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An artist's impression shows three astronauts performing Extravehicular Activity about a low Earth orbit space station.

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UTILISATION AND ECONOMICS OF A EUROPEAN LOW EARTH ORBIT SPACE PLATFORM*

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Space platforms have been proposed as an integral part of the Manned Space Station concept and represents an area where Europe could participate both as a supplier of hardware and as a user. The economic advantage of a Space Platform is seen as providing a permanent, maintainable services unit ("Resource Module") on orbit while facilitating the regular exchange of payloads. A Space Platform would have benefits for microgravity processing, technology testing, astronomy and Earth observation research. The costs of operating a Space Platform facility are compared with possible European demands in these areas and the results used to assess the benefits of European involvement in this area.

1. INTRODUCTION

The Space Station is a complex of facilities designed to extend human capabilities in Space. Besides the manned core station, these facilities are expected to include a Teleoperated Service Vehicle (TSV), a cryogenic Orbit Transfer Vehicle (OTV) and unmanned Space Platforms. The Space Platform is of particular interest to Europe following President Reagan's invitation for international participation in the Space Station programme, as it represents a potential area of participation with relatively few interfaces to the rest of the programme. Without being a "core" element, it would be an important component of the Space Station complex in which there would be substantial European User interest. The Platform provides a point for reduced space operation costs at a price Europe can afford.

A Space Platform is defined as an unmanned orbiting facility in which essential services are supplied by a common Resource Module (power, AOCS, propulsion, active thermal loop) while payloads can be attached or recovered on a temporary basis. The economic advantage of such Platforms is that the basic services for any mission do not have to be re-launched each time but form a permanent facility in orbit. The associated problems are the need to combine varying payloads on to a single Platform, and the larger initial investment required to develop, construct and launch such a Platform or Platforms.

The purpose of this paper is to examine the extent of potential interest in Europe in using such a Platform, the associated costs of development and operation, and the economic attractions to Europe of undertaking such a development as its contribution to the US Manned Space Station programme.

2. PLATFORM DESCRIPTION

Various Platform configurations have been proposed since the mid-1970's and any reference design must therefore be a somewhat arbitrary choice arising from the perceived design drivers. For the purposes of this paper the following features have been seen as important:

Extendability. The Platform shall be capable of being extended to accommodate more payloads and higher power levels than in its initial orbital build.

Serviceability. The Platform shall be capable of being serviced by facilities provided by the Manned Space Station or by visiting Space Shuttle flights or by a robot servicing vehicle.

Replaceability. All components of the Platform shall be capable of being replaced on orbit (possibly with upgraded systems) and returned to Earth without affecting continuity of operations.

Flexibility. The Platform shall be capable of accommodating a variety of potential payloads (not necessarily simultaneously) and operating in the various orbits required with minimal changes to sub-systems.

Compatability. The Platform shall be compatable with other Space Station systems and the Space Shuttle launch vehicle. From a European point of view it would be useful if it were also compatable with Ariane or future European launch and orbital infrastructure systems.

Orbits. The platform may be expected to operate in low Earth orbit similar to, and periodically revisiting, the Space Station (the "co-orbiting" case), or in polar, Sun-synchronous orbit.

In the light of these considerations, the preferred Platform is a "common backbone" configuration, in which Resource Modules and Payload Modules are plugged into a Payload Beam providing common services and docking facilities. As a reference point, the Resource Module is expected to be capable of providing 12 kW of payload power continuously to the Platform. Because of the need to provide energy storage for periods of eclipse this means that the solar array must be sized to provide a bus power of 30 kW in sunlight. Berthing points are provided at eight points along the Payload Beam (including the berthing points for the Resource and Propulsion Modules), in pairs top and bottom and at either end of the Beam. With an interval of 6.0 m between adjacent berthing points on the same side of the beam this gives adequate separation for Payload Modules and allows the positioning of astronomy payloads in particular so that blocking of the field of view by the solar arrays is minimised.

Analysis of the Resource Module systems identified the need to carry the subsystem in eight standardised Orbit Replacement Units (ORUs), to allow duplication of function

* This paper was presented at the 1984 IAF Congress in Lausanne, Switzerland, September 1984.

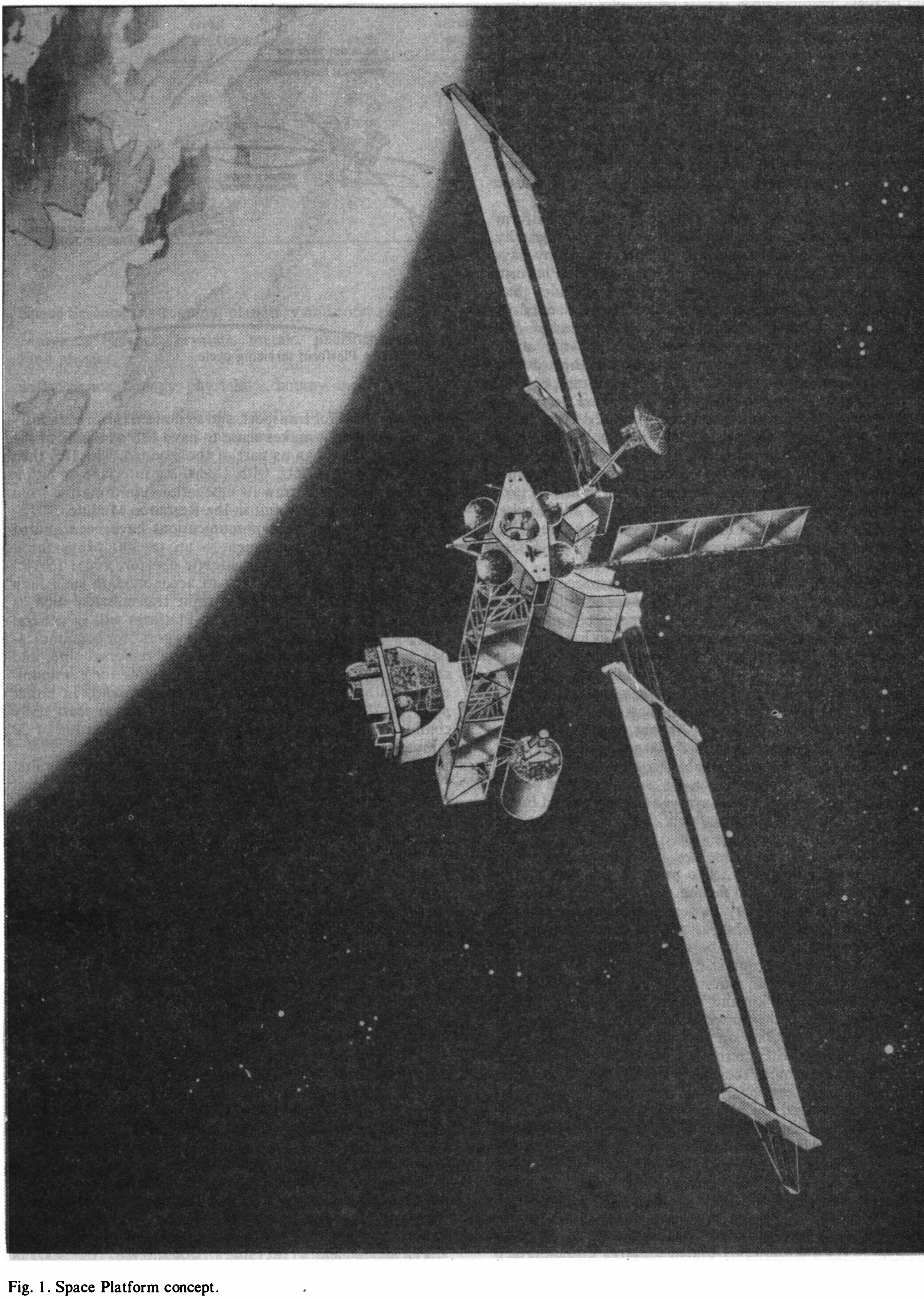

Fig. 1. Space Platform concept.

and in-space maintenance. If it is reasonable to make four of these ORUs "half-size" then it is possible to pack the complete Resource Module on to one standard Spacelab Pallet. The two solar array wings, the active thermal loop radiator and the communications antennae also form "non-standard" ORUs, but the general philosophy is to provide for the repair and replacement of all Platform sub-systems at ORU level without needing to return the complete Platform to Earth. With this configuration it is possible to launch the complete Platform (Resource Module, Propulsion Module, Beam and first Payload Module) in a single Shuttle load.

Co-orbiting with the Space Station, the Space Platform offers the advantages of achieving very low microgravity levels and low ambient contamination for astronomy payloads. To gain these advantages it appears that the Platform will often have to operate at higher orbital altitudes than the Space Station. As a consequence, differential nodal drift will separate the two orbital planes as time passes and continuous access between the two satellites will not be possible. The choice of operating altitude will therefore be set out by the need to periodically revisit the Space Station or provide an "access window" for visits from an orbital servicing vehicle based at the Space Station. If the Space Station is at 370 km, then for annual visits the Platform will have to orbit at above 660 km. Even higher altitude orbits may make it possible to visit the Platform at shorter intervals – say nine months – but too short a visit interval will take the Platform into the lower edges of the van Allen belts. Intermediate visits to the Platform may be possible using the OTV, or providing servicing directly from the Space Shuttle.

As currently configured the Platform Resource Module occupies one berthing position on the upper side of the Payload Beam and provides power, thermal cooling services and data link and communications to the other berthing points. The Platform requires an average "full load" heat-rejection capacity of 15 kW, and even allowing for some thermal storage to average out loads between sunlight and eclipse, some 4 kW of this thermal load originates within the Resource Module itself. This means that the Platform will have to be equipped with fairly large, deployable radiators, although it appears possible to mount some of the radiators on the Payload Beam. As a consequence of the deployable radiators, the solar arrays and the Payload Beam itself, the Platform will be a fairly flexible structure and care will be required over the attitude control.

The Platform has a Propulsion Module of about two tonnes propellant capacity. The primary function of this Module is to carry out orbit raising and lowering. Astronomy payloads in particular may be sensitive to local "environmental contamination" and, as a consequence, on-station attitude control is likely to be carried out using reaction wheels and magnetotorquers. Interestingly it appears that the primary propulsion required to raise and lower the Platform between 380 km and 700 km is very similar to that required for drag make-up were the Platform to remain at the less satisfactory 380 km for the same length of time. System economics will determine whether, in the long term, the Platform returns to the Space Station for servicing at the end of each operational cycle, or it is serviced and has payloads exchanged by a free-flying teleoperator service vehicle. Modularising the propulsion system makes it easier to reload the Platform with propellant and also ensures the regular exchange of the thrusters, which may represent one of the lower reliability components of the system.

Since the Platform is a multipayload facility, it appears probable that it will require internal pointing systems for astronomy and possibly Earth observation payloads along the lines of the Spacelab Instrument Pointing System (IPS). As presently designed, IPS itself occupies nearly a whole Spacelab Pallet for transport, and so if mechanism reliability can be achieved it makes sense to have IPS as a part of the Platform rather than as part of the payload. The IPS then becomes another ORU, with a berthing interface on either end. The IPS would draw its navigational information from the central navigation unit in the Resource Module.

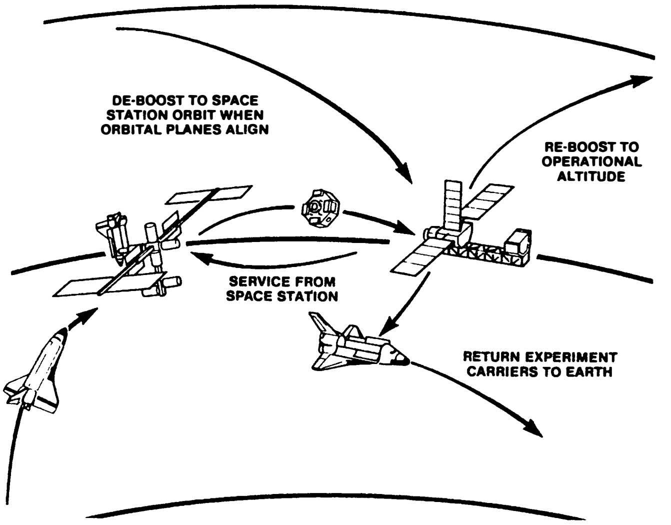

Fig. 2. Space Platform servicing cycle.

Very high data rate communications have been quoted for the Platform requirement – up to 300 Mbps for a Polar Platform carrying a synthetic aperture radar (SAR) payload. It may be necessary to accommodate such high rates *via* a short-range line-of-sight transmission such as proposed for ERS. However, the Platform will in general have a steerable antenna looking "upwards" for communication with TDRSS or a European data relay satellite, and shorter-range "downward looking" systems for communicating with the Space Station and the ground. In either polar Or 28.5° orbit the Platform will have at least daily communication opportunities with the Space Station of 20 minutes or more uninterrupted length.

As designed, the Platform can be launched with its first Payload Module on a single Shuttle flight. In 28.5° orbit the system is volume rather than mass limited, but even in Polar orbit the mass (11 tonnes) allows a single Shuttle launch. On orbit, the Beam would first be assembled or extended, and then, in sequence, the Resource Module, Propulsion Module and Payload Module attached. It appears probable that this assembly would require two RMS arms, but otherwise the whole activity can be done from the Shuttle Orbiter.

3. USERS

It has been recognised from the outset that any plans for Space Stations and Platforms must be driven by the requirements of the users. As a result, considerable efforts are being made both in the US and Europe to identify potential users, their interests and their requirements.

The European Space Agency (ESA) has so far placed two study contracts on a team that represents the interests of research establishments and industry in most of the Member States. Phase I of the user study – European Utilisation Aspects of a US Manned Space Station (abbreviated to EUA-I) – ran from September 1982 to May 1983. Phase II – European Utilization Aspects of Low Earth Orbit Space Station Elements – ran from September 1983 to July 1984.

The objective of EUA-I was to identify potential users in the following basic disciplines:

TABLE 1.Basic Facility Requirements.

Discipline	Orbit Alt (km)	Incl.	Manned Ops	Micro-g Requirement	Platform or Station Facility
Materials Science	NC	NC	Man tended	Important	Either
Life Science	NC	NC	Yes	Important	Mainly Station
Space Science	Impt	Impt	No	NC	Mainly Platform
Communications & Navigation	GEO	0°	No	NC	
Earth Observation	<650	90°	No	NC	Platform
Space Technology	NC	NC	Useful	Some Aspects	Either

Space Science: Astronomy, planetary and solar physics.

Materials Science: crystals, metals, pharmaceuticals, fluid physics.

Life Science: biology, physiology, botany, medicine.

Earth Observation: Remote sensing, meteorology, land and ocean surveys.

Communications and Navigation Space Technology: large structures, space construction, subsystem development.

EUA-II concentrated on identifying more potential users in the materials science and life science areas, as well as renewing the contacts made in the other disciplines during EUA-I.

The study identified a major problem in the mutual lack of knowledge and understanding of the needs of the non-space industry potential users, and what the space environment and space industry can offer. Considerable efforts are being made to bridge the information gap and to provide basic essential background information. This activity is recognised as an important continuing function.

Responses were received from potential users in most of the disciplines listed and it became clear that the choice of orbit height, inclination facility type (station or platform), power required, need for microgravity environment, manned activities, frequency of access etc. to meet all the user requirements posed compatability problems. Table 1 shows the results of a broad assessment of the requirements of the basic disciplines against a few principle characteristics. The table suggests that, with the exception of life sciences, most early missions of an exploratory R&D nature can be accommodated on an unmanned Platform at a nominal inclination of 28.5° and an altitude of about 650 km. In addition, the Earth Observation scientists have considerable interest in a Polar orbiting Platform. The initial reaction of space scientists to payloads mounted on a manned Space Station was not favourable, mainly due to contamination from various sources. There is also concern about the cost-effectiveness of space science carried out in this way. However, detailed considerations of the cost-effective potential of clustered payloads mounted on an unmanned "co-orbiting" platform may prove to be both an economical and affordable compromise for both space and materials science.

European space science is a mature activity that enjoys an excellent international reputation, having evolved over 30 years using balloons, sounding rockets and automatic satellites. Materials and life sciences have not had the same advantage and it is prudent to consider the need for a similar (but shorter) development route for these. In materials science "proof-of-concept" experiments can be flown in sounding rockets like Skylark, or "Get Away Specials" on the Shuttle. Some development processes will require Payload Specialist involvement, using the facilities within the pressurised module of the Space Station. But once these processes are proved it may well be more cost-effective to fly them on an unmanned Platform (which will also give a better microgravity environment) and only access them on an as-needed basis. While manned operations may be required in the development phase, the long-term aim should be to carry out space production of materials automatically on an unmanned Platform.

At present, apart from space technology experiments such as the assembly and development of large antennae, the low Earth orbiting unmanned Platform does not appear to offer much advantage directly to the space communications or navigation sector, because the principal interests are in higher orbits. However, there is a growing awareness of the need to provide in-orbit demonstrations of new sub-system technologies on technology demonstration missions, and the Platform may provide a cost-effective means of mounting such missions.

It must be emphasised that the work done so far on user identification will need considerable extension and refinement before realistic mission models can be derived. However, the cost-effectiveness of any of the proposed missions needs as careful assessment from the outset as the technical aspects. Many future missions, particularly in the material sciences, will have strong commercial implications. This again underlines the importance of economic approaches if space is to be a profitable business for both the user and supplier of space facilities.

4. ECONOMICS

It is still very early to place definitive numbers against the operating costs of a Space Platform. However, the essential justification for such a Platform is one of cost-effectiveness. In the absence of any NASA guides as to pricing policies on the Space Station or even the Space Shuttle in the Space Station era we must attempt to assess these costs *ab initio*. The assumption has been made in what follows that current (i.e. post-1986) Shuttle pricing policies will remain valid with a Shuttle launch price of 79 MAU, but that the advent of the Space Station as a "transport node" will serve to reduce retrieval costs of "standardised payload units" (Pallet and Half Pallet sized units) by allowing simple exchange of available slots in the Shuttle bay, avoiding the cost of "launching a hole" for retrieved payloads.

Initial estimates for the cost of developing the Platform described here is about 340 MAU, of which about 104 MAU is a first unit production cost. To this must be added 79 MAU for the Shuttle launch. The Platform gains over

satellite launches of recoverable free-fliers in that the services do not have to be launched each time for additional payloads. Allowances will have to be made for servcing and replacement of failed systems, however. An initial look suggests that the Platform may require the replacement of four ORUs each year, as well as regular replacement of the Propulsion Module. The value of these items and related maintenance is about 8.4 MAU per annum (excluding launch) – representing a total replacement value of the Platform over 12 years.

A first estimate of the Platform cost per payload, amortised over a lifetime of say 50 payloads, appears as follows:

~	Devpt, prod & launch amortised over 50 P/L	=	7.94 MAU
–	Propulsion: maint, replace & launch	=	1.73 MAU
–	Spares, maintenance, ORU replace & launch	=	3.19 MAU
			12.86 MAU

This is the basic "rent" of a Platform berthing port. To this must be added the cost of launch, handling and (of course) operations. To launch a Half Pallet length payload (1.5 m) by the Shuttle costs 9.5 MAU. To this we should add the cost of insurance, launch preparations, carrier rent and Space Station handling which probably add a further 4 MAU to the total. If, in addition, we had to use a Teleoperator Service Vehicle/Orbit Change Vehicle to deliver the Payload Module from the Space Station to the Platform we might acquire a further 8.5 MAU of charges. The cost of installing a "unit payload" on the Platform is therefore 26-35 MAU, depending on whether the Platform revisits the Space Station each cycle or not.

It is more difficult to make an equivalent estimate for the Space Station. Being a multifunctional facility, it is not clear how NASA will choose to divide its costs between the internal experimental facilities, the external berthing ports and astronaut availability (for instance); nor whether it will choose to amortise its development costs in the user charge. However, we have attempted to make some approximately equivalent cost estimates for the Space Station which indicated that the "rent" for a 90 day period for an external berthing position might be about 8.6 MAU, making the cost of installing a "unit payload" about 22 MAU. We would expect a relation between the rent for Space Station and Space Platform facilities, and these seem to be borne out here. The Station is cheaper for short term payloads, but becomes more expensive if the stay time exceeds about 6 months.

For comparison with these two figures, we might look at the costs of launching a recoverable "free flier" spacecraft like Eureca, or a "standardised bus" spacecraft like Solar Max on equivalent missions. Both have similar payload capabilities to a Platform Half-Pallet. The cost of preparing, launching and recovering a follow-on mission on a free-flier like Eureca, with the carrier costs being amortised over five missions, is about 54 MAU. The cost of flying a multimission spacecraft like Solar Max (launch costs plus bus costs) is about 51 MAU. The Platform therefore offers savings of 18-27 MAU per mission.

A Platform represents a substantial capital investment which must be paid for out of the savings in operational costs it engenders. If the initial investment in this instance is about 420 MAU, then the annual savings must at least exceed the loss in interest on capital – in this case (working on current European investment rates) about 36 MAU per year. To be effective, therefore, the Platform must acquire about two payloads a year. If we were to build two Platforms, one polar and one at 28.5°, the investment rises to about 600 MAU, and we must save 52 MAU per year – or the equivalent of three payloads. Throughputs of this order do not seem unreasonable.

Indeed, if the Platform was seen as a European contribution to the Space Station programme, Europe might not even have to generate this level of specific Platform business. Instead it could trade, *quid pro quo*, with the US for facilities on the main Station.

Above all, the continuing maintenance and user costs for Europe look affordable – about 52 MAU per year. As the steady-state in-service participation level for Europe in the Space Station as a whole this is entirely reasonable, and considerably better than Spacelab, where a single dedicated mission costs about 92 MAU and Europe cannot afford to keep using its own developed facility.

5. CONCLUSION

To be of interest, European participation in the US Space Station programme should provide a distinct and well-defined contribution that supports European interests, improves the cost-effectiveness of European space operations and is affordable both in development and in later operation. It is not necessary that European users should provide all the support for the contributed elements. Indeed, for effective participation it is desirable that there should be *quid pro quo* trades of user facilities between US and European components. However, the European user interest should be capable of justifying the required investment and continuing support funds implied by the technical contribution. The conclusion of this paper is that the Space Platform (or Platforms) appears to represent a cost-effective area of participation in the US Space Station programme, at a cost Europe could afford, and with a function useful both to Europe and the US.

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DEDICATED REUSABLE SPACE PLATFORMS

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This paper deals with the new concept of free-flying and reusable Shuttle platforms, describing their special features and specific applications. The first demonstration of this concept was by the SPAS-01 platform, developed by MBB as a commercial venture, launched on STS-7 in June 1983.

Reusable platforms provide specific advantages, particularly for space processing operations. A significant cost reduction over previous alternatives can be achieved, together with an extension in the operations period (several months) and improved microgravity levels. The characteristics of reusable platform generations for commercial applications are presented.

Finally, the economic and cost aspects are discussed for reusable platforms and future permanent space platforms. Comparing the results, the dedicated reusable platforms will be the logical intermediate step towards establishing a permanent platform and as a supplement to a space station.

1. THE ROLE OF REUSABLE PLATFORMS

The Space Shuttle offers (with its recovery and retrieval capabilities for LEO spacecraft) the possibility of reusable platforms – or free-flying carriers (FFC). Their rôle can be viewed in three different ways:

(1). *A New European Concept for More Economic Space Operations*

The Shuttle dedicated reusable platforms offer substantial advantages for commercial space operations; a cost reduction of up to 50% over previous expendable spacecraft is feasible. Europe has pioneered this new concept; SPAS-01 was released into space, operated successfully and returned to Earth by the STS-7 Shuttle mission in June 1983. It was relaunched in February 1984 and successfully reused.

This demonstration mission was a private commercial venture by MBB/ERNO with the German BMFT (DFVLR), ESA and NASA as customers. The SPAS approach will pave the way for wider commercial use of space, particularly for space processing.

(2) *An Intermediate Step Towards Permanent Platforms in Orbit.*

Permanent platforms for continuous commercial space processing and as space operations centres are possible. The unmanned reusable platforms could be used as development tools to test and verify platform operations in advance.

(3) *A Supplement to a Manned Space Station and Unmanned Space Platforms*

It could operate in this mode because of its inherent technical, economical and operational advantages.

