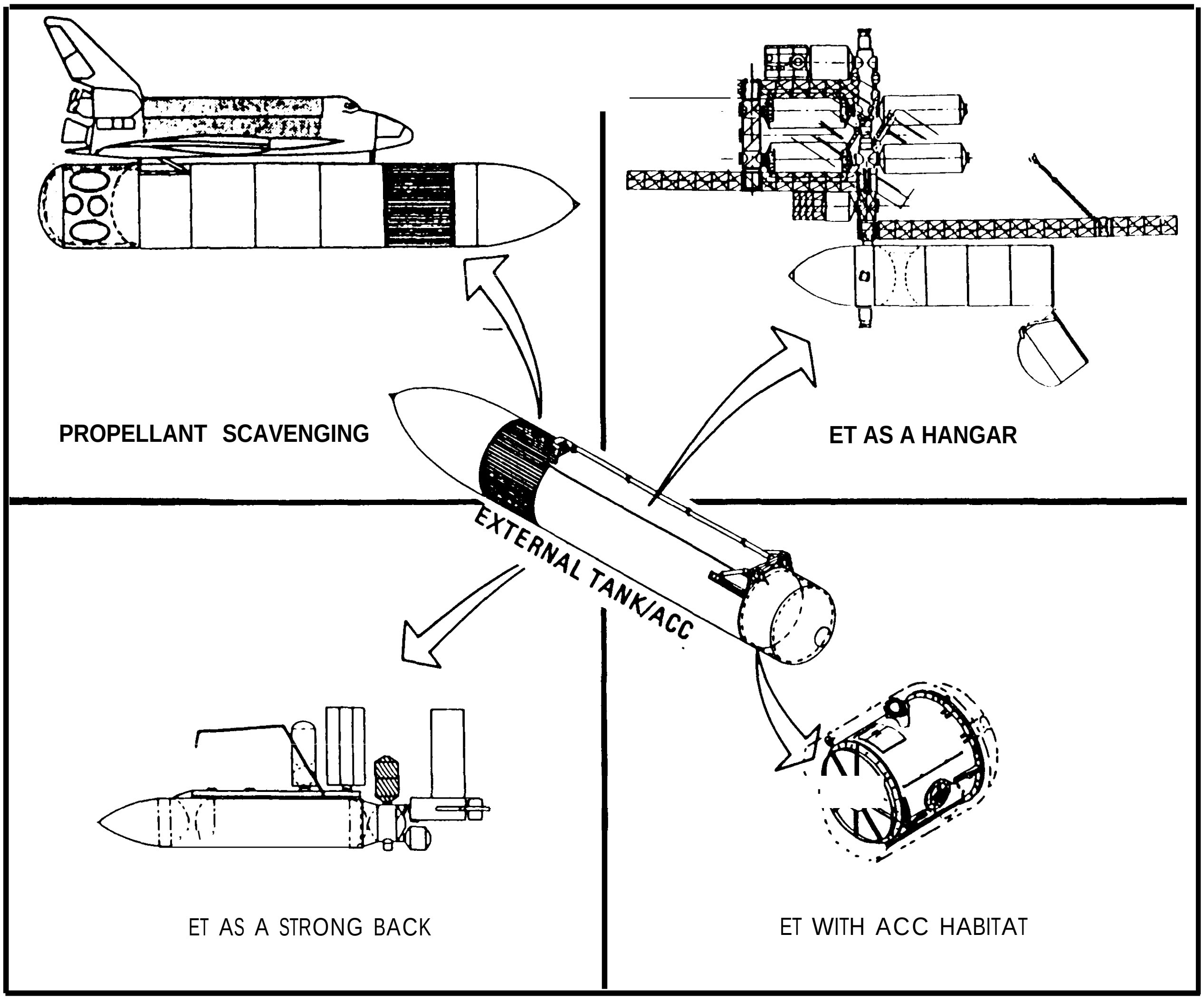


Figure 11 .—Concept of Infrastructure Utilizing Four External Tanks