Three types of dedicated, reusable platforms have been defined by MBB, depending on specific mission requirements:

- ASTRO-SPAS, an astronomical platform for free-flying telescopes
- GEO-SPAS, for commercial remote sensing missions, and

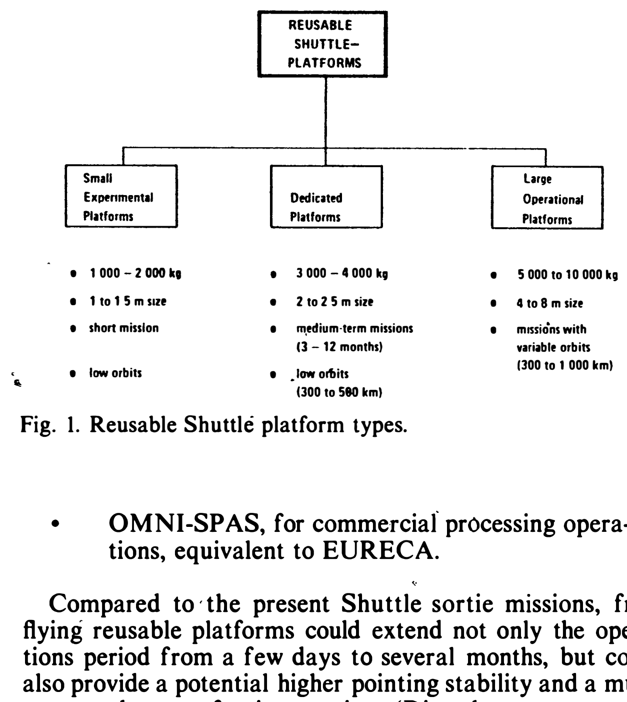

Fig. 1. Reusable Shuttle platform types.

- OMNI-SPAS, for commercial processing operations, equivalent to EURECA.

Compared to the present Shuttle sortie missions, free-flying reusable platforms could extend not only the operations period from a few days to several months, but could also provide a potential higher pointing stability and a much greater degree of microgravity. (Disturbances stemming from the Shuttle and its operations are avoided.)

2. EVOLUTION OF REUSABLE PLATFORM GENERATIONS

The step between the short duration Shuttle missions (presently seven days) using Spacelab modules and/or pallets and a permanent space platform is too large considering the development of mature long-term in-orbit processing equipment and the in-orbit infrastructure required to maintain and resupply permanent platforms. Reusable platforms such as Eureca allow (for, at most, the same cost) the return of the processing equipment after each mission to allow improvements, modifications and refurbishment to take place. This is a requirement for several years. The exchange of only the raw and processed materials between a permanent space station and Earth will be the final and the most efficient step, viewed from the transportation needs.

However, this requires a mature technology for docking and transfer operations, as well as for long-term processing

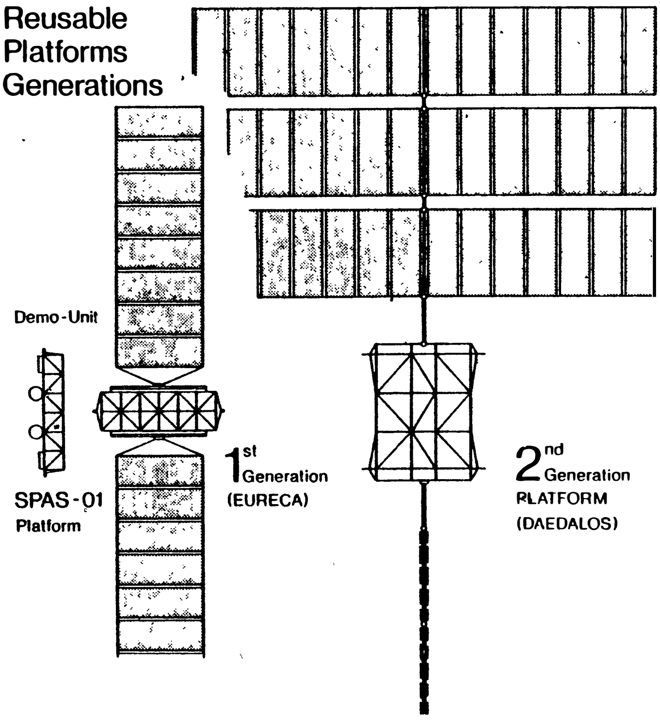

Fig. 2. Reusable platform configurations.

equipment in orbit. Otherwise, failures and expensive orbital servicing operations may ruin any commercially profitable business.

Between the present situation (small, experimental platforms deployed and retrieved during one Shuttle sortie flight) and a real space processing factory (permanent, commercial orbital platform), there seems to be a need for at least two generations of reusable Shuttle-platforms (Fig. 1).

The second generation represents dedicated reusable platforms, such as ESA's Eureca (European Reusable Carrier) built by MBB/ERNO, with a mass range of 3,000-4,000 kg. The platforms need on-board transfer propulsion systems in order to reach higher operational orbits (e.g. 500 km) and for phasing operations with the Shuttle for retrieval.

The third category of reusable platforms defined by the Shuttle's capabilities and constraints and by practical limitations (operations, transportation, assembly and test) may be in the 5,000-10,000 kg mass range. Space processing operations require relatively high power, necessitating both a large solar array (~ 15 kW in this case) and a large deployable radiator.

Practical limitations for stowage, deployment and retrieval operations will define the performance capabilities and the size of large reusable platforms.

Figure 2 illustrates the relative sizes of the three reusable platform generations:

- SPAS-01, the first demonstration unit in a short free-flying mode (few days), battery powered, no solar array,
- first generation platform with 3 to 6 kW solar array and typically a six month period (typical candidate Eureca),
- second generation platform for larger scale commercial operations and 15 kW power demand.

3. SPAS-01, THE FIRST REUSABLE SPACE PLATFORM

SPAS-01, the first reusable demonstration and experimental platform, was launched on Shuttle missions 7 and 41B. This Shuttle-optimised concept (short length, bridge-type configuration) was conceived by MBB in 1978 and studied for a variety of applications, developing as a private venture with commercial project ground rules (commercial procurement of equipment, simplification of design and quality assurance where applicable). The project was financed by MBB and from BMFT and ESA revenue for their experiments and from NASA for renting it as test article and camera platform for Shuttle approach and retrieval testing.

SPAS-01 had a total mass of 1,540 kg, making it the heaviest European spacecraft to date. The payload consisted of ten science and technology experiments weighing about 860 kg.

The subsystems are designed so that independent free-flyer operations are feasible for one to two days in the vicinity of the Shuttle Orbiter (300 km altitude, 28.5° inclination). The total SPAS-01 mission length was five days, with one day attached-mode experiment operations in the orbiter cargo bay.

The SPAS truss structure is relatively simple and inexpensive, but with a good configuration adaptability because of its modular design. The statically-determined cargo bay suspension and the CFRP struts (titanium node framework) results in a structure of high thermal stability, easy assembly and repair (without special fixtures or large tools). Excellent mounting provisions for experiments (e.g. the long Friction Pressure Loss Experiment Container) and subsystems are provided either directly by the node point grid or by standardised mounting plates at the node points.

The onboard data handling system uses the MBB-developed MODUS-concept, providing telemetry encoding, data processing, command decoding and systems control-monitoring, as well as sequencing, attitude control and check-out functions. Attitude control is performed by 12 nitrogen cold gas nozzles with a gyro package (accuracy ± 1°). The pressure vessels are commercially available bottles used in diving equipment.

For the detached mode, an S-band transmitter/receiver-antenna system is foreseen. Electrical power is provided by the Shuttle during attached operations (up to 1,750 W) and by onboard batteries (Ag O Zn; 2 x 70 Ah, about 200 W) during free flight.

4. DEDICATED REUSABLE SPACE PLATFORMS

The first generation of reusable platforms will be mission dedicated since the subsystems differ considerably for the three major mission types. For the second generation of larger reusable platforms, a standardised multimission concept will be assumed.

4.1 Material Processing Missions

Spacecraft mass for material processing missions is postulated to rise from a few tonnes to some 10 tonnes, Space processing has a high power demand (large solar arrays and radiators) but relatively low attitude control requirements (permanent Sun-pointing) as well as low data rates. ESA has decided to develop such a reusable platform, Eureca, based on a German proposal and with about 50% German participation. The prime contractor is MBB/ERNO-Bremen; other subsystems and equipment will also be provided by MBB/ERNO (the structure, the hydrazine propul-

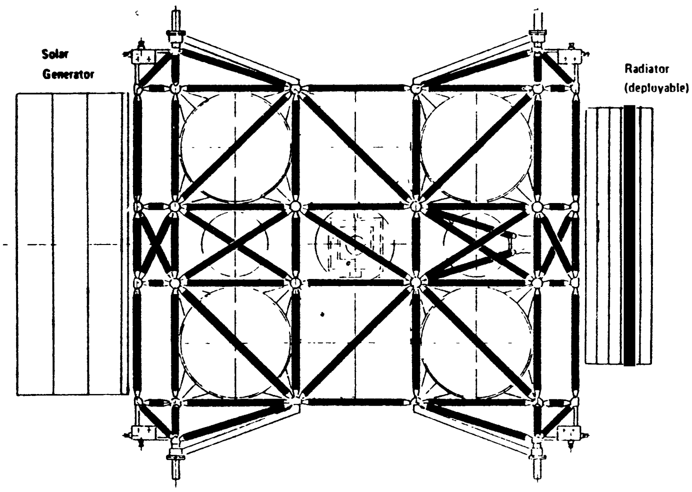

Fig. 3. Second generation platform concept.

sion system and the attitude control system). Phase B of the project was completed between July 1983 and February 1984; Phase C/D was initiated in November 1984 and the launch of Eureca 1 is planned for 1988.

Eureca 1 uses a SPAS-structure of two elements of 1.5 m total width; overall mass is 4000 kg, including some 1,000 kg of projected payload. The payload consists primarily of material processing and research facilities, such as:

- Ellipsoid Mirror Furnace
- Solution Growth Facility
- Protein Crystal Growth Facility
- Multi-Furnace Assembly
- Exobiological Radiation Assembly (ERA)

as well as other, secondary, experiments.

The solar array will provide 5 kW of electrical power, of which only 1000 W is available for the experiments. The large surplus is required for loading the batteries to be used during the eclipse periods on every revolution on the planned 28° inclination orbit. A Sun-synchronous near-polar orbit would reduce the power demand to 50% but increase the launch costs because of lower Shuttle payload capability for high inclination orbits.

While Eureca is under development by ESA under its ground rules (geographical distribution of work, etc.), and will be operated for material science investigations, a commercially-oriented platform for industrial operations can also be considered. A commercial OMNI-SPAS free-flyer has been studied with a total payload in the 4,000-5,000 kg range; the total mass would range between 8,000 kg and 9,000 kg. This is about the size required for electrophoresis operations in orbit as envisaged by McDonnell Douglas in the US.

Figure 3 illustrates the platform structure, using a larger SPAS concept, with a stowed solar array and deployable radiator.

The second generation larger reusable platform, Daedalos, will have a platform size of 4 m wide and 5-6 m length, a total mass of 8,500 kg and an electrical power level of 13 kW. This type is of the size for comparisons with a permanent space platform and associated servicing and logistic flights.

4.2 Astronomical Missions

An ASTRO-Platform applicable for a number of large telescopes has been conceived based on a double SPAS-element approach (like Eureca) with a central mounting system. It is a potential bilateral venture between BMFT and NASA, since both require a reusable low-cost facility for flying various types of telescopes under development (for example, the gas-cooled IR large telescope GIRL or an X-ray Wolter telescope).

Employing a reusable free-flying platform instead of Shuttle-based IPS sortie missions would considerably extend the observation time, besides providing other advantages such as mission independence and flexibility, pointing stability, etc. It would reduce the recurring costs compared to those of expendable (even Shuttle-based) telescope platforms. The most interesting point, however, is the mission cost-per-hour observation time:

400,000 $/h for Shuttle based sortie missions,

50,000 $/h for subsequent missions with expendable conventional Shuttle Platforms

10,000 $/h for missions with a reusable ASTRO-SPAS Platform.

4.3 Earth Observation and Remote Sensing Missions

A small reusable platform for dedicated short-term commercial remote sensing missions has been conceived under the working title of GEO-SPAS. This uses the similar single-element SPAS-structure (like SPAS-01), but has a solar generator and propulsion system for missions of three to six months. Typical payload instruments are:

- Modular Optoelectronic Multispectral Scanner (MOMS) for thematic mapping in discrete spatial bands (e.g. four channels)
- Stereo MOMS, high resolution stereoscopic terrain mapping
- Large Format Camera or Atlas Camera for photogrametic mapping, or
- SAR-System (e.g. of the SIR-A/B-type) for all-weather thematic mapping, or
- Laser/microwave altimeter for determination of along-track terrain height profiles.

Typical missions are mineral explorations, ocean monitoring and medium scale cartography.

The MBB GEO-SPAS approach employs a dedicated low-cost/short-term concept in contrast to the large long-term high-cost Earth resources research satellite projects such as Landsat or ERS-1 and 2. The reusable GEO-SPAS is Shuttle optimised and would be launched, deployed, recovered and retrieved by the Shuttle. Experimental data

TABLE 1. Reusable Platform Characteristics.

	Demo–Unit SPAS–01	1st Generation EURECA (OMNI–SPAS)	2nd Generation (DAEDALOS)
Payload	860 kg	1 300 – 1 700 kg	3 000 – 3 500 kg
Total Mass	1 540 kg	3 600 – 4 300 kg	8 000 – 9 000 kg
Power	1 kW	~ 6 kW	~ 15 kW
Length in Cargo Bay	1.4 m	2.0 – 2.5 m	5 – 6 m
Mission Period	3 days	120 days	~ 200 days
Shuttle Launch Cost	4 M $ (83) for launch 1983	12 – 15 M $ (83) for launch 1987	30 M $ (83) for launch ~ 1992
Rec. Cost (Commercial)	~ 8 M $ (actual total cost)	20 – 30 M $	40 – 50 M $

+) 14 $/gram for total payload mass	Demonstr. Mission	Reusable Platform (self-propelled)					
	SPAS-01	EURECA		OMNISPAS		DAEDALOS	
Total Mass (Kg)	1540	3600	3600	4300	4300	9000	9000
Payload Mass (Kg)	860	1300	1300	1700	1700	3500	3500
Material Share (Kg) (30 to 50%)	260	390	650	510	850	1050	1750
Electrical Power (kW)	1.75/0.2	~ 6		≤ 6		~15	
Mission Period	3 days	120 days		120 days		200 days	
Altitude (Km)	300	500		500		800	
Length in Cargo Bay (m)	1.4	2.2		2.7		5.5	
STS-Length Load Factor	0.102	0.16		0.197		0.4	
STS-Mass Load Factor	0.07	0.163		0.194		0.407	
STS-Launch Cost (M$) (price basis '83)	4 for launch'83 (39M$)	12 for launch'87 (74M$)		15 for launch'87 (74M$)		30 for launch'92 (74M$)	
Rec.(Proc.) Cost (M$) Commercial Venture	8	20	20	30	30	50	50
Amort.+ Refurb. Cost (M$) (10 reflights + 10% of Rec.C)		4	4	6	6	10	10
Total Cost (M$)	12	16	16	21	21	40	40
Material Specific Cost ($/gram)	46 +)	41	25	41	25	38	23

TABLE 2. Platform Features (Reusable).

could be transmitted *via* telemetry links or retrieved *via* tape recorder band or film cassettes.

A larger GEO-SPAS type free-flying carrier could be produced easily if, for example, a combination of optical and SAR-sensors is required.

5. ECONOMICS OF REUSABLE FREE-FLYING AND PERMANENT PLATFORMS

The main characteristics of the dedicated reusable platforms are summarised in Tables 1 and 2. SPAS-01 proved that the cost for a commercial venture could be kept at $8 M. Adding the launch cost of $4 M, the total cost per flight amounts to $12 M, or a payload specific cost of $14/gram. With a materials share of the payload of 30% the material mass specific cost was $46/gram for one flight (≤ 7 days). For larger commercial dedicated reusable platforms based on the SPAS-01/2... and Eureca experience, the procurement cost for an OMNI-SPAS platform could be kept to $30 M. Assuming ten reflights and refurbishment costs each 10% of the original outlay, the recurring costs would amount to $6 M. Adding the launch cost of $15 M, the total cost for a six month mission would be $21 M, or a payload specific cost per flight of about $12/gram. The materials share with respect to the payload mass will possibly be higher for larger units and may range between 30 and 50%, resulting in materials specific costs of $41-25/gram.

Other examples of reusable platform types are presented in Table 2, the scale effect and the effect of materials/payload ratio on the platform economics.

The main characteristics for permanent platforms are listed in Table 3, assuming that the permanent platforms will have similar dimensions and will also be launched by one Shuttle mission (for easier comparison). The platform should be resupplied every 6 months, with its processed material return to the Shuttle, and serviced and maintained every two years. The in-orbit service/maintenance and losgistics/resupply should be performed by an Orbital Manoeuvring Vehicle (OMV), for example MBB's IOTLV, (Inter-Orbit Transfer and Logistics Vehicle), also launched, deployed and retrieved by the Shuttle. Cost estimates for the OMV-type IOTLV for the mission, placement of the permanent platform in orbit, logistics resupply and maintenance are given in Table 4, ranging between $14 M and $24 M.

TABLE 3. Main Characteristics for Permanent Platforms.

- Electrical Power	≥ 15 kW
- Mission Period	10 years
- Logistics/Resupply Mission by OMV	every 0.5 years
- Maintenance/Servicing Mission by OMV	every 2 years
- Altitude of Platform	800 Km
- Altitude of STS/MSS	300/400 Km
- Platform Length in STS-Cargo Bay	5.5 m
- STS-Load Factor	0.407

TABLE 4. Cost Estimates of Assumed OMV (IOTLV Type).

(price basis '83)

Mission	Placement	Logistics	Maintenance
Recurring Cost (M$)	26	40	45
Amortization (M$) (40 reuses)	0.7	1	1.2
Refurbishment (M$) (10% of R.C.)	2.6	4	4.5
R.C. per Flight (M$)	3.3	5	5.7
STS-Launch Cost (M$)	10.7	18	18
Total Cost per Flight (M$)	14	23	24

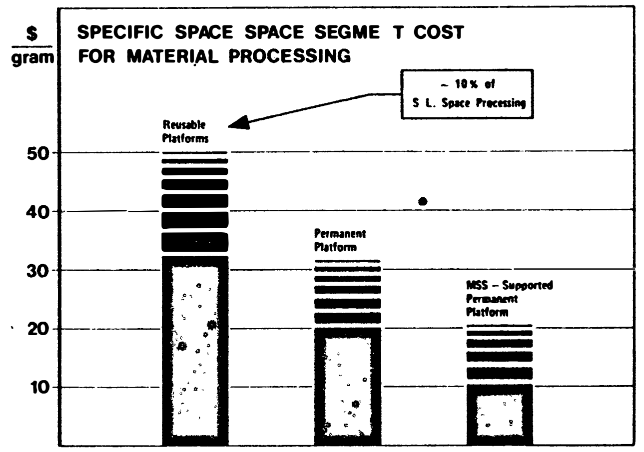

Fig. 4. Specific space segment cost for materials processing.

Table 5 presents commercially-relevant values for a comparable permanent platform. Excluding the non-recurring cost and the development cost of robotics for in-orbit servicing, the platform recurring cost was assumed again to be $50 M. In addition, five maintenance sessions during the ten years of life, each 10% costing of the procurement cost, have been assumed, together with 20 logistics resupply missions with a total value of $36 M. Total platform cost: $111 M.

The OMV must be considered in two ways: Shuttle-based and the Manned Space Station-based IOTLV. The total OMV-service would amount to $594 M in the first case and $277 M to $360 M in the second, depending on whether IOTLV-propellant could be supplied free (by Shuttle Orbital Manoeuvring Systems budgeting) or not.

The total cost for a permanent platform on a ten year mission would be $735 M (STS-based OMV) or $418 M to $501 M (MSS-based OMV). For processed materials of 20 x (1,050-1,750 kg), the payload mass specific cost would amount to $6-9/gram and the material share mass specific cost to $21-35/gram (STS-based OMV) and to $12-23/gram (MSS-based OMV).

6. CONCLUSIONS

Dedicated reusable platforms can be justified in two ways:

1. they will be a logical step between
   - expendable free-flying carriers and permanent platforms
   - short-term Shuttle-sortie missions and permanent platforms

   for many experimental, pre-operational and operational missions of medium duration in materials processing, life sciences, remote sensing, astronomy, etc.

2. as illustrated in Fig. 4 the specific space segment cost for materials processing using dedicated reusable platforms (ranging between $25 and $50/gram) will amount only to about 10% of Spacelab processing specific costs and will be a factor of three to four cheaper with respect to

The introduction of permanent platforms could further reduce specific costs by a factor of 1.5-2.5 ($12-14/gram) depending on the type of OMV. The permanent platforms require, however, a larger investment (development cost and investment for installations of in-orbit infrastructure) and longer to reach operational status. Reusable dedicated platforms are thus an intermediate step towards permanent platforms in space processing and supplementary elements to a space station in Earth observation and astronomy. The inherent features of retrieval and reusability mean a substantial reduction in space operations costs. Reusable platforms will therefore be an important tool for commercial space operations.

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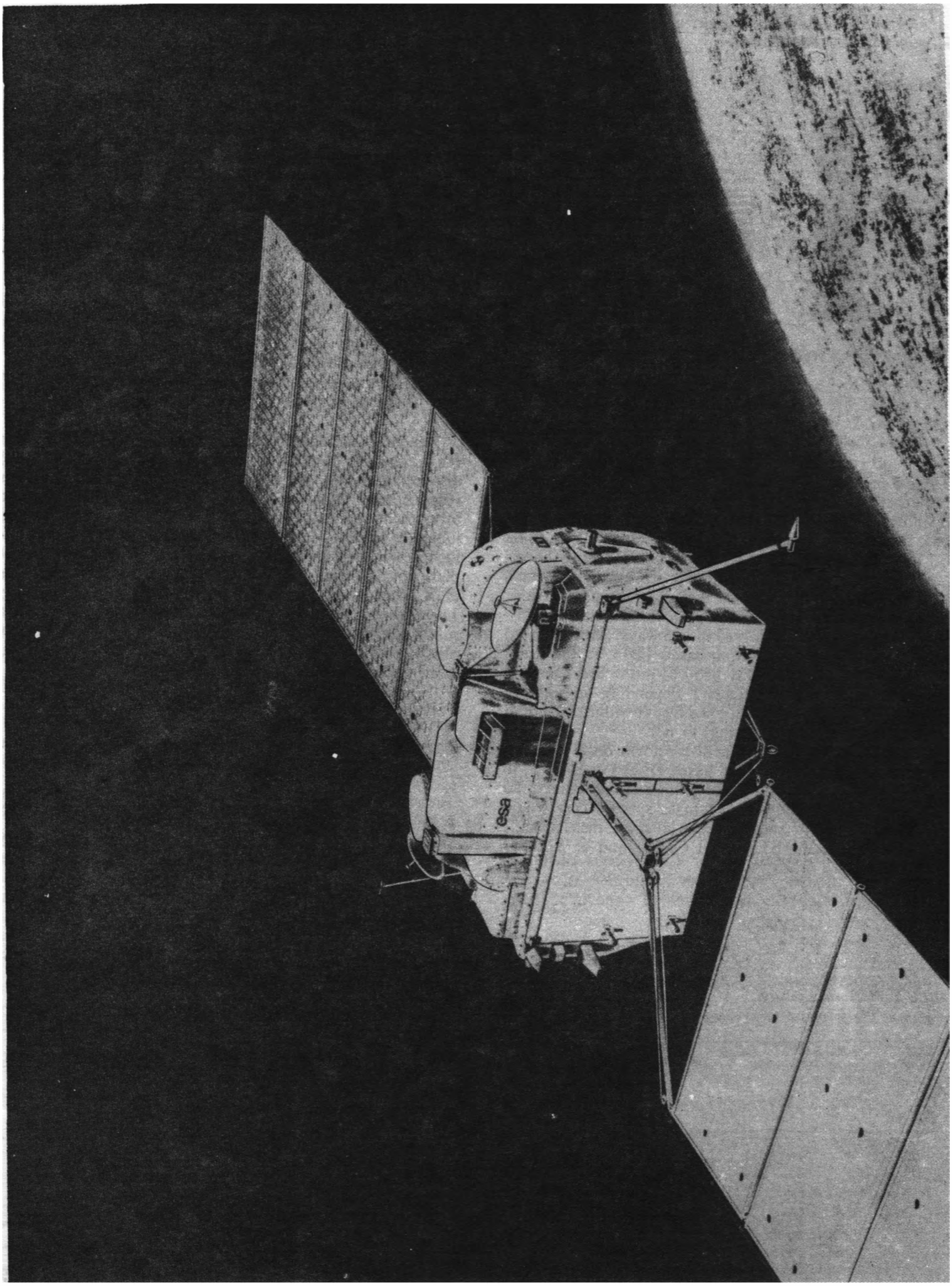
Presented at the 18th European Space Symposium, BIS, London, June 1983.

TABLE 5. Platform Features (Permanent Platforms).

	Permanent Platform (+ OMV)					
	STS-Based		MSS-Based			
Total Mass (Kg)	9000		9000			
Payload Mass (Kg)	4000		4000			
Material Share (Kg) (30 to 50%) per 180 days	1050	1750	1050	1750		
Platform STS-Launch	30		30			
Cost (M$) (price basis '83)	for launch '95 (74 M$)		for launch in 2000 (74 M$)			
OMV-Cost-Share + Launch (M$)	594		143			
1 x Transportation	14		14			
20 x Logistics/Resupply	460		100			
5 x Maintenance	120		29			
Platform Cost (M$) (Comm.Vent.)	111		111			
Platform Recurring Cost (M$)	50		50			
Platform Resupply (M$)						
Cost (20 x 0.1 x 18 M$)	36		36			
Platform Maintenance (M$)						
Cost (5 x 0.1 x 50 M$)	25		25			
STS-Transport Cost (M$) for Logistics/Maintenance Goods	—		incld. OMV Prop. 217	w/o OMV Prop. 134	incld. OMV-Prop. 217	w/o OMV Prop. 134
Total Cost (M$)	735		501	418	501	418
Material Specific Cost ($/gram)	35	21	23	20	14	12



Eureca, the first dedicated reusable space platform.

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SPACE STATION USERS

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Following the many successful ventures in manned space flight achieved by the US using the Apollo programme, the Shuttle and more recently Spacelab, the way is now becoming clear for the next major thrust – the Manned Space Station. The USSR, through Soyuz and Salyut, may be expected to achieve a similar goal. It is the continuing success of the Shuttle that has encouraged the initiation of the Manned Space Station Programme (MSS) as the next major goal for NASA and others who may join the programme.

The Initial Operational Capability (IOC) is planned for 1992 but it is recognised as most important that potential users of the facility are identified as soon as possible so that their requirements are properly considered in the design evolution. These users will almost certainly include many aspects of non-space technology industry as well as the traditional space user community. This paper gives a short description of the various disciplines of space science, material science, life science, Earth observation, communications and navigation and space technology. This review describes some of the relevant key features of the space environment, particularly microgravity, the capabilities of man, and how they may be exploited on the MSS.

The paper concludes with a description of the related studies being carried out on behalf of the European Space Agency and identifies the approach and some of the difficulties experienced in this new area of space involvement. It concludes that there are significant difficulties in identifying potential users and that strong efforts must be made in matters of mutual education. However, although this new era of space industrialisation is just beginning it is felt that there are significant commercial benefits to be gained, particularly in the fields of material science and processing. An enormous amount of work and investment will be necessary to see the programme come to fruition.

1. INTRODUCTION

The success of the Shuttle has encouraged the initiation in the United States of the development of the Manned Space Station (MSS) as the next major goal for NASA and others who may join the programme.

This paper broadly reviews the uses to which such a station can be put and to indicate who might be the potential users of such an advanced versatile facility and how they can be identified.

NASA are considering an Initial Operational Capability (IOC) for the basic station to start in 1992 at the earliest. Thus, potential users are being asked to project their plans and ideas a long way ahead without knowing the technology that will be available at that time. This task is particularly difficult for those potential users who have had little or no previous contact with space activities.

2. WHAT IS A SPACE STATION?

Space station studies have been going on for a long time in both NASA and US industry, USSR and, to a limited extent, in Europe. As yet, it has not been policy to define a fixed concept. Many schemes have been suggested and the possibilities seem endless, even with the constraint that all elements or parts thereof must be capable of being carried into low Earth orbit (LEO) using the existing Shuttle fleet.

The MSS can be considered as a permanent orbiting facility at 700 km nominal altitude and 28.5° inclination, having a crew of between 6 and 12 people who will stay in orbit for 90 days before being returned to Earth by Shuttle. The crew will comprise a small number of actual astronauts who are responsible for the flight operations of the station, together with a larger number of mission and payload specialists who are responsible for the operation of the various payloads. These specialists need not have the fitness standards and flight experience of astronauts but will be highly trained, reasonably fit scientists, engineers and technicians from a wide range of scientific and technical disciplines. These categories are already flying in the current Shuttle programme and on Spacelab.

It is important to understand that the current definition of a space station is not a single facility but a number of facilities which are all related to the core station. The facilities will probably comprise:

- The main core station with crew habitation capabilities
- Unmanned platforms co-orbiting with the core station
- Unmanned platforms in polar orbit
- Unmanned platforms tethered to the core station
- Manned manoeuvring units for local activities (MMU)
- Teleoperated manoeuvring systems (TMS)
- Orbital transfer vehicles (OTV) used with the core station as a transport node

There can be several combinations of these elements giving a large number of options but for the purposes of this paper the facilities considered will be limited to those principal items shown above.

Although no single concept has been chosen, a major study effort has been made in space station architecture. This is a new approach to design but on reflection it is the logical one because the MSS must not only provide working facilities but must also provide comfortable long-term living accommodation with additional facilities for rest, leisure and hygiene. These are factors that are taken into account by architects designing factories and homes on Earth.

3. WHO ARE THE POTENTIAL USERS?

Perhaps the simplest way to identify potential users of an MSS is to review a number of classical disciplines and to assess the relevance or otherwise of the space station to those disciplines. Those considered are:

- Space science
- Materials science and applications
- Life science and applications
- Earth observation
- Communications and navigation
- Space technology

3.1 Space Science

With the exception of materials science and life science the potential users of an MSS are reasonably easy to identify and contact because of previous involvement in space activities. However, this does not imply that the MSS is of immediate interest to them. The use of an MSS requires a quite different approach from that associated with unmanned automatic satellites. The main environmental characteristics of an MSS are microgravity and hard vacuum but these are of little significance to either the astrophysicist or the solar physicist. For space science the main features required of the carrier vehicle, be it either unmanned automatic satellites or MSS, are a highly stable observing platform with an extensive sky coverage and a minimum of instrument contamination. This contamination can be, for example, due to chemical, magnetic or electrical sources, each of which may be found more on an MSS that an unmanned satellite. Some of these sources of contamination and the associated effects are as follows:

	Problems
Contamination by water vapour, carbon dioxide, solid particle outgassing	
– column density (Mol cm^{-2})	– deposits;
– back flow (Mol cm^{-2} Sr^{-1})	– absorption;
– glow (W cm^{-2} Sr^{-1} m^{-1})	– emission.
Pointing disturbances	
– crew motion, control motion (arc sec)	– loss of spectral and spatial information.
– vibration, acceleration	
Thermal control/stray light	
– temperature stability of telescopes	– alignment;
– shielding against Earth/Sun	– focus and background.
Highly energetic particles	
– fluxes (proton, neutron, electron, γ)	– noise;
– dependence on altitude, inclination and solar cycle	– spikes; variation of responsivity.

Space science is a mature activity that has been learnt from 30 years of experience using balloons, sounding rockets and unmanned satellites. Because of this long background there has been a continuing interest. In fact, there are enough proposed space science missions to last to the end of this century, based mainly on the use of conventional satellites. It would be an interesting exercise to test these missions against candidate transport systems. Because of the mature state of space science it may be deduced that there is not a strong case for an MSS in near or medium term activities. However, later programmes requiring the use of very large instruments may well use the MSS. The following suggestions have been made for MSS applications to space science missions:

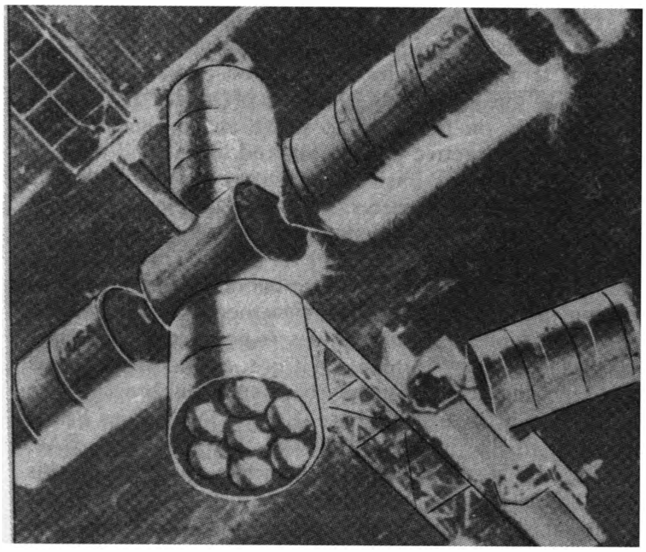
- tethered platforms help to overcome problems of contamination and stabilisation
- polar Sun-synchronous orbits giving better sky survey
- highly eccentric orbits to give further sky coverage, avoidance of stray light and radiation belts
- use of a transfer vehicle between the MSS and free-flying platforms on different orbits
- manned astrophysical observatory
- deployment and alignment of large antennae and interferometers
- provision of pointing systems for large telescopes (dia ~ 10 m, mass ~ 3T)
- recycling and refilling of cryogenic facilities
- coating of astronomical mirrors, avoidance of oxydising atmosphere

This list is not exhaustive and clearly poses many additional problems of space technology. If these questions can be satisfactorily answered then it may be expected that the space scientists will give serious consideration to the MSS for future missions.

3.2 Materials Science

It is expected that materials science will be a major user of the MSS facilities, mainly due to the availability of a continuous microgravity environment. The MSS can be used in both the R&D role and as a space manufacturing facility. It is worth noting that for many years materials science experiments have been carried out using sounding rocket flights such as Skylark, which can give about eight minutes' experience of microgravity. Although this time is short, it has enabled a considerable amount of fundamental work to be done and the proof-of-concept of more elaborate experiments to be demonstrated. The main users will be in the fields of metallurgy, crystals and semi-conductors, pharmaceuticals and bio-processing. Experiments have been flown aboard several Shuttle flights, as well as Spacelab, that have demonstrated the value of having man in the loop where his unique tactile skills, subjective observation, judgement and reaction to the unexpected have proved invaluable. There should be no question of carrying out experiments in space or processes which do not require the unique characteristics of space. Several potential users have expressed the view that their interest in space would be to obtain a better understanding of processes being carried out on Earth and thus lead to a better product. There is also an interest in producing materials which are impossible to produce in a normal gravity environment.

Microgravity has the greatest significance in processes that involve very tightly controlled separation as, for example, in drug refinement. Gravity causes sedimentation of varying density components in a fluid and also convection which is a further bar to precise separation or mixing. If these two effects can be eliminated then very high purity materials and fault-free crystals can be produced. A number of the separation teachniques, such as electrophoresis and



A concept for an LEO Space Station.

TRW

electro-osmosis, have been used for a long time in terrestrial laboratories but the production rate and quality of the samples was relatively low. For example, the use of continuous flow electrphoresis in a microgravity environment gives yeilds of more than 700 times and a purity four times better. Thus, potential users may be summarised as those who require:

- access to a space laboratory to produce unique materials or to carry out fundamental R&D work which is impossible on Earth
- abilty to produce super pure materials in practical amounts for tests on Earth, including reference standards
- the use of man to develop processes which can be carried out automatically on unmanned platforms but man-tended from the MSS.

The products envisaged have a very high specific value and are part of a very competitive international market; therefore, there are many aspects to be considered other than the purely technical. These include typically proprietary rights, security, ownership, operating availability and tariff and crew involvement. The long-term view is that such materials processing should be carried out completely automatically once all the facilities have been tested and demonstrated by man.

3.3 Life Sciences

The MSS can provide a unique facility for workers in the specialised fields of life sciences such as:

- Space medicine and physiology
- human and animal biology
- radiation biology
- gravitation biology
- exobiology
- psychology

A full study and understanding of these topics is necessary to ensure safe conditions for the whole MSS crew, including mission and payload specialists. These conditions include personal health, hygiene, rest and leisure as well as helping to provide proper working facilities. Psychological aspects are important because crew members are living and working in close proximity in a novel environment for long periods of time. Crew compatibility is essential.

Life scientists have a strong interest in a number of material science aspects, such as the presentation of exotic materials and the links with biochemistry. The users will be scientists rather than industrial companies as they see the MSS as an excellent vehicle with a crew that can also participate as subjects. This approach has been used on most Shuttle flights and Spacelab. The orbit and its inclination are not critical.

3.4 Earth Observation

Earth observation is concerned with the studying and monitoring of dynamic processes of the atmosphere, oceans and land from space. This study requires continuous global coverage which is best performed by a combination of geostationary and polar orbiting satellites. At present the MSS reference orbit only gives a limited coverage capability, the inclination being a critical limitation. The MSS can be used to provide a base for launching instrument-carrying platforms into polar orbits, although there are difficult technical problems with propulsion and fuel.

These platforms should be available in modular form to vary their size and orbit and should be recoverable. One large platform does not offer sufficient flexibility. The platform requirements can be summarised as:

- large and small types, Earth pointing 3-axis stabilised
- orbits to be both Sun-synchronous and non Sun-synchronous
- mission duration of one year
- recovery is desirable
- high data rate ~ 300 Mb/sec with onboard processing
- altitude 300-1,000 km
- a geostationary platform would be useful at some future date

These aspects should be considered when thoughts are being given to more advanced Earth observation projects beyond ERS-1. The users are essentially the same as those already involved because Earth observations and remote sensing is becoming an established service as well as a continuing science.

3.5 Communications and Navigation

The MSS in low orbit and 28.5° inclination does not offer direct benefit to users of communications and navigation services. It does offer considerable indirect benefits to those users when used as a transport node to achieve geostationary orbits by means of an orbit transfer vehicle (OTV) launched from the MSS. The cost benefit studies undertaken by some US companies have shown significant advantages of this method of achieving GEO.

Another significant application of the MSS is the ability to assemble very large antennae in LEO prior to moving them to GEO by means of the OTV. The MSS can offer a good base for development and test of large lightweight

structures which would not be possible on Earth. The ability to repair or refurbish large communications satellites has been suggested but at present there are a large number of technology problems to be solved as well as economic trade-off to be done before this activity is commenced. The successful retrieval, repair and relaunch of the Solar Max mission by the Shuttle in April 1984 has demonstrated that this capability is now reality.

The potential users of the MSS in this field are mainly the same as those already involved in the design and operation of communications systems, including satellites. This is now becoming a mature, established commercial business and will react only if positive cost-effective advantages can be clearly demonstrated for the MSS.

3.6 Space Technology

The MSS offers considerable opportunities for those involved in spacecraft design, manufacture and operation. So far, all vehicles designed to operate in space can be tested only on Earth which implies attempting to compensate for gravity and atmospheric effects. These simulations are never entirely satisfactory because it is virtually impossible to simulate microgravity, vacuum, thermal cycles and radiation in the correct time phasing over extended periods. The MSS can provide a base for testing a wide range of components and assemblies in their correct working environment. Some examples are:

- deployment and retraction of large solar arrays
- dynamic behaviour of large structures
- reaction control system thruster performance *in vacuo*
- long term exposure of materials to thermal and radiation environment
- antenna pattern measurements
- instrument calibration including sensors
- rendezvous and docking technology
- satellite deployment, retrieval and repair

The potential users of the MSS in this way are all of the major aerospace contractors, including component and materials suppliers. This work could be carried out on a co-orbiting unmanned platform but man-tended from the MSS.

4. HOW ARE POTENTIAL USERS BEING CONTACTED?

Making contact with existing users of space facilities such as space scientists, communications companies, Earth observation organisations and space companies themselves was reasonably straightforward. However, the difficulties became apparent when attempting to contact organisations and companies outside of the broad space community. The gap between the space community and those potential users of MSS was very large and understandably so. They did not understand what could or could not be done in space and the converse was generally true of the space community who, for example, have little real idea of the nature, say, the pharmaceutical and bio-processing industry, exotic metallurgy and crystal production. Thus, it has been necessary to initiate a lengthy two-way education programme, which has provided a fascinating insight to both sides. This need has been recognised in the increasing number of symposia and seminars now being organised by learned societies and industry with the considerable support of both ESA, NASA and the UK Department of Trade and Industry. The events are primarily concerned with bridging the gap and attempting to inform the widest possible range of audiences of the industrial potential of space. There is a clear emphasis on the need to make space operations a commercially attractive proposition and to this end there is an increasing use of business consultants to provide the specialised marketing aspects.

The European Space Agency, as part of its Long Term Preparatory Programme (LTPP) on Space Transportation Systems (STS), is sponsoring a number of studies on various aspects of potential European involvement in space station activities and one of these studies is concerned with user aspects. The study, "European Utilisation Aspects of Low Earth Orbiting Space Station Elements," abbreviated to EUA, is now in its second phase. Led by DFVLR as Prime Contractor to ESA and supported by MBB/ERNO, BAe, MATRA, Dornier System and Aeritalia is aimed in this phase at identifying potential European users in materials and life sciences. This type of study is quite different from the usual technology topics. It requires a lot of patience, tact, stamina and good communications. It is worth noting that the task has become somewhat easier since the continuing success of the Shuttle and, particularly, the impact made by Spacelab. Potential users now have a much better feeling for what it is about.

The outstanding problem remains one of cost. It may be possible to attract interest on a technical level but as most of the companies contacted are commercial they always ask, "How much?" Therefore, to be commercially viable it is essential that realistic cost guidelines should be available as soon as possible, otherwise the interest being carefully cultivated will fade.

It is also essential to ensure that the requirements of serious potential users are fed systematically into the overall MSS requirements, particularly if they have a financial commitment to the MSS. NASA are making strong efforts in this area. As well as financial/commercial aspects, the many facets of intellectual property rights, proprietary rights, commercial security, availability of the MSS/platform, company involvement and crew training must be addressed.

If space industrialisation is to become a practical proposition, it must be demonstrated to be safe, reliable, and a comparatively low risk operation. This will not be achieved either easily or quickly and will require a considerable continuing public relations effort by both the aerospace industries and agencies concerned.

Contacts should be sought at the highest level in a company where overall policy decisions and commitments are made. Large companies usually plan their business at least five years ahead and quite often 10 and asking them to consider MSS involvement invariably poses serious resource problems which can stiffen resistance to new and expensive ideas. The important point for their consideration is: can they afford not to be involved, bearing in mind the nature of their competitive markets?

Although it would appear that there are many difficulties associated with the identification and establishment of potential users of the MSS, it is felt that the potential is both real and large as a business opportunity. It should not be rejected because of a lack of understanding.

ACKNOWLEDGEMENTS

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AN EVOLUTIONARY SPACE STATION ARCHITECTURE

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A space station, an investment in permanent space occupancy, is justifiably concerned with evolutionary growth, adaptability and interchangeability. The system proposed here for its construction is based on the premise that whatever configuration is first launched will be found less satisfactory than envisaged in ground-based studies. At this point, re-arrangement would be preferable to starting all over again.

To assure construction of any shape (or any size) of assembly, the system is a trusswork of equal-length bars, habitable modules interchangeable with struts. There are six standard units and no adapters. The key element is a nodal sphere made from 12 identical sub-assemblies, each corresponding to a face of a bulged rhombic dodecahedron. Each port includes a berthing mechanism that allows lateral engagement.

Habitable modules are integrally stiffened shells with standard patterns of attachment fittings for equipment installation, an extension of the concept that transformed a Saturn S-IVB stage into the Orbital Workshop of Skylab.

External appendages (antennae, solar arrays, etc.) plug into ports in the nodes at the assembly's edges, while hangar spaces are multi-cell volumes inherent in the lattice. Clocking and identification of the port interfaces assure correct assembly.

Not an alternate configuration, the construction system could build any of them.

1. INTRODUCTION

The Space Station will differ from previous space programmes by being not only re-usable but continuously in use. Since it will be revisited regularly and can therefore be frequently up-dated, it does not require advanced and risky technology at the outset. However, it must inherently possess adaptability for new technology as it develops. It is imperative that this capability be achieved without rebuilding the basic framework. This means that initial priority should be given to mounting provisions, distributive systems, standard interfaces and basic geometry.

This paper offers a system designed to meet these specifications. Not intended as an alternative to any Space Station configuration, it is a means to constructing any of them and, if necessary, converting from one to another. Developed initially as a set of modules for long-duration Shuttle Orbiters, the system was expanded to "evolve" into an embryo Space Station. Attention has therefore been focused on general construction rather than specific forms.

Earth-bound fabrication activities such as cutting, drilling and trimming produce chips that are swept up and discarded after falling to the floor. In space, they produce floating clouds of dangerous debris. Similarly, loose bolts, nuts and washers, if lost, threaten the reliable operation of machinery. Clearly, standardised, pre-installed attachment provisions and captive fasteners must be emphasised.

Skylab experience offers precedents for such standardisation. The walls and partitions built into an S-IVB hydrogen tank to make an Orbital Workshop were made of open lattice grid, a regular pattern of nodes 107 mm apart at the intersections of bars forming equilateral triangles. The construction was open to drain hydrogen fuel, since it was originally intended to function as a working stage. The triangular form was necessary for carrying shear loads across an open trusswork. Figure 1 shows a typical installation of equipment and the S-IVB that was modified to house the living and laboratory quarters. It is evident that any installation on this standard "pegboard" could be removed and replaced by any other equipment designed to fit the pattern without the cost and delays from negotiating changes in a structure designed without these accommodations.

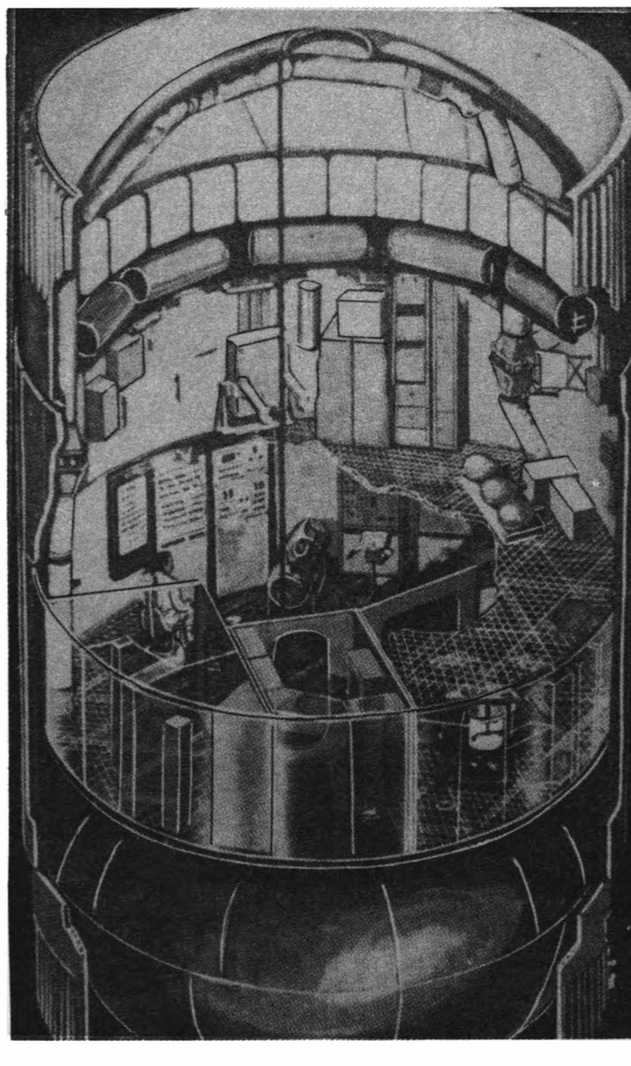


Fig. 1. The Skylab Orbital Workshop, showing the grid floor.

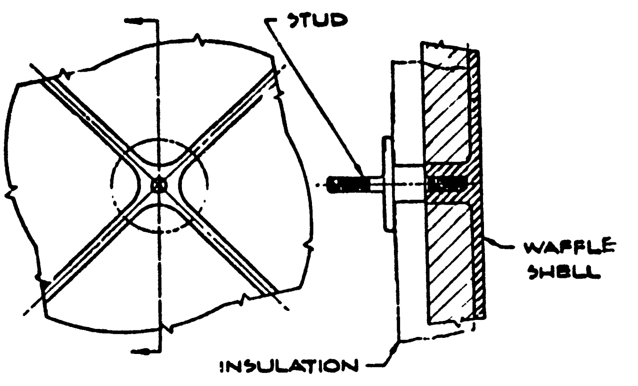


Fig. 2. Standard stud in S-IVB tank waffle node.

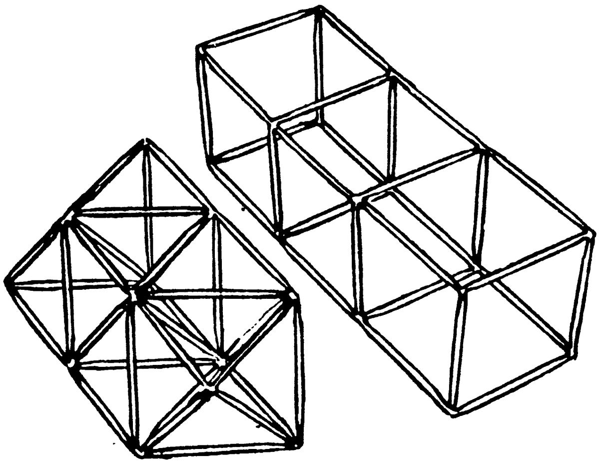


Fig. 3. Models of cubic and tetrahedral space trusses.

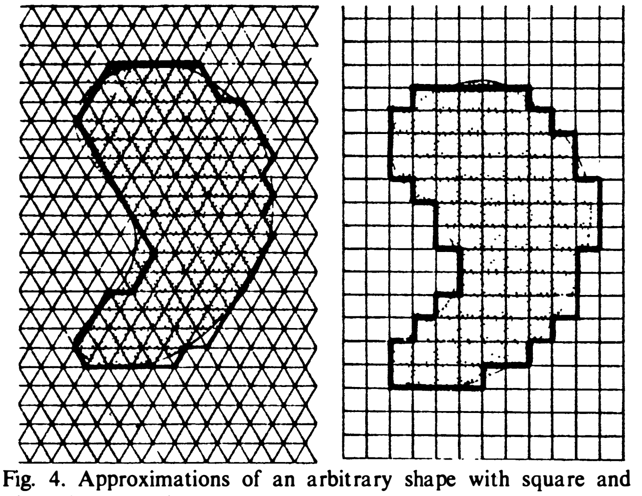


Fig. 4. Approximations of an arbitrary shape with square and triangular networks.

The whole habitable frame and associated equipment (about 17,000 kg) was suspended from the waffle-stiffened S-IVB cylinder. Fortuitously, this structure contained about 2,000 attachment opportunities at the intersections of stiffening ribs. These were exploited by installing a stud in a tapped hole at these locations (Fig. 2).

In this case, the tapping operation was a pre-launch rework; for a space station, such provisions must be designed in at the start. The discovery of inherent accommodations accidentally offered by the structural arrangement was, in Skylab, followed by intentional inclusion of similar capability in the added structure. If Skylab had not fallen out of orbit before it could be re-boosted, it would even now be able to accept new equipment in exchange for the old. For the Space Station, better initial planning should provide even more versatility.

It is obvious that the growth and adaptability so desired in the installed subsystems must also be a prominent and planned feature of the subsystem that supports all of them: the structure. In fact, it should start there. Structure, in this sense, connotes "architecture" and all that implies: space allocation, protection, accessibility and maintainability, along with its more obvious role as a sustainer of loads.

In response to this compelling logic, the system here proposed for space stations:

- Is not an alternate configuration: it implements any of them
- Can fill all of space - or any part of it
- Has elements sized by the Shuttle payload bay
- Is structurally efficient, its growth and controllability not being limited by low natural frequency
- Uses only six basic construction units with standard interfaces and component mounting provisions
- Considers pressurised modules and construction struts interchangeable parts of a common lattice
- Permits evolutionary growth, shrinkage and reconstruction in another form *after* initial operation
- Requires little new technology at the start but can accommodate any that develops later

To summarise, this system is not only "technology transparent,' as requested, it can also be called "configuration transparent."

2. GEOMETRIC CONSIDERATIONS

If a large space lattice is to be truly versatile, it must be able to assume any shape. To do this, it must consist of identical cells or cell groups endlessly repeatable. If the edges of such cells are equal-length elements (a desirable condition of standardisation), two basic systems are derived:

- Cubic: square faces and corners
- Tetrahedral: equilateral triangles

Both forms can be modelled three-dimensionally, as shown in Fig. 3.

To explain space networks in a two-dimensional manner, square and triangular area arrays are depicted in Fig. 4. The small patches shown can be expanded infintely, if necessary. Their three-dimensional equivalents are cubic and tetrahedral lattices. The latter is somewhat misnamed because space cannot be filled with tetrahedrons. Bars running in the same six directions as the edges of a tetrahedron divide space into tetrahedrons and octahedrons in the ratio of two to one. However, the nodes are all identical; 12 bars converge at each intersection.

As indicated, an arbitrary shape can be approximated with either array, though the triangular one, running in three directions instead of two, can more closely approximate the slope of the figure's outline.

For any large space structure, the Space Station included, the tetrahedral truss is structurally superior to the cubic form because triangles are inherently rigid and stable. A cubic lattice is made stable by adding diagonal struts or cables, thereby creating triangles; but in this case the lengths

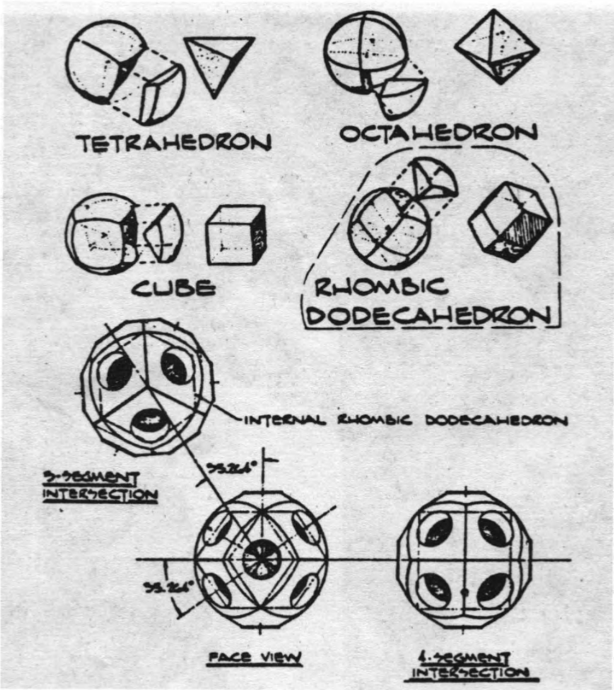


Fig. 5. Polyhedral subdivisions of spheres and a spherical node for a tetrahedral lattice.

are different. So, for a cellular system or a crystalline lattice, the rational choice is tetrahedral, both for large frames and for clusters of habitable modules. Inconsistency of geometric arrangement implies sets of cost-incurring adapters.

The apparent popularity of cubic cells may stem from a universal understanding of the geometry at an intersection. It is also obvious that the polyhedron that presents a face normal to each of the lattice bars is a cube. It has not often been recognised that a pressurised node with no preferential directions of strength (as in an infinite lattice) needs to be a sphere divided into six identical bulged patches, the projections of a cube face on a surrounding sphere. Instead, most airlocks have been cylinders, or intersections of them.

What has rarely been recognised is that for a tetrahedral there is also a polyhedron with a face normal to each incoming bar on which an interface can be centred. Figure 5 shows some polyhedral subdivision of spheres. The cubic version has already been mentioned. The form of interest for the tetrahedral lattice is the rhombic dodecahedron. Not generally known to designers of large space structures, it is well enough known to students of polyhedrons to have been given the name it bears. In a close hexagonal packing of spheres in space, where 12 spheres are in contact with a central one while touching each other, the planes of tangency at the points of contact around the central sphere are the faces of a rhombic dodechedron. It, like the cube, when packed against others of its kind, completely fills space without voids. This seems to be a necessary characteristic for the node of a universal space-filling lattice. The literature indicates that this polyhedron and the cube are the *only two* with identical faces that possess this property.

A model of this shape at a tetrahedral nodal intersection is shown in Fig. 6. It is the key element in an endlessly repeating lattice system which, by its ability to fill all of space, can also fill any part of it. Thereby, it permits the construction of any space station configuration or, for that matter, an assembly to carry explorers to the vicinity of Mars.

The foregoing discussion treated nodes in the lattice as a given condition, although the existence of such units has been the subject of debate concerning the question of affordability. Without any formal economic analysis, this uncertainty should be settled by rational discussion. Firstly, a node should be expected to function as an airlock and a space station without airlocks is unthinkable. In addition, even the simplest two-dimensional array (the square one

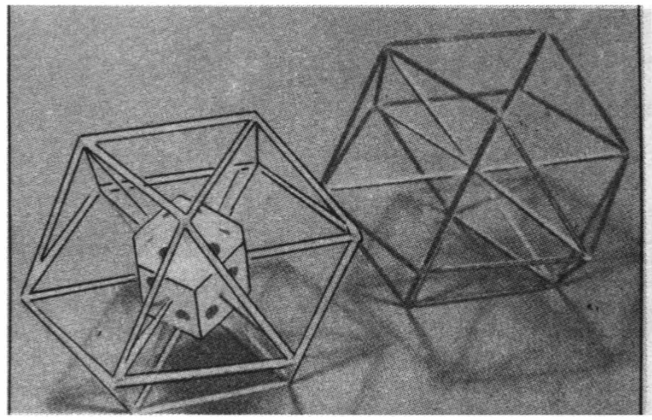


Fig. 6. Model of a rhombic dodecahedron at a tetraherdral lattice node.

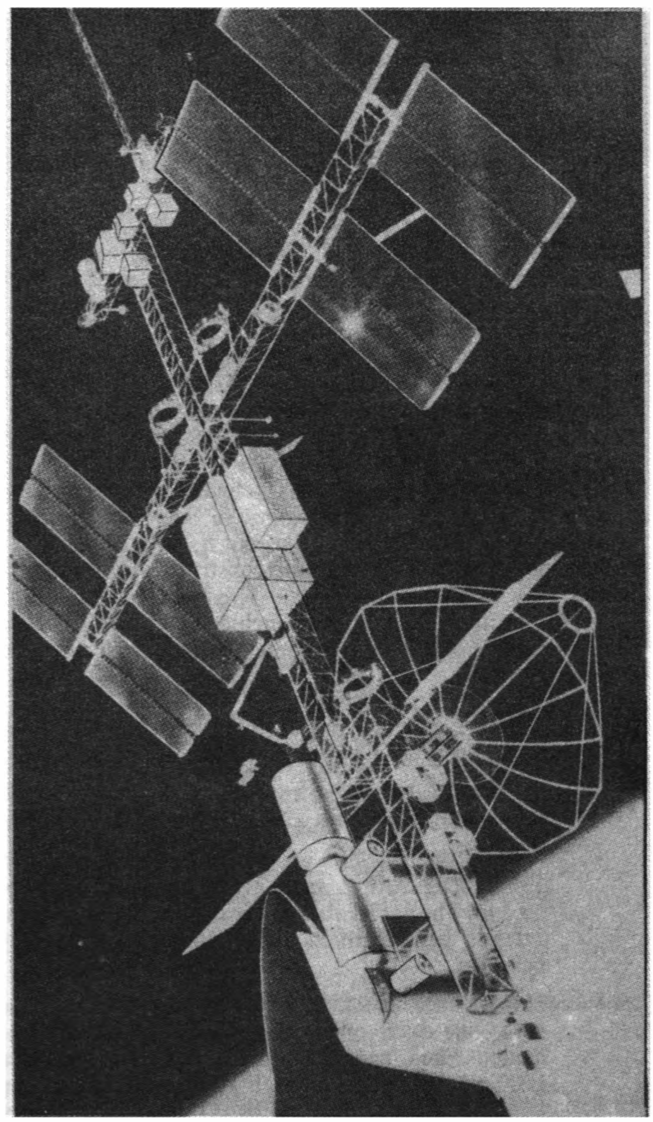


Fig. 7. Space Station study reference configuration, the "power tower."

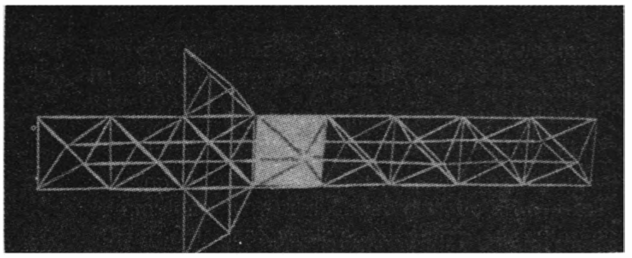


Fig. 8. Representation of a tetrahedral "power tower."

shown in Fig. 4) has intersections where four bars meet. Each bar has two end connections. Therefore, to come out even, the infinite array must have twice as many bars as junctions. The triangular array has three times as many bars as intersections, and a three-dimensional tetrahedral lattice requires six times as many bars (or modules) as nodes. Therefore, for universal adaptibility, nodes cannot be integral with bars because the required numbers of each are different. Growth would be restricted and more nodes (or the equivalent) would be procured than are required.

3. APPLYING THE CONSTRUCTION SYSTEM

The Space Station depicted in Fig. 7 is the initial all-up configuration of the so-called "power tower." This design is the reference for the definition phase Space Station studies. It features a deployable structural main frame that links appendages such as power-generating arrays, experiments, hangars, antennae and habitable modules. The external size differences between initial and growth versions is small. Chiefly, the power-generating systems switch from solar cells to heat-cycle turbines, the number of pressurised modules increases and the main frame is reinforced with parallel beams. Increases in mass and technology state are not matched by size or shape changes in basic architecture. Deployable mainframes do not permit it.

The design's counterpart in the construction scheme proposed here is shown in Fig. 8. This is a model of the main frame; appendages are not included. While the overall arrangement is essentially the same, there are basic detailed differences:

- The core structure is erectable, not deployable, each bar representing a span of 17.76 m.
- Some of the bars - any appropriate clustered group - are habitable modules with attendant nodal airlocks.
- Appropriately scaled up, the assembly as shown is 134 m long with a span across the stub arms of 50.3 m. The deployable power generating equipment extends beyond these arms, supported on rotary bearings.
- Hangars are screen-enclosed octahedral cells of the core, one such opportunity being shown on the model. Each hangar cell has a volume of over 1700 m^3, accessible through a triangular door (one removed side) 15 m wide by 13 m high. Probably four or five such cells are usable as hangars in the size of assembly shown, though the core itself can be expanded indefinitely.
- An assembly of this size and form is made from 120 bars and 40 nodal joints, both of variable composition. In all, 240 connections must be made after the bars are made up and transported to the assembly point. The connections are built into the standard units with no loose parts and no adapter brackets.

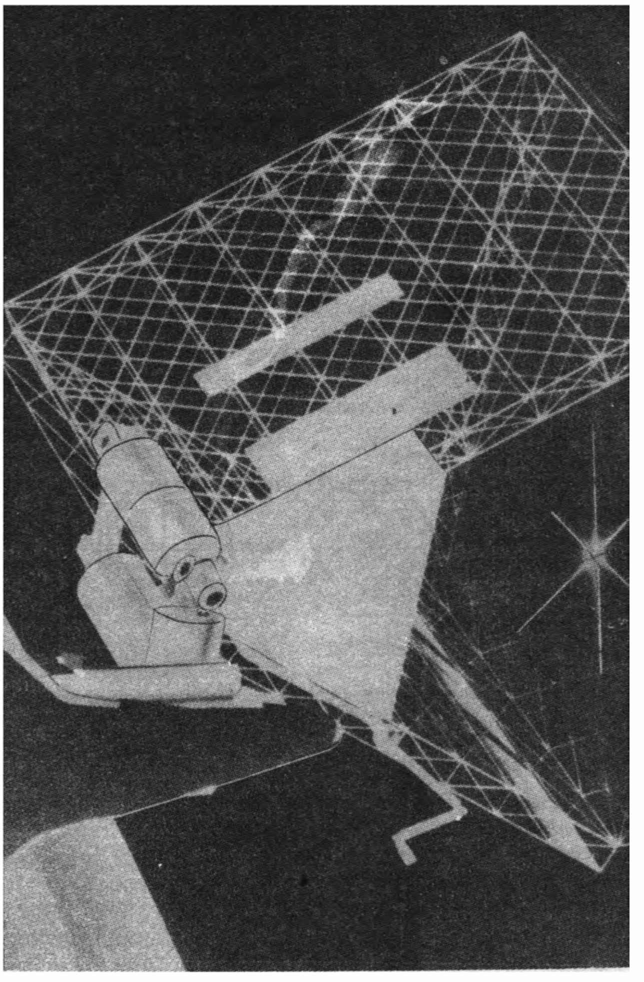


Fig. 9. "Delta" configuration studied by NASA.

A now-discarded configuration that received considerable early attention is the "delta" space station (Fig. 9). As designed, its three deployable structural panels each contained about 1600 members, almost 5000 altogether, including splices. It was designed this way "to minimise EVA" as stated in the final report. While this statement may be true for an identical design, one intended to be erectable would be expected to entail much fewer and larger elements.

Figure 10 shows another model representing the "delta" design as built with the tetrahedral truss system. As expected, while it is about 47 m high, it uses only 147 bars and 51 nodes. As many as 10 of the bars are standard pressurised modules, interconnected through six nodal balls; the rest consists of standard struts and corresponding nodal fittings. Unoccupied nodal ports are available for EVA, docking and accessory modules. As the manned portion of the station increases in size, bars and nodal connectors can be replaced by habitable modules and nodal airlock balls.

Solar panels on top of the configuration are assumed to be NASA-developed fold-up panels contained in split boxes extended by an "astronaut" or the equivalent, stretching the solar blanket between box-halves. In this case, the panels are double blankets 7.9 by 33.5 m in size; there are 16 altogether, providing about 4250 m^2 of collection area for 400 kW or more of power. The arrays do not all have to be there at the start, nor does all the structure. Between the solar panels and the occupied modules at the apex of the delta is a hangar space made by removing structurally unnecessary bars from the centre; it is a large octahedron

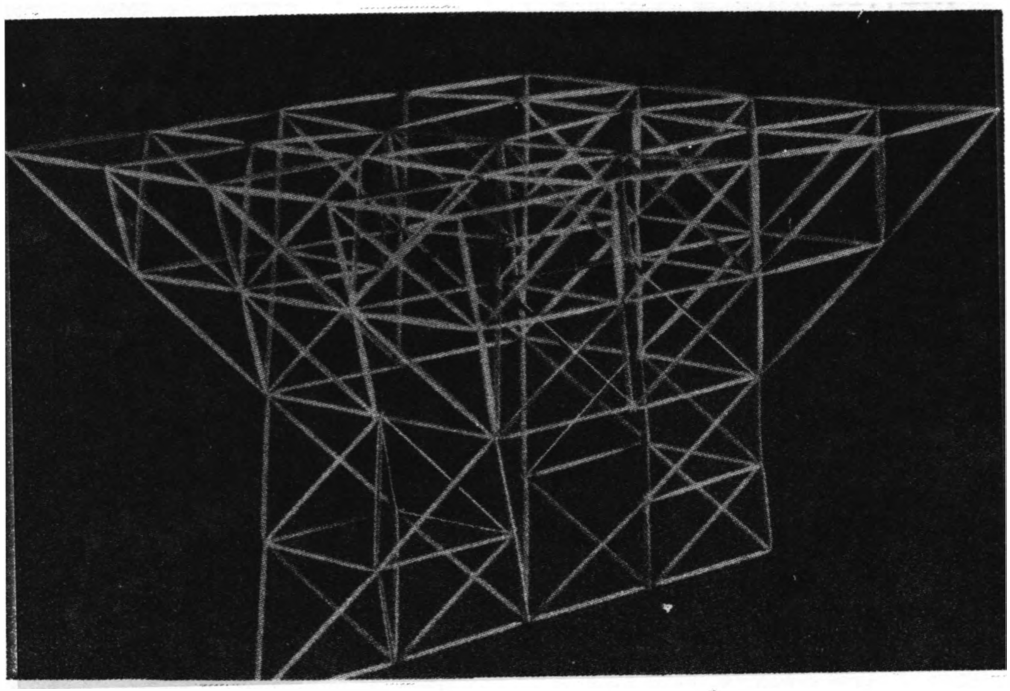


Fig. 10. Tetrahedral version of the "Delta."

with 33.5 m edges. Its volume is about 10,500 m^3. Note that slices at appropriate angles through the lattice uncover square patterns where they may be needed.

4. ELEMENTS OF THE SYSTEM

The "meccano set" for a universal tetrahedral construction system consists of six basic units (five, if a habitable module is always made in a single size). At least three of these elements make up each of the assemblies in the configuration models. Figure 11, showing how the standard 16.76 m spacing is filled by standard units, identifies the first three elements, as follows:

1. Nodal Airlock. This is the spherical entity subdivided into 12 identical rhombic subassemblies that is the key to the lattice geometry and provides ports for EVA, docking or accessories.

2. Habitable Module Cylindrical Barrel. This is the standard shell segment for all habitable modules: laboratories, command centres, sleeping quarters or workshops. Each segment's length is the same as the distance across opposing flats of the nodal ball to allow the combinations shown. The assumed diameter is 4.32 m.

3. Habitable Module Cone End. This unit closes out habitable spaces, incorporating at its narrow end the same attachment and functional interface as must be built into each of the 12 faces on the nodal ball. Its 60° conical shape is determined by the equilateral triangular relationship with adjacent units.

Where the structural frame extends beyond the inhabited volume of a space station, the node-to-node spacing is maintained by the remaining three standard elements:

4. Half-Strut. This unit is a tapered structural column with androgynous connectors on both ends. Its length is half that required to reach between structural cluster fittings at the nodes ("hedgehogs").

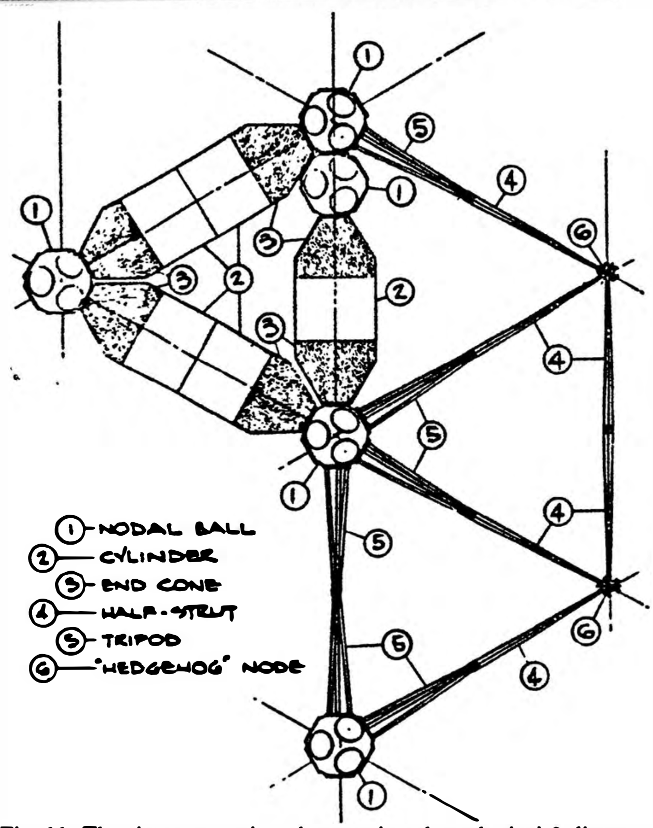


Fig. 11. The six construction elements in a hypothetical 2-dimensional assembly.

5. Folding Tripod. All ties between pressurised units and the open structural frame are made through this unit. Its length is half the distance between the opposing faces of two nodal balls. It combines with a half-strut when the elements at the nodes are dissimilar.

6. "Hedgehog" Cluster Fitting. This is an assembly with 12 stubs identical to the androgynous ends on assembled strut pairs. The stubs are geometrically related in the manner of faces on airlock nodes.

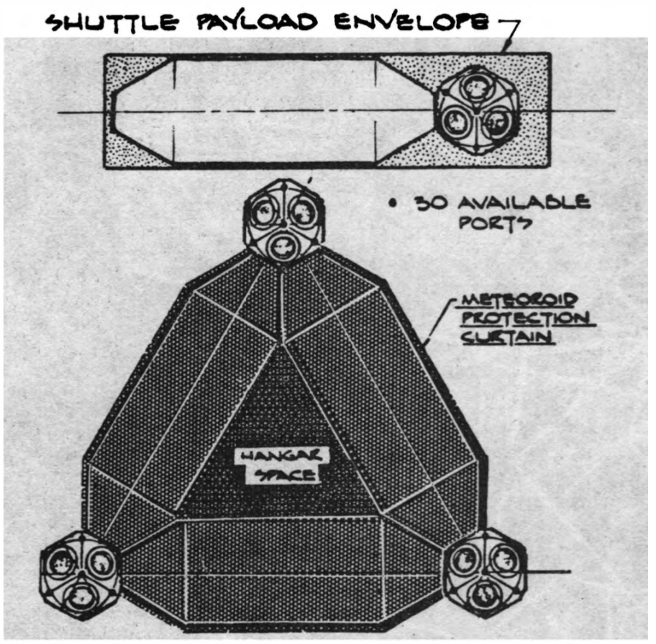


Fig. 12. A minimum closed configuration carried in three Shuttle launches.

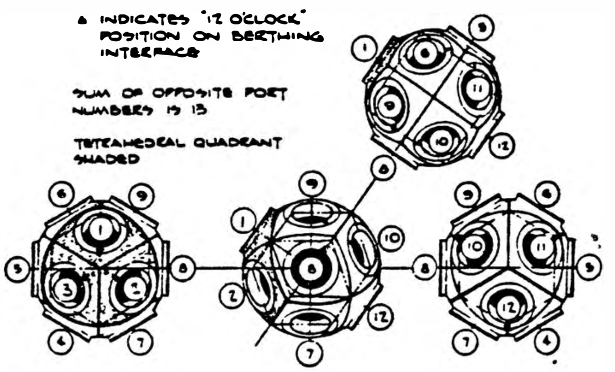


Fig. 13. Nodal port "clocking" and identification.

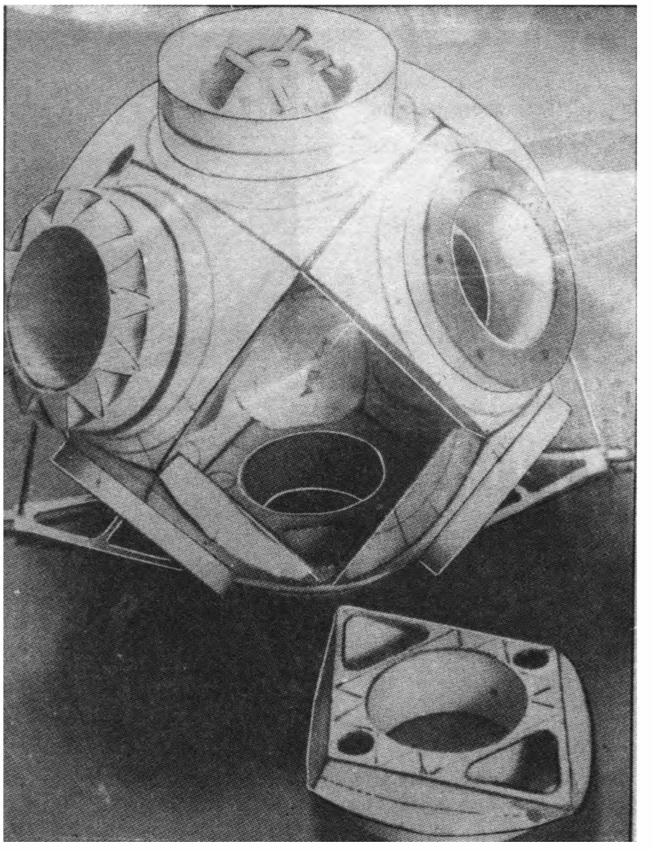


Fig. 14. Nodal airlock ball with standard sub-assembly (lower right) and accessories - thruster group and battery pack.

The system is sized by the assumption that one Shuttle load consists of one airlock ball and one full-sized 13.4 m habitable module as shown in Fig. 12. For the start of a space station, the first launch should probably orbit a power module complete with attitude controls and a small propulsion system. When the following three launches bring up three bay-filling payloads, as shown, a minimum system can become operational. This small system could barely sustain a 2 or 3 man crew between resupply visits but it would be a start.

The 12 port node is the determinant of the construction when its 12 identical sub-units are properly identified. The orientation and labelling of the faces for this purpose are shown in Fig. 13. It starts with a 3-face patch forming the spherical projection of a face of a tetraherdron. There are four such groups to a ball. As illustrated, the groups are 1-2-3, 5-6-11, 4-7-12 and 8-9-10.

Note that the "12-o'clock" angular position of each port is pointed toward the centre of the group, most clearly shown in patch 1-2-3. When this procedure is followed for all four patches, the opposing ports on the ball are always oriented in the same direction. Therefore, nodal balls spatially oriented in the same manner always correctly align with cylindrical modules whose ends are also "clocked" alike.

Assembly aligment can be automatically assured when the polyhedral faces are numbered like cubical dice (whose opposite face numbers add up to 7); for a 12 faced entity like this, the sum of opposite face numbers is 13. Thus, when a habitable module end is plugged into port 5 of a ball, its opposite end fits port 8 of the next node. The proper assembly of any space station arrangement can be defined unambiguously in this manner.

5. NODAL AIRLOCK BALL

In a lattice assembly of habitable modules interconnected by spherical nodes, any nodal unit is an airlock. As such, it must be sealable to prevent loss of the breathable atmosphere. This, in turn, leads to a requirement for inward opening doors, one for each penetration, or 12 in the element appropriate for tetrahedral truss geometry. In the airlock photograph shown in Fig. 14, one of the 12 identical subunits is shown removed (at lower right). Accessories shown plugged in include a 4-thruster propulsion unit and a suggested battery pack.

A spherical shape is indicated for good reasons, not the least of which is that a round door covering a circular opening fits well against the spherical shape near the opening. Internal space is less likely to be cluttered with unstowable hatches. Spheres are, of course, the most efficient form of pressure vessels, while their compound curvature also makes them resistant to compressive forces. Circular holes in spheres also remain round and planar under pressure, simplifying the problem of maintaining an effective seal.

Figure 15 shows in some detail how a rhombic subassembly can be constructed. It is double-walled for a rigid docking interface. In addition, the curved and planar surfaces enclose a space through which system runs (wiring, fluid lines, etc.) can be routed and interconnected. Since the inner polygon is a machined open grid lattice, it not only

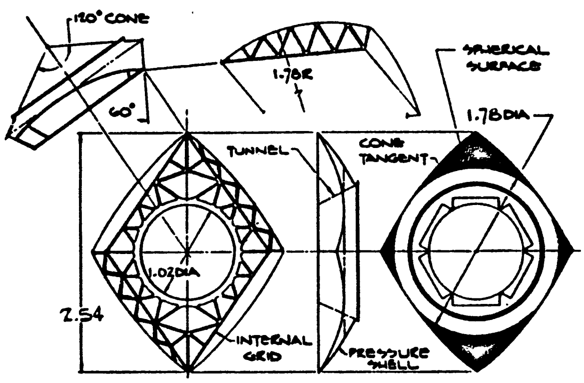


Fig. 15. Rhombic sub-module assembly.

protects and supports these system runs but allows access to them. Integral to these panels is a door jamb and sealing surface. Twelve identical units like this form a 3.56 m diameter sealed ball. The diameter selected is the minimum required to stow hatches between 1.02 m openings without encroaching on them. For larger openings, proportionately larger nodal balls are required, this enlargement being limited by the clearance in the Shuttle payload bay.

Although it has not been indicated, a further intention for adaptibility, is some form of socket, stud or similar attachment opportunity at each of the 14 "corners" of the structural ball. At these points, inner and outer structures converge, offering locally high strength. While there is no specific requirement for such provisions, the opportunity, if offered, will almost certainly be used. If passed up, it will be difficult to add later.

Since the lattice intersection must accommodate as many as 12 attached modules, nodes at the edges of any configuration offer many unoccupied ports, usable for docking, EVA or standard plug-in accessories like the previously-shown propulsion and storage units, or tanks for consumables or antennae. Any accessories, once developed, are directly transferable to another port, another module or a different configuration.

It is obvious that an adaptable nodal shell can be used in many ways. It could be a manned module for a recovery, repair and service vehicle. With nearly 11.5 m³ of volume inside the inner polyherdon, it could be fitted for life support of a four man crew for ten days to two weeks. Essentially the same vehicle can serve at a space base as a rescue "lifeboat." Among the accessories that could be developed for this role is a remote manipulator turret.

Figure 16 illustrates a proposed docking/berthing interface for this system. The type developed for Apollo is unsuitable because, projecting beyond the interface plane, it prevents lateral approach; it fills the tunnel, requiring disassembly before use; and the mating faces are different. The single-use Apollo/Soyuz device, although androgynous (both sides identical), also projects awkwardly across the interface plane.

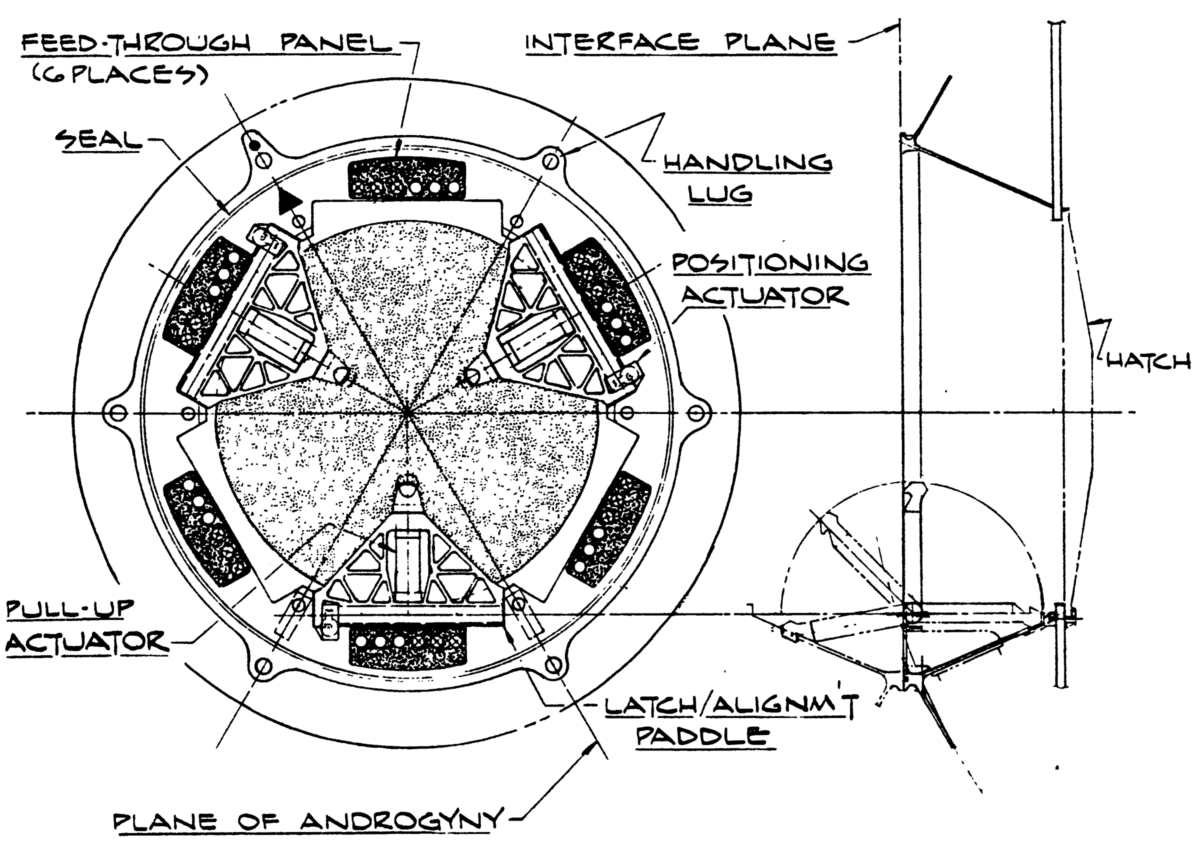
These precedents and the unique problems of this closed system combine to define the docking requirements:

- Androgynous (one system to develop)
- Flush faces for lateral engagement
- Positive guidance for head-on encounter
- Light connection before pull-up
- Minimum size and weight (many identical ports)

An added feature proposed for this mechanism is retractability to move out of the way when a port is occupied by an accessory module.

As a consequence the suggested method features *inward-*

Fig. 16. Docking/berthing interface for lateral assembly.



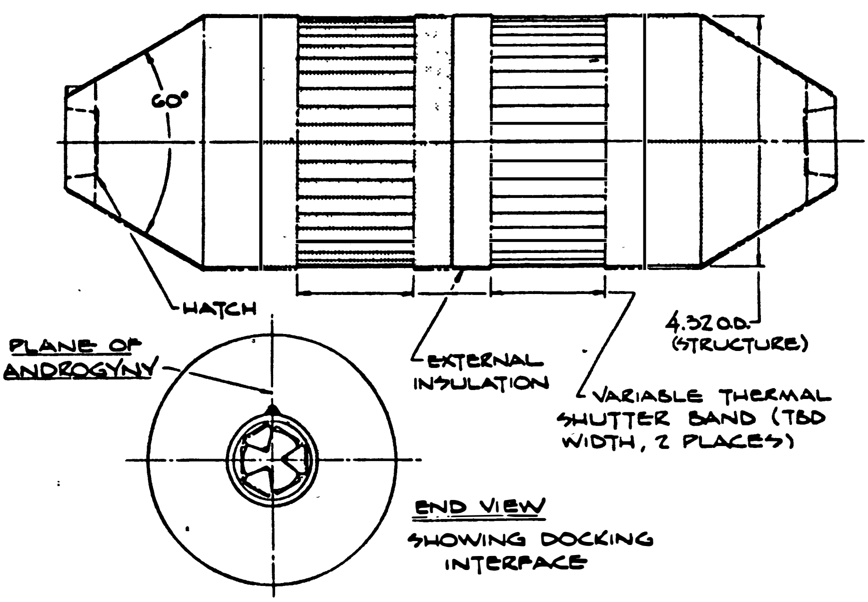


Fig. 17. Universal habitable module.

sloping triangular paddles, motor-driven through a range of positions appropriate to each operational mode. With hooks at their ends, they also perform the latching function by reaching through the opening in the opposing interface and engaging sockets in the tunnel wall. When fully engaged and locked, the paddles from both mating units lie inside the opposing tunnels, leaving a clear passage available for immediate use.

For a typical head-on docking the paddles are extended at an angle such as 45°. As the interface planes near each other (approximaely 25 mm short of complete closure), a spring-loaded detent hook (not shown) prevents recoil while the paddles further expand to engage. After the hooks enter sockets in the opposing tunnel wall, a pull-up actuator in each paddle rigidises the connection.

As the figure shows, the paddles can be positioned anywhere in a range exceeding 180°. For lateral insertion into the structural stack, the paddles are flush with the interface plane or below it. As soon as the mating units are approximately aligned, the paddles extend to centre the connection and continue to the engaged position. When withdrawn completely into their own tunnel, the paddles and latches are out of the way of an installed submodule whose attachment points can be the six spots shown at the hinge ends.

The paddles are driven to any commanded position by worm drive actuators located at the end of the hinges and bussed together by a chain, perforated tape or similar drive girdling the tunnel. Each actuator is indirectly connected to the paddle it drives by a spring and damping system built into the base hinge.

All of the mechanisms described and the dimensions assumed are tentative and subject to revision as a result of further study or such approvals as will be required for an international standard. Whatever develops will become an international standard, one that is long overdue.

6. UNIVERSAL HABITABLE MODULE

The habitable module required for most Space Station functions seems to be close to the same length and diameter as the now-operational Spacelab, but while Spacelab has been funded and developed, its design has been concerned with a single unit (of variable length) compatible with the Shuttle Orbiter payload bay. Little thought has been given to clustering multiple units into space station assemblies; particularly, the end geometry does not lend itself to assembly in any way but tandem. To a considerable extent, the thinking applied to all previous manned vehicles has concentrated on making one unit work. Much of this thinking can, it is hoped, be applied to the module introduced in Fig. 17.

Shaped for the tetrahedral truss assembly method, this module has relatively long conical ends with converging space which, if intelligently used for service functions, should be no disadvantage. The module is envisaged as a stiffened shell with entry only at the ends; any exposure or exist to the vacuum of space or to other modules is through airlock nodes at the intersections. Except for circumferential bands with thermal control shutters, it is completely covered with multilayer insulation of any appropriate variety.

Since a leak-tight presurised canister with this much volume, once built, should find many useful applications, the structural shell has been designed to maximise adaptability and usable volume. Typical shell construction for both cylindrical and conical sections is shown in Fig. 18. The integral external stiffening ribs form an isogrid array of equilateral triangles with intersection nodes spaced about 180 mm apart. The panels are machined from large aluminium alloy plates about 20 mm thick, leaving a skin of about 1.5 mm between ribs. Each nodal intersection incorporates an outer socket and inner button for all the attachments to the shell. A suggested detachable captive collet fastener for all interior attachments is shown in Fig. 19.

There are no frames in this construction, not even where transportation trunnion fittings are attached. Frames are avoided because these fittings introduce their loads into the shell tangentially at patches with enough fasteners to match the load-carrying capacity of the nodes. No additional shell reinforcement is expected, though it can be provided if necessary by leaving enough extra material in the machined plate. The trunnion fittings, needed only for transport, are removable, being attached by the releasable fastener shown in Fig. 18.

The versatility of this construction is further demonstrated by a standard window construction (Fig. 20). Instead of removing the whole shell area, only the skin between stiffeners is cut out - in as many pockets as viewing requirements dictate (16 in the example shown). The outer edge is sealed

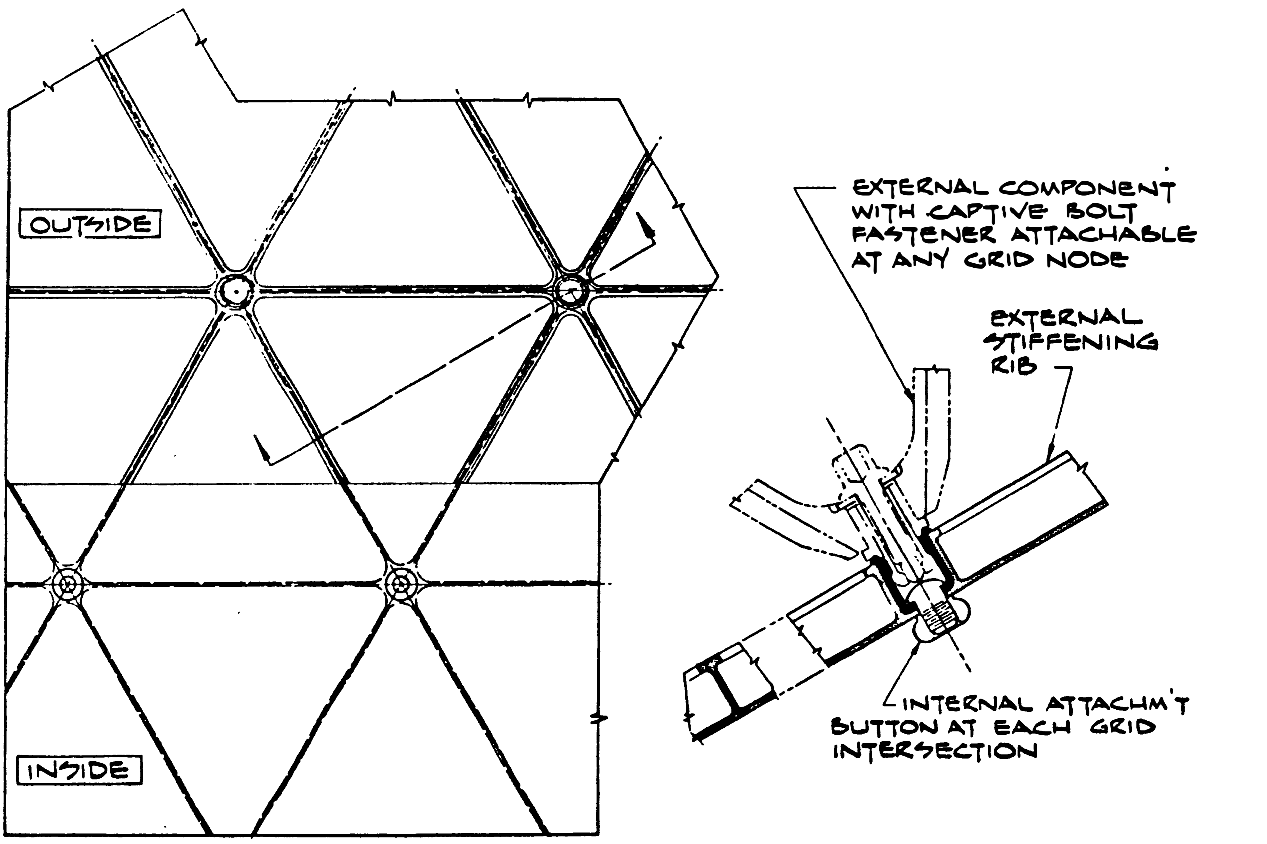


Fig. 18. Integrally stiffened pressure shell with standard nodal attachment provisions.

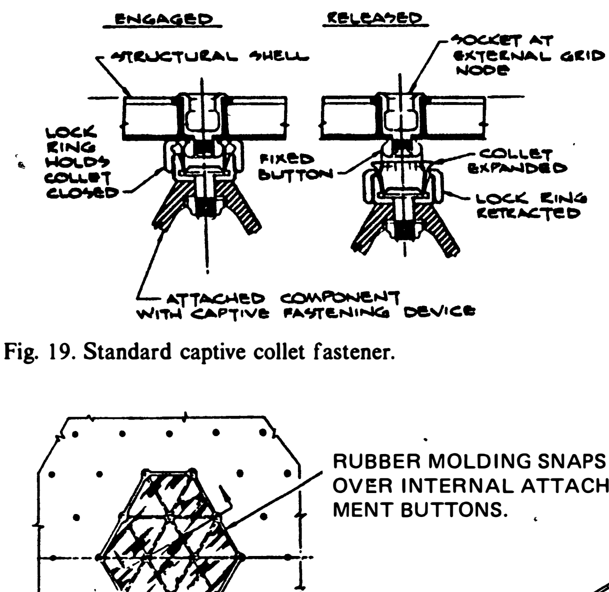


Fig. 19. Standard captive collet fastener.

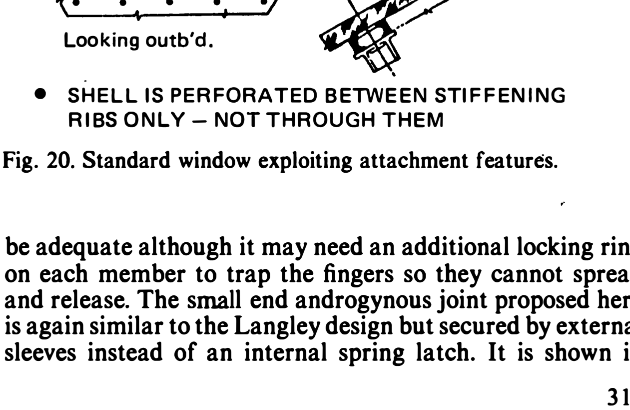


Fig. 20. Standard window exploiting attachment features.

by an elastomeric molding of appropriate cross section for window retention. Its underside includes sockets that are retained by the ubiquitous internal buttons around the edge. Each of the buttons at nodes in the middle of the window also retains an elastomeric supporting collar. This mid-panel support allows the clear pane to be thinner. Reinforcement to replace the skin removed for vision can be an internal bonded doubler or enlargement of the local ribs if the window location is known before the panel is machined. With the generous structural margins expected for the pressure loads, no reinforcement may be necessary.

This module is larger than those shown in most space station design descriptions. However, having been sized by STS payload bay dimensions and compatibility with the nodal ball, it should probably stay as it is. Any extra volume is sure to be found useful after the start of service.

7. CONSTRUCTION STRUTS AND NODES

As has been indicated in Fig. 11, there are three combinations for struts bridging the node-to-node spacing. This is caused by the different size of the two elements serving as nodes; pressurised balls are significantly larger than strut-connecting "hedgehog" fittings. Where there are no habitable modules, the nodal span is covered by two identical half-struts. Between nodal balls, if such a situation is realistic, two tripods are appropriate. When the gap between a "hedgehog" and a nodal ball is filled, the two elements are combined. This means that the middle joint on a tripod must be the same as that on a half-strut. In the nested strut system proposed every two-element column can be made from elements of the kind developed by the NASA Langley Research Center. For the centre joint at the large end of the strut, and in the corresponding position on a tripod, the androgynous multi-fingered joint already developed should be adequate although it may need an additional locking ring on each member to trap the fingers so they cannot spread and release. The small end androgynous joint proposed here is again similar to the Langley design but secured by external sleeves instead of an internal spring latch. It is shown in

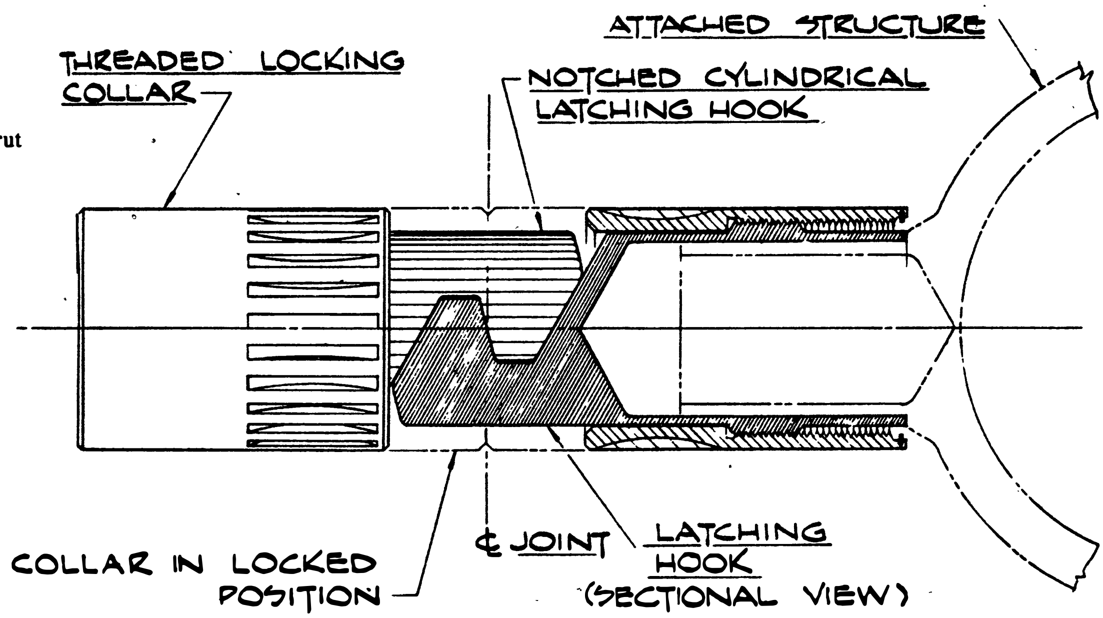


Fig. 21. Androgynous strut end connector.

Fig. 21. This is a well-known mechanism, generally secured by a single outer sleeve. However, since in an androgynous connection both sides must be identical, two threaded sleeves are used. This choice offers a bonus: the two can be tightened against each other to minimise play in the joint. Once the ends are brought together by hand, advancement of the first collar holds the assembly firmly enough to simplify operation of the second collar and subsequent tightening.

The foldable tripod can be attached at three of the six available spots on the docking interface. Since the space between two legs is as wide as the access opening diameter, the port remains usable for EVA and the legs themselves should be useful handholds.

Where construction struts meet at a node, there is a "hedgehog" cluster fitting corresponding to an airlock nodal ball. As illustrated in Fig. 22, the stubs project in the same directions as elements emanating from ball nodes. The "12 o'clock" position at the interface converges on the centre of three-stub groups exactly in the same manner as previously described for docking ports. The same numbering strategy can also be employed here.

As with airlocks, a "hedgehog" is made from identical stubs with rhombic bases. These bases, welded along their edges form the same polyhedron.

As the figure demonstrates, "hedgehog" fittings attached to each other can, by themselves, make a double-faced truss sandwich panel. With appropriate trunnion adapters, the extended assembly should serve well as a cradle for its own transportation to orbit; a pair of these cradles could, between them, support their struts for the ride.

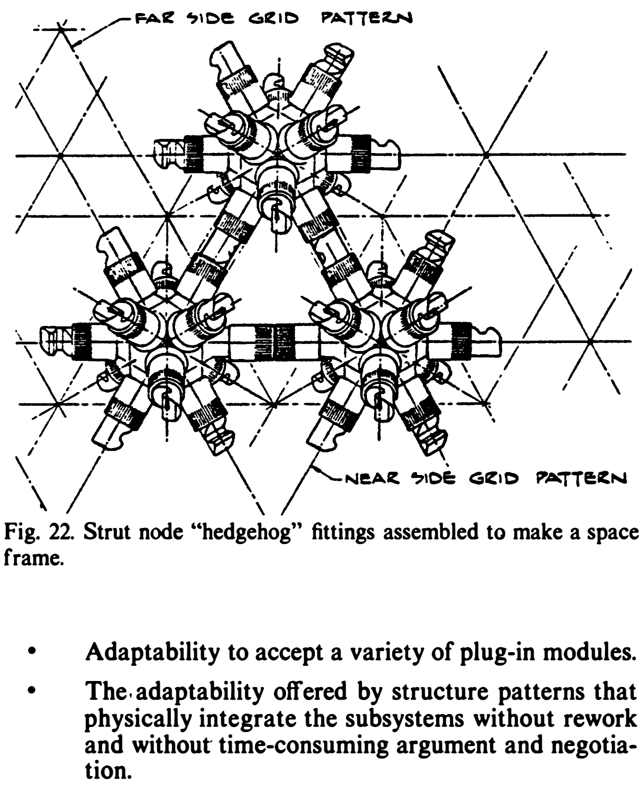


Fig. 22. Strut node "hedgehog" fittings assembled to make a space frame.

8. CONCLUSIONS

The Space Station is a new and different type of programme; it will be a continuing process and not a one-off event. As such, it will demand the characteristics offered by this construction system:

- An efficient structural system which, because it uses the only stable polygon available, the triangle, is inherently rigid; growth is not limited by low natural frequency.
- The adaptability that makes it rebuildable in another form.
- Adaptability to accept a variety of plug-in modules.
- The adaptability offered by structure patterns that physically integrate the subsystems without rework and without time-consuming argument and negotiation.
- The adaptability inherent in structural frame consistency, the construction struts and pressurised units conforming to the same lattice geometry - no extra adapters.
- The economy offered by developing only six interchangeable core construction units.
- The economy of identical interfaces and identical sub-units which, at an early stage, offer the cost benefits of quantity.

While it is desirable to study and understand what a space station must do, and, in the course of such study, to define what the starting configuration should be, this sytem permits major changes of mind after first service and for an indefinite period thereafter. In short, the development of the elements can proceed without a definite configuration decision.

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THE US SPACE STATION PROGRAMME

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In January 1984 President Reagan committed the US to a permanently manned Space Station by the early 1990's. This paper reviews the uses of such a station, the outline schedule and the prospects for international cooperation and commercial operations.

1. INTRODUCTION

On 6 February 1985, President Reagan reaffirmed the US commitment to the development of a permanently manned Space Station. In a major address, Mr. Reagan said:

> "We have seen the success of the Space Shuttle. Now we are going to develop a permanently manned Space Station and new opportunities for free enterprise because, in the next decade, Americans and our friends around the world will be living and working together in space."

The President's annual State of the Union Address is a major political event for both the Executive and Legislative branches of the government. It was in 1984's State of the Union message that Mr. Reagan first announced the Space Station decision. At that time, the President gave to the National Aeronautics and Space Administration (NASA) a new and historic task:

> "We can follow our dreams to distant stars, living and working in space for peaceful, economic, and scientific gain. Tonight I am directing NASA to develop a permanently manned Space Station and to do it within a decade.
>
> "A Space Station will permit quantum leaps in our research in science, communications, and in metals and lifesaving medicines which can be manufactured only in space. We want our friends to help us meet these challenges and share in the benefits. NASA will invite other countries to participate so we can strengthen peace, build prosperity, and expand freedom for all who share our goals."

The response in Congress to the President's initiative has been positive and supportive. Both the House of Representatives and the Senate have carefully reviewed the Space Station Program. In providing the initial funding, Congress has endorsed the idea of a Space Station as the next logical step in space for the United States. Just as importantly, this legislative action reinforces the bipartisan partnership between the President and Congress that has characterised the American space programme from its inception.

An equally important feature of the American space programme has been its international flavour. Nations from around the world, but particularly from Europe, have joined with the US in the exploration and utilisation of space. Spacelab, the Infrared Astronomical Satellite (IRAS) and future programmes such as Galileo and Space Telescope are all examples of how, working together, we can enhance our knowledge.

The Space Station will continue this tradition of international cooperation in space. In his 1984 State of the Union Address, President Reagan spoke to America's friends and allies and invited their participation in the US Space Station Program. He reaffirmed that invitation in 1985's State of the Union Address and the Space Station Program will again be on the agenda of the 1985 Economic Summit to be held in Bonn, West Germany.

It should be noted here that NASA's cooperation with the United Kingdom has been particularly productive. The UK has been a partner on some of our recent successful cooperative programmes, such as the Infrared Astronomical Satellite, conducted with the UK and the Netherlands; the Active Magnetosphere Particle Tracer Explorers project, operated with the UK and the Federal Republic of Germany; the multilateral Satellite-Aided Search and Rescue System; and through major contributions to the Space Shuttle programme, such as ESA's Spacelab. Furthermore, the US/UK partnership will continue with the development of the Improved Stratospheric and Mesospheric Sounder (ISAMS) instrument that will be flown on the Upper Atmosphere Research Satellite (UARS) observatory.

NASA welcomes the European decision, taken in January 1985 in Rome at the ESA Ministerial Conference, to accept the President's invitation by endorsing participation by the European Space Agency (ESA) in the Space Station Program. This decision, by itself, does not spell out the precise nature of Space Station cooperation. Current discussions between NASA and ESA, as well as the work to be done during the next two years, will accomplish that. NASA is confident that the reservoir of good will that exists in both organisations will lead to meaningful cooperation.

2. THE SPACE STATION

The Space Station is unlike any other programme that NASA has undertaken, for it will be a permanent facility in space. No longer will one simply visit space. When it becomes operational, people will be living and working in space around the clock, 365 days a year, well into the next century. The Space Station is also different because it is evolutionary in character. The initial Space Station will have the built-in potential for phased, evolutionary development to meet future requirements.

The evolutionary character and permanent nature of the Space Station place a new and difficult engineering challenge both upon NASA and its international partners. The rewards will be great, for it will significantly enhance the mutual capabilities to operate in space.

It will consist of a manned base and associated mantended platforms, as well as collateral support equipment. Incorporating both manned and unmanned elements, it will advance the technologies of automation and robotics. In response to a US Congressional directive, NASA is carefully analysing the potential for the extensive use of automation

and robotics aboard the Space Station and for utilising the Space Station as part of a national programme to advance these technologies.

The Space Shuttle, whose capability for frequent and routine manned access to Earth orbit makes the idea of a Space Station viable and attractive, will play a key role in Space Station development and operations. The Shuttle will carry the station elements into space and help to assemble them on-orbit. It will be used as a test vehicle for the development of Space Station technologies. The advanced technologies that will be exploited on the Space Station will spur scientific exploration of the Solar System and the Universe by both manned and unmanned vehicles. They will invigorate Earth applications and the study of Earth as a global system while stimulating research and development on innovative systems and techniques. In conjunction with Spacelab, the Shuttle will provide valuable operational experience for the Space Station user communities. The Space Shuttle will, of course, be used for logistics and crew rotation once the Space Station becomes operational.

The Space Station will be a versatile and effective facility, serving a diverse range of functions. It will be:

- A laboratory in space for conducting science, as well as the development of new technologies and related commercial products.
- A permanent observatory, to look down upon the Earth and out into the Universe;
- A servicing facility where payloads and spacecraft are resupplied, maintained, upgraded and, if necessary, repaired;
- A transportation node where payloads and vehicles are stationed, processed and propelled to their destinations;
- An assembly facility where, due to ample time on-orbit and the presence of appropriate equipment, large structures are put together and checked out;
- A manufacturing facility where human resourcefulness and the servicing capability of the Space Station combine to enhance commercial opportunities in space;
- A storage depot where payloads and parts are kept on orbit for subsequent deployment; and
- A staging base for future endeavours in space.

3. SPACE STATION PLANNING GUIDELINES

From the outset of Space Station planning in 1982, the US has followed a consistent set of guidelines setting forth major management and engineering criteria:

Management Related:

- Three year detailed definition (5-10% of programme cost)
- NASA-wide participation
- Development funding in FY 1987
- Initial Operation Capability: "within a decade"
- Cost of initial capability: $8,000 million
- Extensive user involvement
  - Science and applications
  - Technology
  - Commercial
- International participation

Engineering-Related

- Continuously habitable
- Shuttle-dependent
- Manned and unmanned elements
- Evolutionary
- Maintainable/restorable
- Operationally semi-autonomous
- Customer-friendly
- Technology-transparent

The initial operational capability (IOC) of the Space Station Program will occur within a decade. As originally estimated, the programme envisages a US investment of some $8,000 million (1984 dollars) to achieve this capability. This estimate does not include operational costs nor the costs of scientific or commercial payload development. The investment of NASA's potential international partners will enhance the Space Station, thus providing a more capable IOC Space Station for all participants to use. An in-depth, two-year definition period began in the US in April 1985. The utilisation emphasis that marked the preliminary NASA Space Station study activities will continue through the definition phase and into development.

Noteworthy among the engineering-related guidelines is the requirement for the Space Station to be operationally semi-autonomous from the ground. For a facility that will be permanently manned and in operation 365 days a year, the type of extensive, tightly controlled ground direction used in the past is prohibitedly expensive and probably not warrented, given likely advances in technology and increased emphasis on human productivity.

4. CURRENT ACTIVITIES AND PLANS

During 1984 and early 1985, NASA has set in motion a number of activities that are central to understanding the Space Station Program. A complex, technical effort of Space Station definition and preliminary design, "Phase B," began with US industry in April 1985. These studies will provide NASA with the necessary data upon which to scope the hardware development phase. The Phase B analysis will also incorporate the man-tended studies that Congress directed NASA to conduct. The Phase B analysis will be keyed to identified user requirements that NASA has studied extensively over the previous two and a half years. These requirements are a primary driver of Space Station design; they will be continuously refined and updated throughout the life of the programme.

NASA has discouraged its bidding Phase B contractors from forming formal teaming arrangements with firms outside the US. NASA is not looking for government-sponsored relationships between companies during Phase B that could tie the hands of NASA and its international partners while structuring this long-term cooperative programme. However, NASA does not object to US firms procuring from firms outside the US as part of their Phase B activities, consistent with applicable laws and regulations.

Concurrently, with emphasis upon user requirements and the Phase B definition and preliminary design studies, NASA has initiated a major programme of technology development. The development of advanced technological options for the Space Station is an activity of the highest priority, one to which NASA is devoting substantial resources. This Advanced Development Program is intended to provide technology design options for the Space Station. Within this programme, selected high leverage generic technologies are focused for Space Station applications and are matured to a prototype level in order to demonstrate their feasibility,

establish their performance and quantify the risks (cost and schedule) associated with their potential introduction into the Space Station development effort. This selection and focusing process for technology options is built upon a generic base of space technology. This programme has been initiated and will be continued throughout the definition phase so that NASA is assured of the technologies determined to be appropriate to carry into system development. A total of $52 million (FY 1985 dollars) was planned for 1985 to turn these concepts into prototype hardware and to conduct the necessary tests and evaluation. Additional resources will be committed in 1986. To accomplish this activity, NASA has established a series of technology test beds at the NASA field centres to quantify and validate the performance of advanced components and subsystems in a ground laboratory environment. Evaluation and testing of some of these technologies have already been initiated in a number of major discipline areas, including attitude control and stabilisation, power, thermal, environmental control and life support, auxiliary propulsion, data management, structures and mechanisms.

NASA's current activities include initial efforts for the development of a Space Station operations concept. Operational considerations must be a part of all planning, even at this early stage of the programme. NASA encourages and expects its international partners to participate in establishing this operational concept. An International Operations Concepts Working Group has been established with the international partners to exchange information on this subject.

To implement these and the other activities of the Space Station Program, NASA has established a management structure which features a three-tiered allocation of responsibility. Level A at NASA Headquarters in Washington, D.C. is responsible for the policy and the overall direction of the programme. Level B, located at the Johnson Space Center in Houston, Texas, is responsible for programme management and the technical content of the programme. Level B is also responsible for integrating the work of Level C centres which are responsible for discrete project elements. The Level C centres are the Marshall Space Flight Center in Huntsville, Alabama; the Goddard Space Flight Center in Beltsville, Maryland; the Kennedy Space Center in Florida; the Lewis Research Center in Cleveland, Ohio; and the Johnson Space Center, which conducts both Level B and Level C activities.

The programme plan envisages a 21-month (April 1985-January 1987) Phase B definition and preliminary design effort with the hardware development phase, or "Phase C/D," beginning in FY 1987. This constitutes a slight adjustment to earlier plans that showed an 18-month Phase B. Early in 1986, a series of technical reviews will be conducted that will result in the definition of a Space Station baseline configuration to which the rest of the Phase B analysis will be directed. These reviews are major milestones in the definition programme and will include participation by international partners. At the end of the Phase B activity, scheduled for early 1987, NASA will begin the competition in the United States for Phase C/D.

This programme plan assumes a strong role for NASA in programme management and provides genuine competition among US industry. It is supportive of meaningful international participation in the Space Station Program. It gives a strong voice to the Space Station user communities and establishes a significant effort in technology development. Most importantly, the Space Station programme plan will be based on a detailed definition which is the only way that the US as well as Europe, Canada and Japan can assure credible cost, schedule and technical projections. Finally, it is a plan that will enable NASA to meet the goal set by President Reagan of developing a permanently manned Space Station within a decade.

5. THE SPACE STATION PARTNERSHIP

Over the past 25 years the US has entered into over 1,000 agreements for cooperative space-related activities with over 100 nations and international organisations. These activities have been of mutual benefit to both the US and the nations involved. Perhaps the most notable recent examples are Spacelab, developed by the European Space Agency for the Space Shuttle Program, and the Shuttle's Remote Manipulator System, built by Canada and used so effectively in April 1984 in the repair of the Solar Maximum Mission spacecraft. A key example in future programmes is the retropropulsion module provided by West Germany for the Galileo spacecraft.

A number of primary criteria or guidelines have been followed in these programmes. Government-to-government agreements are reached in which each partner accepts full technical and financial responsibility for their portion of the programme. Clean technical and management interfaces will be established and technical information will be exchanged as necessary to achieve effective interfaces. A major consideration is utilisation by the partner of the end product.

There are three primary aspects of international participation in the Space Station Program:

- *User:* Defines missions and utilises station capabilities;
- *Builder:* Participates in definition and development programmes; and enhances station capabilities; and
- *Operator:* Participates in system operation.

As a customer-oriented facility, the Space Station will be available to countries whether or not they participate in the development phase. A nation with significant involvement in the development phase as a builder will have a role to play in the operation of the Space Station itself. NASA hopes that ESA, Canada and Japan, as partners in the endeavour, will be involved in all phases of the programme: development, utilisation and operations.

6. CURRENT INTERNATIONAL ACTIVITIES

As previously mentioned, the potential of international cooperation in the Space Station Program has been a primary planning criteria from the outset and in the 1982-1983 time frame NASA encouraged potential partners to perform their own mission analysis activities. Such analysis activities were undertaken in Canada, Europe and Japan. The results have been exchanged and updated in a continuing series of workshops. All inputs are now being updated (pre-April 1985) prior to the initiation of definition studies. The commitement to long-term utilisation of Space Station capabilities is a primary objective for international partnership in the programme. The NASA reference configuration developed as a point of departure for the Phase B definition studies has been shared with ESA and other potential partners. Each has provided NASA with the reference configuration(s) which they currently envisage for the elements which they will analyse in their own Phase B studies. The European Columbus Preparatory Program, endorsed at the ESA Ministerial level, addresses a broad range of Space Station elements for both initial and long-term operational scenarios.

In order to further coordinate pre-definition activities and share status information, three international workshops were held in Washington, D.C. in 1984 at which preliminary guidelines for international cooperation in the programme were presented by NASA and discussed with officials from ESA, the UK, France, Germany, Italy, Canada and Japan. At the last workshop, a proposed set of technical guidelines was also presented and discussed. These will be discussed

further and evolve as Phase B studies are coordinated on compatible schedules in order that information will be available on all elements of the initial Space Station at the time it is baselined early in 1986.

The guidelines for international cooperation in the Space Station Program are based upon those successfully followed in more than 25 years of cooperative international activities. The unique, long-term nature of the Space Station Program, however, has given rise to an additional significant aspect of the international cooperation we propose. The fact that this programme will span several decades suggests that a true partnership will incorporate on all sides a commitment to utilise the Space Station. Consequently, we propose that the ownership and responsibility for sustaining engineering of internationally-provided elements will rest primarily with the international partner.

Agreement in the form of Memoranda of Understanding (MOU) to coordinate activities during Phase B will set the framework for cooperation during this phase. In addition, they will establish a process to identify elements for the initial Space Station that could be developed by international partners.

As noted earlier, the financial and technical responsibility for the international components of both Phase B and Phase C/D rests with the participating countries.

As of April 1985, a number of Space Station elements were under consideration by potential partners as candidates for international development. The ESA Columbus Program declaration includes the study of pressurised modules, unmanned payload carriers and ground support facilities. Canada has reported its intention to study construction and servicing facilities, solar arrays and remote sensing facilities. Japan is studying the concept of a multi-purpose experiment module. Each of these potential investments, if realised, would add significantly to the capabilities of the Space Station. And they could lay the basis for long-term, mutually beneficial partnerships in the Space Station Program.

7. COMMERCE IN SPACE

In the US it is believed that the private sector role in space will increase substantially in the future. A key dimension of US national space policy is to foster such participation. The policy states in part:

> "The United States Government will provide a climate conducive to expanded private sector investment and involvement in space activities, with due regard to public safety and national security."

Space is already commercialised. In the US and Europe, the communications industry is now to a greater degree space-based. In the UK, for example, industry has benefited from an early recognition that communications satellites are a profitable undertaking. Expendable launch vehicles and upper stages are presently subjects of commercial investment. Efforts to make remote sensing from satellites profitable are underway in France and the US and materials processing is also a candidate for space-based commercial activities. Research in Italy, Japan, West Germany and the US point to a potentially large market for materials processed in space.

In response to a recent Presidential directive intended to accelerate participation of the US private sector in space, NASA has begun to re-examine its own role in fostering the commercial utilisation of space. New policies and accompanying organisational changes are to be expected. The Agency realises that the initial front end risks of space ventures must be reduced. It understands that the research data base supporting such ventures must be expanded. It also understands that respect for intellectual property and proprietary data are essential requirements for any commercial endeavour in space. It is recognised that for space to realise its true commercial potential, practical-minded businessmen must be convinced that their company can profit by going into space.

In planning the Space Station, NASA has focused on ensuring that the Space Station is beneficial for use by customers, one category of which is expected to be commercial enterprises. The benefits to commercial customers of an operational Space Station in orbit and "open for business" are multifold. The Station itself, as a permanent facility, offers the kind of programme stability and continuity that private investors seek. Another benefit is the capability represented by the pressurised laboratrory module(s) that will serve both science and commerce. Another is the repair and assembly capability the Space Station will have. Still another, and perhaps a critical one, is the presence of man, permanently and without the constraints of time on-orbit associated with present space activities.

Further into the future, as new technologies mature and as experience is gained with the Space Station's repair and assembly capabilities, commercial prospects look even brighter. Indeed, it is not difficult to see a dedicated module, or even a separate Space Station, owned by private business, devoted exclusively to commercial operations.

8. CONCLUSION

The US has embarked upon a new challenge that will enable all participants to realise a new level of capability in space. The Space Station will provide a permanent human presence in orbit around the Earth. It will be a truly versatile facility, one that will expand the frontiers of knoweldge, push the development of technology and stimulate commercial enterprise in space.

It will provide for the accumulation of knowledge through its discoveries in fundamental physics, the study of terrestrial processes in the absence of gravity, and in the study of the Earth, the Solar System and the Universe itself. The Space Station will also contribute to our intellectual strength by serving as an intellectual stimulant to future generations. In general, the space programme has done many things to move our young people in the direction of technical education and academic excellence. This is genuinely important, not only to the space venture, but also to the strength of any international programme.

The Space Station will be a symbol of international cooperation. In the 1984 State of the Union Message, President Reagan spoke of the rationale for making Space Station a focal point of peaceful cooperation in space. The President's invitation underscored his convictions that an international Space Station will provide a focal point for space operations well into the 21st century and that international cooperation in this programme can be mutually beneficial to both the US and its partners.

NASA looks forward to such participants and is dedicated to making the Space Station a legacy of this century to the next. NASA looks forward to working with its friends in Europe as well as in Canada and Japan to make it one that is of true benefit to all.

NASA's goal is to make the Space Station a true and highly visible symbol of international cooperation in space as well as a place where men and women of many nations can live, work and learn. While some may want to focus on the risks inherent in undertaking a collaboration of this magnitude, it is believed that there are much greater risks in not making the effort – in failing to try. Only by taking the next great step together can one truly keep alive the splendid possibilities that await these joint endeavours.

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ASSEMBLY AND MAINTENANCE OF SPACE PLATFORMS

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A proposed Space Platform configuration is examined from an assembly and maintenance viewpoint. The new possibilities in space system design are discussed with emphasis on ways to reduce initial and recurring costs. Regular maintenance cost factors for very long life operations are reviewed.

1. INTRODUCTION

An evolving configuration of the optimum Space Platform for the early 1990's is providing a focus for consideration of practical assembly and maintenance operations. The various systems and prospective payloads will interact during the preliminary design phase. New design drivers are in-orbit construction and maintenance. The Space Platform will be much less constrained by launch vehicle accommodation. During the long operational life of 20 years or more there will be various hardware failures. Repair of failed elements of the Space Platform system will be a routine part of mission operations.

Maintainability can be divided into two operations modes. First, the Space Platform or Manned Space Station must be sufficiently autonomous to maintain operations or at least power down in a stable way in order to allow subsequent repair action. This can be considered as hands-off operations maintenance. Hands-on maintenance involves physical technical intervention to effect repairs. The hands may be astronaut gloves or a robotic manipulator. The development of both modes of maintenance is the main avenue towards increasing space system capabilities. Larger space systems will emerge to increase productivity in communications, remote sensing, materials processing and exploration. In-orbit assembly and maintenance will become standard practice for long life growth-compatible systems.

2. ASSEMBLY

2.1 Schedule

Four assembly scenarios are apparent:

1. Shuttle-launched, deployed/erected and commisioned.
2. Shuttle-launched to early Space Station followed by deployment/erection and commissioning.
3. Shuttle-launched to Space Station with a Servicing Base for subsequent operations.
4. Ariane-launched and supported by robot servicing vehicle or Hermes mini-shuttle.

The choice of assembly mode will depend on the project timing. An early start would lead to the Space Platform (SP) being ready for flight before the Manned Space Station (MSS) was sufficiently large to provide assembly/servicing facilities for non-MSS systems. A polar Sun-synchronous orbit mission will be Orbiter-based until a polar orbit MSS is constructed. The configuration and compatibility of MSS servicing workstations has not yet been defined but the need for it to be highly utilised would drive the facility design towards compatibility with the Space Platform and all other foreseen in-orbit assembly/servicing missions.

It is thus fair to assume that the Space Platform in its Shuttle Cargo Bay launch configuration will be accommodated on the MSS. The assembly operations from Orbiter or MSS will therefore be very similar but with more relaxed timelines for MSS. As with all systems studied for the Space Station era, the assembly task will be performed with a combination of robotic systems and manned EVA. Initial Space Platform assembly will be based on the anticipated equipment inventory and STS Orbiter constraints [1].

2.2 Infrastructure

The greatest advantage of the SP must be clearly appreciated. It is capable of growth and adaption to suit advancing technologies and customer requirements. The maintenance scenarios will also evolve to reduce recurring operations costs.

In Orbit Infrastructure (IOI) elements such as the Orbital Maneuvering Vehicle (OMV) and telepresence robotics are sources of programme schedule risk if included in the baseline scenario. The advantages of OMV operations to increase Space Transportation System (STS) delivery of payload to the Manned Space Station or other near Earth orbit facility that is above the nominal Shuttle orbital altitude of 150 nm (277 km) are attractive [2]. Initial lowest risk use of an OMV would be as the attached Propulsion Module (PM). The PM would not have free flight capability, thus reducing development effort required for baseline operations. Complete return of the Space Platform to the Shuttle Orbiter would be mandatory.

A step forward would be the inclusion of configuration change capability while remote from the Orbiter or MSS. This would entail the operation of a Telepresence Robot Arm system. Two options are apparent: locating the arm on the SP or on the OMV. The first requires high mechanical reliability without any servicing during the normal maintenance/payload servicing sorties of an OMV system (servicing the servicing tool would be problematic). The technological and programme risk of this approach would be unattractive.

Similarly, the full capability OMV/TMS equipped with multiple arms, to 'hang' on to SP and simultaneously work on the Platform and its Payloads, will appear only after a systematic development and demonstration mission programme.

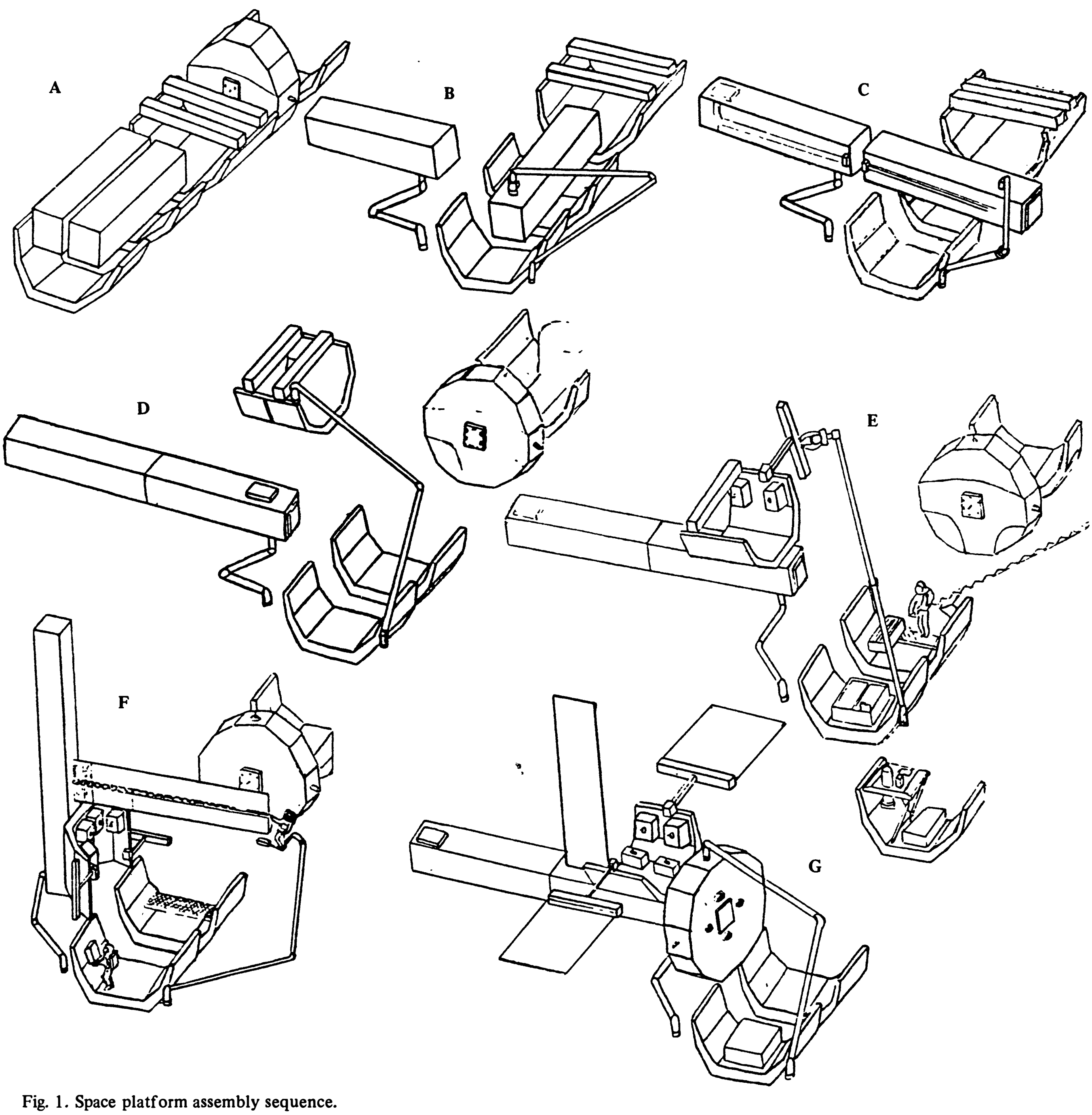

Fig. 1. Space platform assembly sequence.

The SP does provide a focus or such Technology Demonstration Missions. The TDM should be considered as payload and not part of the initial baseline Platform System.

2.3 Orbiter Sortie Operations

The Space Transportation System Orbiter will have a relatively short mission duration of seven days, typically. Assembly equipment will be limited to Remote Manipulator System units (1 or 2) and/or the Handling and Positioning Aid (HPA) that is under consideration by NASA [3].

Two paired astronaut EVAs per mission are standard capability. STS mission rules at present dictate that a full day must elapse between EVA sorties. The Orbiter Airlock can accommodate only two suited astronauts. The space suits presently used are pressurised at 4 psi (0.3 bar). This requires the reduction of the Orbiter cabin pressure and a lengthy decompression cycle for the two suited crewmembers. A 0.6 bar suit is being developed and can be assumed to be operational in time to support initial Platform assembly.

STS Orbiter Servicing Facilities are:

1. Sortie operations for seven days.
2. Remote Manipulator System
3. Handling and Positioning Aid (proposed)
4. Extravehicular Mobility Unit (spacesuit)
5. Manipulator Foot Restraint ('Cherry Picker')
6. Tool Kit

7. Manned Maneuvering Unit
8. Man-in-the-loop

2.4 Assembly Scenario

This section will consider the initial assembly and subsequent reconfiguration operations of the baseline Space Platform concept.

With Orbiter cargo bay doors open the Space Platform modules will be exposed to space as a complete suite of modules. Environmental testing will not have been performed on the complete system on Earth. The Orbiter will be equipped with the Remote Manipulator System and the Handling and Positioning Aid which is a shorter, stiffer arm intended to provide a berthing point for spacecraft and upper stage to payload mating in the cargo bay [4].

The HPA will be activated and driven to a position ready to receive the first section of Payload Arm carried on two half pallets (Fig. 1a). A payload berthing point on the Payload Arm will serve as the interface to the HPA. The RMS will withdraw the Payload Arm section after latches have released it from the pallets. The second section of Payload Arm will then be released and moved by the RMS into alignment for the connection of the two sections (Figs. 1b and 1c). Further study is required to determine the optimum configuration of the arm joint. Service lines may be pre-connected by means of looped lines and the arm joint hinged to allow a 180° swing to lock position. This would eliminate only one of many sets of in-space connections so the arm sections will probably be totally modular to allow for future growth.

When the structural connection of the Payload Arm sections is complete the RMS will be used to remove the Resources Module from the Orbiter and locate it above its berthing interface at one end of the Payload Arm (Fig. 1d). Depending on the reach of the HPA, the arm may have to be re-docked at another berthing interface on to the HPA before the Resources Module can be attached. The Space Platform modules will be equipped with EVA provisions such as hand holds and portable foot restraint system attachment points.

The docking of the RM to the PM would be done without manned intervention as all the necessary drive units would be incorporated into the active berthing port on the RM. Either limited internal or external power would be required to effect the operation of the active berthing interface. Auxiliary power can be provided *via* the RMS.

Two astronauts would egress from the Orbiter airlock and make ready to engage the Payload arm interconnects (Fig. 1c). The connector system would be of a common design so that standard tools such as a motor-drive unit would be positioned and activated to operate the connector drive-in systems. The astronauts will move on to the RM and effect the initial deployment of the solar array masts from their launch stowage positions to where the folded blankets of cells can be extended (Fig. 1e). This EVA task will greatly simplify the design of the solar array system as automatic deployment mechanisms will not be required.

While one astronaut deals with the solar arrays the other can deal with the installation of the main communications antenna/power amplifier module at the aft end of the RM. The Antenna Module would be released by the astronaut and transferred from its launch position on one of the half pallets by the RMS. The attachment point of this appendage would probably be directly into the communications ORU (Orbital Replacement Unit) if access geometry permits.

The erection of the thermal radiator mast and panels is possible when the top of the Resources Module is clear of solar array hardware. The kit of parts will consist of columns or unfoldable truss segments with quick connect joints developed for compatibility with spacesuited assemblers [5,6,7] (Fig. 1e). The RMS will be controlled by a crewmember within the pressurised cabin to transfer a crate of mast parts to a workstation in the forward area of the Cargo Bay. With feet firmly anchored by a foot restraint, the astronaut will rapidly build a mast. In order to hold the mast in a safe, stable attitude as it gains length a guide assembly will be provided as special tooling. The astronaut will attach a section and then push the mast through the guide until the next attachment point is reached. Finally, a baseplate will be fitted and the mast will then be ready to move to the Resource Module or a mounting point on the Payload Arm. The structure will be strong enough to take the acceleration loads imposed by the Propulsion Module. A strut, to take Propulsion Module acceleration loads, may be required to reduce the mass of the mast. An astronaut will supervise the RMS positioning of the mast and activate latches to secure it.

As this work progresses, the astronaut who built the mast will return the now-empty crate and unlock a second containing the radiator panels. The RMS will collect the crate, which will be configured as a Manipulator foot restraint workstation. The astronaut at the mast will lock into the foot restraint on the crate from where panels can be reached, removed and placed on the mast (Fig. 1f). The crate may be designed to dispense panels in a way similar to ammunition magazines. The panels will be plugged into the mast. The fluid connection will be made either at the plug-in stage or after there is a structural lock-in.

The optimum configuration that will allow redundancy and survivability of coolant circuits and indepdendant faulty panel removal is yet to be studied. The thermal subsystem will then be charged with fluid. Activation of the Resource Module will commence at this stage so that the pumps can be operated and the system can serve the other Platform ORUs as they are progressively powered up. The Freon will be stored in a pressure feed tank carried in the cargo bay. The transfer may be made *via* the HPA fluid coupling or by a more direct connection at an accessible Berthing Port such as the one opposite the RM. The HPA would place the aft end near to the Freon loading station where the astronaut would make the connection. The radiator will be checked for leaks by a sensitive mass spectrometer to detect Freon-12 as the astronaut is carried past the entire radiator mast by the RMS. Corrective action would be taken if a leak was detected.

After six hours of EVA the two astronauts will retire to the Orbiter airlock. During the mandatory rest day, Space Platform systems will be checked-out by mission control *via* the TDRSS link. The RMS and HPA will be used to relocate the Propulsion Module (Fig. 1g), Payload Module and possibly the Instrument Pointing Systems. Both modules will be docked in the normal teleoperator mode. System checks will continue with any problems logged for attention on the second EVA. The solar arrays will be cycled through a complete deployment and retraction to the transfer-boost configuration and the array drives rotated, as will all mechanical devices such as instrument doors, navigation star trackers and payload mechanisms.

If satisfactory performance is confirmed, the Platform AOCS will be given orbital state vectors and then released for free flight checks with the Orbiter still available nearby. A re-docking will be made to allow for a second EVA to complete any contingency tasks. If nominal progress has been made to this point, servicing procedures will be evaluated where removal and re-installation of an ORU will be performed by the RMS and by the astronauts in order to compare simulations with the actual situation. Once declared fully operational, the Space Platform would be released to start its first mission.

2.5 Rationale

The Space Transportation System allows greater flexibility in spacecraft design. Philosophies based on expendable launcher accommodations do not have to apply to payloads with the Orbiter. For example, unmanned launches require that the payload is equipped with mechanisms to effect the deployment of antennae, solar arrays etc. The cost of a six hour EVA consisting of two astronauts equipped with standard STS EVA equipment [1] is quoted as $200,000. The cost of developing an Antenna Deployment Mechanism can approach this so that a full complement of deployment mechanisms would exceed the cost of an EVA. After the satellite is raised clear of the cargo bay, an astronaut simply retracts a launch lock pin, swings an arm carrying a dish reflector and re-inserts the locking pin.

The development time for a spacecraft could be significantly reduced as the cost certainly would be for a Shuttle dedicated design. Since the Space Platform baseline is such a case, awareness of the simplifications that are possible must be impressed on the designers. A substantial inventory of equipment that is flight qualified now exists. It should be the first choice before new designs are required. The modularity principle ensures that assembly and change-out is a straight forward matter given the appropriate tools. Only the solar array retains a significant mechanical actuation capability because of the need to retract during boost phases. Even the solar array system could be simplified if trade-off studies show that a more robust manually deployed (non-retracting) design can tolerate the relatively mild acceleration caused by the Propulsion Module main engines. The Radiator Mast could be a deployable system but it is felt intuitively that the development cost is not justified when a lower mass design can be produced that requires manual erection and has good stiffness characteristics.

The cost attributable to deployable appendages requires trade studies of the mechanism option compared to the EVA option. The design, development, manufacture and flight qualification cost has to be assessed. Similarly, a simple manual operation design must be costed and the procedures verification costs added along with user chargable cost for STS operations. When project resources are considered, a strategy that maximises the utilisation of existing techniques, such as the EVA capabilities, will be a more efficient utilisation of funds.

2.6 Design Drivers

Structure:
Grapple fixtures for manoeuvring Platform elements in orbit.

Latching system to hold Payload Beam sections within the cargo bay.

Stowage for the various erectable elements of the Space Platform in order to withstand the launch loads.

Fastener commonality.

Electrical:
Minimal interface with the Orbiter. A power management panel in the Orbiter aft flight deck can be equipped to provide isolation of power for heaters and essential avionics. Essential power for SP must be supplied from batteries during the assembly phase.

Safety:
Manned space flight rules will apply.

Two fault tolerant safety provisions will be mandatory with special consideration of Propulsion Module, Appendage Deployment, Assembly sequence to allow for mission aborts from orbit, Remote Manipulator System (RMS) and Handling and Positioning Aid (HPA) Translations. Pyrotechnic bolts are to be avoided.

EVA:
Astronaut Paths, Work Positions, Accessibility of Work Areas, Manual Extraction or Retraction, ORU Handling, Compatibility with RMS, Manipulator Foot Restraint and Astronaut, and Manned Maneuvering Unit and Astronaut in Extravehicular Mobility Unit (Spacesuit).

Tool simplification and commonality.

3. MAINTENANCE

3.1 Constraints

Opportunities to carry out maintenance/servicing activity on the Space Platform will be limited by celestial mechanics and the In-Orbit-Infrastructure.

The first restriction dictates the propulsion system requirements and deliverable payload. Access to the SP operational orbit will be as restricted as access to lower orbits occupied by the Manned Space Station or Shuttle Orbiter. There are several rendezvous and servicing scenarios. The choice is dependant on many interrelated factors including timescale, support equipment, service availability and cost.

The major factors to be considered are:

1. OUTAGE TIME COST to customer and platform operator due to:

   Scheduled Maintenance
   Unscheduled Maintenance
   Failure.

2. PROPULSION COSTS

   Move complete Platform
   Move experiment carriers
   ORU exchange
   Expendable replenishment (fuel)
   Propulsion Module servicing cost
   OTV servicing cost.

3. ACCOMMODATION COST FOR SERVICING:

   At Platform in operational orbit
   At Shuttle on a servicing mission
   At the Manned Space Station:
     for Platform
     for Experiment Carriers
     for ORUs
     return to Earth refurbishment
     specialist servicing crew.

4. ROBOTIC TELE-OPERATOR (remote from manned servicing facility):

   ORU standard interface
   Locations
   Handling Sequences
   Experiment carrier support
   Versatility factor for unplanned tasks
   Mobility/power source
   Servicing of teleoperator cost.

5. MANNED EVA SERVICING

   As above for Teleoperator
   Special tooling and versatility factors
   Life support logistics
   Manned OTV 'Tug' costs.

6. REFURBISHMENT

   At Platform
   At MSS
   At Shuttle
   Return to Earth:
   at launchsite base
   at Equipment manufacturer
   at SP operations centre.

7. SPARES:

   Modules at ORU level
   Modules for replacement within ORU
   Parts for strip and re-build in orbit at a servicing workshop on MSS.
   Logistics: Earth-orbit-Earth
   In space spares storage.

8. GROUND SUPPORT

   Training and training facilities
   Procedures verification/test
   Tool development
   Mission Control Centre
   Mission support at launch site
   Refurbishment locations.

When attempting to determine the servicing configuration of the Space Platform the following points are apparent:

1. The servicing capability of the Manned Space Station will become available only when additional capability has been added after the Station has been established in its minimum module baseline configuration.

Before the Space Station era:

2. Satellite and Space Platform servicing will be conducted from the Shuttle Orbiter.

3. Substantial experience will be derived from the Orbiter's role over the next 7-8 years.

During the Space Station era:

4. Servicing equipment/tools developed for the Orbiter will be used at the Manned Space Station.

5. The Orbiter will continue to service satellites and the Space Platform in certain orbits such as Polar Orbit.

3.2 Maintenance Scenarios

The baseline Space Platform servicing locations are:

- At the Shuttle Orbiter
- At the Phase 1 Space Station
- At the Phase 2 Space Station with a satellite/OTV servicing base
- At a higher orbit accessed by an unmanned Teleoperator Service Vehicle

The recurring tasks will be:

- Exchange ORU's
- Repair/replace *in situ* systems
- Exchange Payload Modules
- Service Payload Modules
- Reconfigure Platform for new payloads (including control software)
- Exchange Propulsion Module
- Fluid Transfer

3.2.1 Orbiter Servicing Sortie Mission

The implication for the Space Platform is that the servicing scenario will be similar to the initial assembly scenario. The Platform will be commanded to perform orbit change burns that would place it within rendezvous range of the Orbiter. The RMS will make first contact and once locked to a grappling trunnion it will draw the Orbiter and Platform closer. A hard dock to the Handling and Positioning Aid at a berthing point on the Platform will follow. The Platform can then be positioned to provide visibility of a work area to the crew at the aft Orbiter flight deck windows. Orbital Replacement Units that have been designated for replacement by fresh units will be disconnected by means of the RMS.

The ORU will be attached to a temporary holding point while the RMS is driven to remove a new ORU from its launch pallet and transfer it to the Platform's Resource Module. With a new ORU in place, telemetry will be analysed by Platform Mission Control to assess the correct functioning of the new unit that is now connected to the Platform system. A similar sequence will occur for Payload Module changeout. The RMS will be attached to the PM and the Berthing point will be commanded to an un-locked mode. The new PM will be installed in the reverse sequence.

Propulsion Module exchange will also be required but refuelling may be all that is required as servicing options expand. After assembly and nearby free flight trials, the Space Platform will use its Propulsion Module to attain a higher operational orbit with the required phasing. In order to rendezvous with the Orbiter for subsequent servicing, the Propulsion Module will be used to return to a Shuttle-optimum orbit. A regular task at each maintenance visit will be the replacement of the Propulsion Module. This can be arranged by means of a propellant transfer from a tank kit in the Cargo Bay. However, the propulsion system may be in need of servicing so it may be more cost effective to exchange the entire Propulsion Module with a fully fuelled and checked-out unit. The interface between the PM and SP is expected to be a standard berthing port. Thrusters are to be used only on the PM, thus further simplifying the interface. Complete Propulsion Module exchange would also eliminate propellant transfer systems that would have to reach out to the PM still attached to the large SP. Propellant transfer operations proposed for the near future involve spacecraft that can be accommodated within the cargo bay, as was Solar Max.

The exchange of Propulsion of Payload Modules will be by means of the RMS controlled from within the Orbiter. The adoption of a standard Berthing Port will enhance these operations.

3.2.2 OMV Servicing Scenario

The availability of the Orbital Maneuvering Vehicle (OMV), or Teleoperator Maneuvering System (TMS) as it was formerly called, will increase the operations scenarios and cost options. In the OMV-assisted mode the Orbiter would attain an optimum circular orbit. The OMV would then be released with the Payloads, ORUs and propellant for the Space Platform which would still be in its higher operational orbit. The transfer and rendezvous would be completed over several orbits [2]. Either the OMV or the

SP would have to be equipped with a robot arm with an end effector kit to provide the dexterity needed to allow ORU and Payload exchange. Propellant resupply would be similar to the unmanned approach developed for satellites in GEO.

The above Teleoperator mode of Space Platform servicing will require a significant increase in the flight readiness of Teleoperator Technology. Dependence on this hardware for initial operations would be an unnecessary project risk. Such developments will occur as a reduction of operating costs can be demonstrated.

3.2.3 EVA

There will be a level of activities that will not be achievable without EVA. Minor modifications and repairs will be done during the two-man EVAs of a standard STS mission. Equipment that is not packaged within an ORU will also need to be serviced. Erected elements needing attention will be reworked by EVA. This could include tasks such as replacing a faulty part of a solar array or star tracker. Replenishment of consumables may well be an EVA-dependent task in order to minimise automated equipment development costs.

Such a servicing sortie requires that the servicing tasks are all timelined and procedures are proved prior to flight. This requires a complete diagnosis of the Platform condition from telemetry. Contingency tool kits will be provided for repairs that are deemed necessary from on-site inspection by the astronauts.

3.2.4 Space Station Servicing Base

The performance of the Servicing at the Space Station [8, 9, 10] will relax the time constraint and reduce the mission specific hardware inventory that would have to be launched and charged to the user on an Orbiter servicing sortie. Major refurbishment will be feasible at the Space Station.

It is likely that the Space Station will evolve into a servicing and assembly base for other space systems. Facilities can be expected that will be adaptable to suit all foreseeable in-space assembly, service and test tasks. The amount of activity will prove to be unacceptable to many users. They will opt for free-flying platforms from which to conduct their experiments, observations or materials processing.

When a pressurised workshop module/facility is provided it will be feasible to plan for ORU repair in-orbit. Replacement components would cost less to launch than a complete ORU. As a principal user, the Space Platforms would impose requirements on the Manned Space Station servicing facility. Such requirements must be identified and detailed during the Phase B study of the baseline configuration. Some studies have already attempted to catalogue servicing facility features but an actual user system will make the greatest impact on Space Station Servicing Base architecture.

Orbiter-based servicing will require specific pre-mission planning. All tools, Orbital Replacement Units, repair kits and exchange payloads will be constrained by the single launch, limited in-orbit stay and limited EVA time. Space Station based servicing will be less constrained in terms of time. The Phase 1 Space Station will not have extensive satellite servicing facilities. A hard dock berthing may not be possible or desirable until navigation procedures in close proximity to the MSS are established. Early servicing may thus be done with the Space Platform co-orbiting at a safe distance. A Teleoperator Maneuvering Vehicle or astronauts with Manned Maneuvering Units would be required. If extensive servicing similar to that which can be performed on the Shuttle Orbiter is required, the free flying, co-orbiting, option will not be satisfactory.

Research so far has indicated that the most efficient arrangement for servicing is achieved with the aid of a Remote Manipulator arm. Massive items can be safely and quickly moved and an astronaut can be held at a workstation without the aid of fixtures on the craft being serviced. All reaction forces are "grounded" by a structural path. A spacecraft will be held on a servicing stand/cradle or it will be held by a Handling and Positioning Aid that is a RMS-optimised for very large masses such as Orbiter to Space Station links.

Thus remote servicing will require that the Teleoperator system has some of the above described capability. Without a structural "ground" the Teleoperator system will have a high attitude control thruster propellant usage and hence higher operating costs. Early trials of a teleoperator system could be conducted on the Space Platform co-orbiting with the Space Station.

The Phase 2 Space Station will have provision for the support of Orbital Transfer Vehicle operations. The cryogenic-fuelled "Space Tug" is expected to have hangars for Tug storage and an integration facility where satellites that have been assembled for use in geostationary orbit are mated to the Tug. In order to generate maximum revenue, the facility will cater to many IOI systems including the Space Platform. The Earthly analogy is the maritime dry dock [8, 9, 15]. Many artist concepts have been published but the most versatile and safe idea is the large hangar; depicted as a large open-ended box. Spacecraft assembly or disassembly would be done within the hangar for protection of astronauts and equipment. Only very large appendages such as antenna reflectors and solar arrays would require work to be done away from the hangar.

Internal features of the hangar would include Remote Manipulators and "cranes" for linear translation of equipment. Airlocks and pressurised workshops would be attached, as would Manned Maneuvering Unit service bays. Pressurised workshops will permit more intricate repairs without the encumberance of spacesuits. Skylab and Spacelab experience has shown that complex repairs can be made to devices such as tape recorders and instruments while in zero-g. Laminar flow work benches will drag loose parts towards a grill for retrieval.

4. PHASE C/D DESIGN AND MANUFACTURE

4.1 Awareness

It will be essential to have a close liaison between all participants at the Servicing architecture level. Since servicing capability will develop from existing STS capability, a two way information network must be established. Prime contractors for IOI systems must have a focal point within their organisation for guidance on assembly and servicing aspects. If clear systems configuration control is not instigated early in the product life cycle the maintenance scenarios may be more expensive with programme schedule and cost impact.

All major system designers must allow for serviceability:

1. Everything is eventually replaced. The principle requires development of maintenance and checkout systems.
2. Failure detection
   - ORU status monitoring
   - Fluid loss sensors and shut-offs incorporated in disconnects and vulnerable points.
3. Repair technique development for non-ORU items
   - Punctured fluid line by-pass hardware and tech-

niques
- Failed valve replacement
- Damaged docking connector repair
- Thermal control coating repair
- Repair or replace criteria

4. ORU servicing
- Simple replacement task
- Standardised transportation
- Integration at box level
- Commanality and reduced manufacturing costs

5. Distributed System Servicing
- Sensors, fluid and electrical lines, structures etc.
- Difficult for robots: extensive EVA
- Plan for access
- Design for reliability
- Safety

4.2 Autonomous Space Systems

In the past, and to a great extent today, spacecraft have been controlled largely by ground personnel with support from mainframe computer systems. Future spacecraft will have to be less reliant on ground controllers and equipment in order to minimise recurring operations costs and staffing problems associated with very long duration missions. The capabilities of automation hardware and software will allow highly autonomous spacecraft operations [11].

The Manned Space Station specifications call for five days without routine Space Station ground support and 24 hours without any communications with the ground.

An important operating capability will be the controlled degrading of operations as systems fail and back-ups are switched in. In an extreme scenario the SP would have to power down into a stable mode in order to allow subsequent repair. The challenge for Artificial Intelligence technology can be summarised:

- On-board autonomy
- Built-in test equipment
- Expert systems
- Manned Space Station rules.

4.3 Manufacturing Costs

The new technology field of Artificial Intelligence and autonomous operations will have to be applied on the ground during hardware manufacture. Built-in test equipment will have to automate testing of sub-systems during manufacture and subsequent integration. The quality assurance philosophy will have to accept this reduced level of testing.

The same tests will be conducted in orbit. In order to cope with reduced reliability, redundant systems will be provided with autonomous switch-over in the event of a failure of the primary system. All concerned with the design and manufacturing effort will have to realise that replacement or repair of the failed system will be routine during servicing operations.

The potential cost reduction through reduced quality assurance procedures has been offered as a means of cutting acquisition costs. This is fine in theory but will require the undoing of much space engineering orthodoxy.

5. OPERATIONS

5.1 Transportation

Servicing missions could be conducted by teleoperation with no return-to-Earth capability. The drive towards reusability would make this scenario unlikely. Shuttle-based servicing would include the return-to-Earth capability for all Space Platform-related hardware. Similarly, Space Station-based servicing missions would make recycling of hardware feasible; either in-orbit or by a return to Earth and subsequent relaunch.

TABLE 1. The Essential Earth to Orbit Transportation Cost Comparison. Inter-Orbit Transportation Costs Must be Added to the Basic Launch Cost.

	STS	A5/Hermes	SSTO
Cargo Bay	4.5 m dia 18 m	3 m dia 7 m	4.5 m dia 9 m
Polar Orbit 500-800 km			
Payload (Tonne)	16.7	1.5-2.5	4
Crew	6-7	2-4	
Cost (MAU/Tonne)	5.2	28	1
MSS Orbit: 400 km			
Payload (Tonne)	29.0	4.5	9
Crew	6-7	4-6	
Cost (MAU/Tonne)	3.0	15.5	0.5

The prospect of a Hermes orbiter supporting Platform operation needs consideration as well as the STS. Some preliminary comparisons are given in Table 1.

The cost of the Ariane 5 launch is expected to be approximately 60 MAU. For the Hermes mini-shuttle a detailed costing of missions would be premature but a parametric comparison of STS costs indicates that the transportation cost can be expected to be approximately 70 MAU per launch. This is based on the operating cost breakdown of the US STS [12, 13, 14]. Similarly, the payload mass delivered to the reference orbits is still a matter of speculation.

A single-stage-to-orbit recoverable transportation system such as a second generation Shuttle or the HOTOL concept would have a specific cost of 0.5-1.0 MAU per tonne [13]. Ultimately, the recurring transportation cost will be significantly reduced by such a fully re-usable launcher.

Servicing mission scenarios can be devised for any launch system; recoverable or expendable. Non-recoverable options would seem to be undesirable for any potential Platform or Space Station user that they can be excluded for low Earth orbit missions. The use of the Hermes concept for servicing would have to be based on other than economic considerations. Only when the Shuttle cargo bay is grossly underutilised would the Hermes system approach Shuttle based servicing costs. Beyond basic transport costs, servicing equipment development would impose redundancies in the In-Orbit-Infrastructure. Such duplication of the Remote Manipulator System, for example, is unlikely to be justified within the international Space Station partnership. Teleoperator systems will be developed but an expendable Ariane launcher would only be cost effective for initial delivery of the equipment.

5.2 Maintenance Support on the Ground

Space Logistics is, to some, a new aspect of space operations. It arises out of the operation of long-lived, standardised systems such as space transportation systems. Some US launcher systems have been operated for more than 25 years.

There is also a trend towards standardisation of spacecraft such as the Hughes 376 communications satellite bus.

A number of logistical problems that occurred for these systems can be expected to be experienced in future space operations. Some of the more significant of the problems were:

1. Insuring a continuing supply of critical components, some of which eventually represent obsolete technology.
2. Maintaining continuity of production of consumable items in the face of uncertain and variable future use rates, and frequently, low overall demand rates.
3. Maintaining production and testing quality standards necessary for aerospace reliability over extended periods of time.
4. Obtaining industrial support for low-volume high-standard aerospace component production when lower-technology, higher-volume markets are available (particularly in electronics).
5. Making effective decisions on levels of stockpiling of lot-produced items (in most cases, eventual requirements were under-estimated).
6. Replacement of key manufacturing or operational skills lost through personnel attrition in long programs.

In planning for the Space Platform, potential problems like these must be anticipated. To do the necessary planning, new or previously unapplied techniques must be used.

"Front-end" logistics analysis has been used in military logistic probelms where there is early recognition of logistic operations as a major systems element. This will certainly be the case for the Space Platform with transportation to orbit cost as the recurring cost driver. Trade-off studies must assess the sensitivity of operations due to the above listed variables. Where detail of the system is not available at the conceptual phase, the problem must be reduced to functional elements and resources computation factors assigned by similarity to existing equipment. The output of the analysis must be in engineering terms: change the technical requirements and assess the outcome in terms of resource consumption. Finally, the most influential parameters must be identified and controlled so that the design of the system will be successful over its entire intended life [10].

For the Space Platform project a first step will be to identify, at the start, those components, subsystems or systems based on rapidly changing technologies, and thus most likely to become obsolete over the possible life of the Platform system. The modular design should be used to allow the easiest replacement of such potential problem components.

5.3 Mission Control

The Space Platform Operations Center will need to be a small core organisation responsible for the continuous operation of the Space Platform over a period of several decades [16]. This will present challenges similar to those to be faced by the Space Station ground support organisation. The evolution of such bodies will be driven by cost reduction efforts. A high degree of computer surveillance of Space Platform systems can be expected. Logistics management and servicing sorties planning, training and operations might require the bulk of staff effort. In order to retain suitable engineering staff, it may be appropriate to roster operational servicing sorties in orbit amongst the permanent staff who would normally perform the ground support functions.

The Space Platform management organisation would grow and diminish depending on the market demand for new platforms and payloads. Interface control and documentation should be such as to minimise new user costs; thus encouraging new business.

A Space Platform Control Center is envisaged where most of the on-ground activities are based and administered. It would serve as a centre of European manned space flight operations with special facilities such as EVA simulation laboratories and neutral bouyancy tanks. Such training aids are most applicable to in-orbit maintenance operations.

6. EVOLUTION

The evolution of the space infrastructure will be influenced by the collective government/industry concensus on the need for in orbit assembly, servicing, refurbishment, repair, resupply and modification.

A major consideration will be initial cost and recurring operating cost. A trade-off is possible so that long term mission operating cost will be a more significant factor than the initial design, development and manufacturing cost.

The Space Station has been advocated as a means of reducing costs for many types of mission that would use it as a transportation, assembly and servicing node. Operational benefits of an operational space industrial infrastructure include:

1. Extended Lifetime: could be indefinite but would actually be limited by competition from more advanced systems with lower operational/life cycle costs.
2. Low Acquisition Cost: equipment reliability will not have to assure an operational lifetime of ten years as seen on communications spacecraft.
3. Improved performance through upgrades of the Platform Bus and the Payloads will be a normal aspect of operations with periodic servicing visits.
4. Multi-mission and multi-revenue versatility. The orbital facilities will be economic assets similar to terrestrial research facilities that continue to be used after completion or termination of the original project.
5. In-orbit autonomous operations will reduce the ground support, mission control, infrastructure. A small operations base will manage the orbital facility and its servicing. Standard interfaces will allow customers to make their own payload arrangements.
6. Technology Demonstration Missions (TDM) in the period 1983 to 1990 will prove a range of STS support equipment and techniques. Flight crews and space engineers will learn how to perform servicing tasks. The assembly of the Space Platform will itself be a major demonstration of in-orbit construction.
7. The unmanned Space Platform will, most likely, be operational before the Space Station. The initial mission may be in polar orbit since payloads of greatest maturity will be in need of the platform for remote sensing and astronomical missions.
8. Commercial ventures in materials processing in space will generate a demand for the unmanned Platform after trial operations onboard the Space

Station. From the mid-1990's, the SP can be adapted to co-orbiting missions with the MSS. Space factories producing pharmaceuticals, semiconductors and new space-unique materials will be supported by the Platform. Current studies indicate a man-tended scenario with pressurised modules to allow easy "shirtsleeve" periodic servicing between long periods of unmanned microgravity operation.

7. CONCLUSION

Space Station-related studies have reached a point where the major elements can be examined to establish ways of achieving operational advantages. The trend towards reusability will lead to space systems with indefinite operational lifetimes through a maintenance or servicing infrastructure. The unmanned Space Platform has the potential of promoting and maintaining routine in-space commercial industrial activity.

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SPACE PLATFORMS AND AUTONOMY*

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The term "autonomous systems" has come to signify a broad class of systems that perform complex control, management and implementation functions independently or in a fashion relatively independent of direct external, real-time control. Such systems find obvious application in the realm of space flight.

Because of the rapid evolution in this field, terminology might be a problem. The terms and definitions coming into more or less standard use at the Jet Propulsion Laboratory are presented as a precursor to a broad survey of the status and prognosis for autonomous and automated systems and the requisite technologies.

While autonomous systems find growing applications in all classes of space related activities, e.g., ground facilities, launch vehicles, sortie vehicles and Earth-departure spacecraft in particular, the focus of this paper will be application to space platforms, i.e., Earth-orbiting spacecraft with limited intrinsic mobility. Within the space platform category, interesting distinctions exist with regard to use of autonomous systems and automation, depending on whether such platforms are inhabited or uninhabited, multipurpose or relatively dedicated, and revisited (serviced) or not.

The question of where functional control resides (on the ground or in orbit) and the question of where and how human supervisory control is introduced are both keys to the application of autonomous systems. Each question must be answered on a case by case basis.

To analyse such issues and others associated with autonomous systems and automation of spacecraft functions, it is conceptually useful to apply the idea of functional partitioning which is described in this paper. The use of estimated life cycle cost or of life cycle cost and benefit approaches to autonomy/automation decision-making appear to be particularly appropriate for the dawning competitive era in which most potential users of Earth orbit will have a choice of platforms and modes of access. In general, the process of defining and designing the appropriate degree of autonomy or automation is made more difficult by the high levels of risk and uncertainty stemming from the newness and rapid evolution of the technology.

NASA's Space Station Program is becoming a major application of autonomous systems and automation. Some aspects of the programme with respect to autonomous systems and automation are described. Finally, a survey is given of what appear to be key technologies in areas such as operations-oriented languages, the human-machine interface, artificial intelligence and robotics.

1. INTRODUCTION

With the advances in automation techniques over the past decade, space operations are now moving toward more autonomy, even as a system becomes more complex. In the past, and to a great extent today, spacecraft have been largely controlled by ground personnel with support from mainframe computer systems. Future spacecraft will be less reliant on ground controllers and equipment because the rapid increase in the capabilities of automation hardware and software will allow highly autonomous spacecraft operations.

This paper is a survey of where and how autonomous space systems might be used for space platforms and their associated ground operations. Emerging automation technologies permit greater flexibility to choose where particular operating functions are performed. This flexibility introduces opportunities to reduce costs and/or to increase productivity by relieving onboard and ground personnel of tedious, repetitive, or complex fast response tasks that are better suited to machine function.

Space platforms, the subject of this paper, are orbiting facilities with limited inter-orbit mobility, long operational periods and perhaps some capability for configuration modification and exchange of payload elements. Definitions related to space platform autonomy, a description of general applications of autonomy, and a description of some methods of analysing potential applications are the topics discussed. The paper concludes with a discussion of the NASA Space Station concept as a major driver for autonomy implementation and a summary of the technologies most important to space platform autonomy.

2. AUTONOMY DEFINITIONS

Part of the problem in most discussions of autonomy is the lack of acceptable or standard definitions. The following definitions are becoming standard for discussions of autonomy at the Jet Propulsion Laboratory (JPL):

Spacecraft Autonomy. The independence of the man/machine flight system from direct, real-time control by the ground over a specified period of time.

Machine Autonomy. The independence of the machine from direct, real-time control by humans. Machine autonomy may be applied in flight or on the ground.

Automatic or Automated Process. A process that is controlled in a repetitive fashion until disturbed or modified by external inputs.

Autonomous Process. A process that incorporates control structure logic and internal and/or external sensory inputs to assess the appropriateness of its automatic functions and to modify the automatic process as needed.

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Algorithmic Autonomy. The mode or situation when a machine is programmed to respond to a predefined set of conditions with a predefined set of actions. The actions may be conditional, that is, "if this happens, do that." However, both the conditions and the responses are governed completely by the designer's ability to anticipate the situations that the machine will face. Therefore, algorithmic autonomy works best for well understood situations.

Artificial Intelligence (AI). "A discipline that attempts to make computers do things that, if done by people, would be considered intelligent."

Expert Systems. An artificial intelligence technique that is currently the most promising for practical application. These expert systems are "problem solving" computer programs that can reach a level of performance comparable to a human expert in some specialised problem domain. In most expert systems, the model of problem-solving in the application domain is explicitly in view as a separate entity or "knowledge base" rather than appearing only implicitly as part of the coding of the program. The knowledge base is manipulated by a separate, clearly identified control strategy, often referred to as an "inference engine." These systems use a combination of AI problem-solving and knowledge representation techniques.

Teleoperation and Telepresence. Remote manipulation in which humans are responsible for generating control signals. An example of teleoperation is the handling of nuclear material, where a human manipulates a glove whose motions are repeated by a mechanical hand, which manipulates the hazardous material in a remote location. Teleoperation requires that the human operator be able to see the object being manipulated, either directly or by visual sensors; while telepresence requires that the operator be able to receive feedback of the manipulative forces (i.e., "feel" what the remote manipulator is feeling). Effective teleoperation often requires that the user have a good sense of presence at the remote tasks (i.e., telepresence).

Robotics. Machines that perform with human supervision all aspects of an action, including sensing, analysis, planning, direction/control and effecting/manipulating.

Fault Tolerant Computing. Computers (hardware and software) tolerant of, and able to compensate for, internally and externally caused systematic and random errors, such as radiation-caused randomisation at the bit level ("single event upsets"). Particularly necessary where high speed computing and, hence, very small circuits are required.

Funtional Partitioning. Part of a logical process for making autonomy-related decisions, which consists of allocating or partitioning portions of functional descriptions of the Space Station between the ground and onboard and human and machine.

High Order (Procedure Oriented) Languages. Computer languages which permit an operator or designer with minimal programming experience to compose complex procedures for equipment testing and control. Procedures written in such a language may be executed directly on suitably equipped computing equipment, and allow the user to easily specify understandable input and output formats. Such a language may be employed in both flight and ground processors.

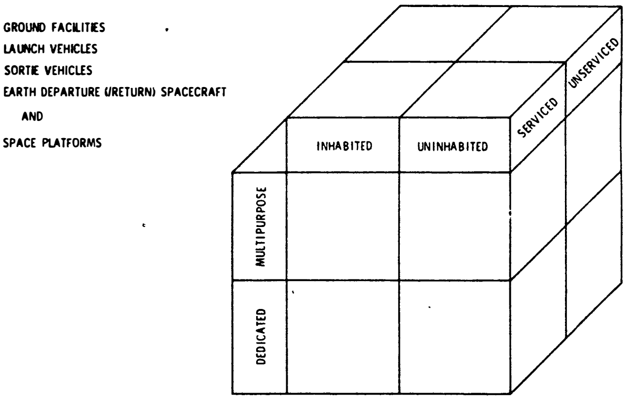

Fig. 1. Applications of autonomous systems.

	INHABITED		UNINHABITED	
	DEDICATED	MULTIPURPOSE	DEDICATED	MULTIPURPOSE
SERVICED	MATERIALS PRODUCTION FACTORY - CREW WELL-BEING - HUMAN PRODUCTIVITY - OPTIMAL USE OF SERVICING CAPABILITY	CORE SPACE STATION - CREW WELL-BEING - MISSION SEQUENCING AND PLANNING - HUMAN PRODUCTIVITY - OPTIMAL USE OF SERVICING CAPABILITY	HUBBLE SPACE TELESCOPE - OPTIMAL USE OF SERVICING CAPABILITY - RELIABILITY	SPACE STATION'S PLATFORMS - MISSION SEQUENCING AND PLANNING - OPTIMAL USE OF SERVICING CAPABILITY - RELIABILITY
UNSERVICED	SPACELAB - CREW WELL-BEING - MISSION SEQUENCING AND PLANNING - HUMAN PRODUCTIVITY	SPACELAB - CREW WELL-BEING - MISSION SEQUENCING AND PLANNING - HUMAN PRODUCTIVITY	COMMERCIAL COMMUNICATIONS SATELLITE - LONG LIFE - RELIABILITY	MOBILE SATELLITE-X - LONG LIFE - MISSION SEQUENCING AND PLANNING - RELIABILITY

Fig. 2. Examples and key functional requirements associated with the classes of space platforms.

3. APPLICATIONS OF AUTONOMOUS SYSTEMS

Autonomous systems and automation find application in all aspects of exploration and the utilisation of space. Different applications impose different functional requirements upon such systems depending upon the nature of the spacecraft and missions involved. Some key categories with respect to autonomous systems for use in space platforms (the focus of this paper) are shown in Fig. 1.

For our purposes, space platforms are defined to be Earth orbiting spacecraft with limited intrinsic mobility. Current or planned examples of the various categories of space platforms are shown in Fig. 2, together with key functional requirements associated with each category. The term "platform" encompasses the older term "satellite," but also includes a wider range of spacecraft than is usually evoked by that term.

In programmes now being planned or in development stages, the general trend in platform design is towards increased duration in orbit, with concomitant emphasis on servicing (e.g., physical revisitation for refurbishment and/or replenishment). Low Earth orbital platforms will be the first to be routinely serviced, with geosynchronous orbital platforms to follow, possibly by the late 1990's. Note in Fig. 2 that Spacelab is shown as "unserviced" in keeping with the definition of "serviced" platform implied above, i.e., a

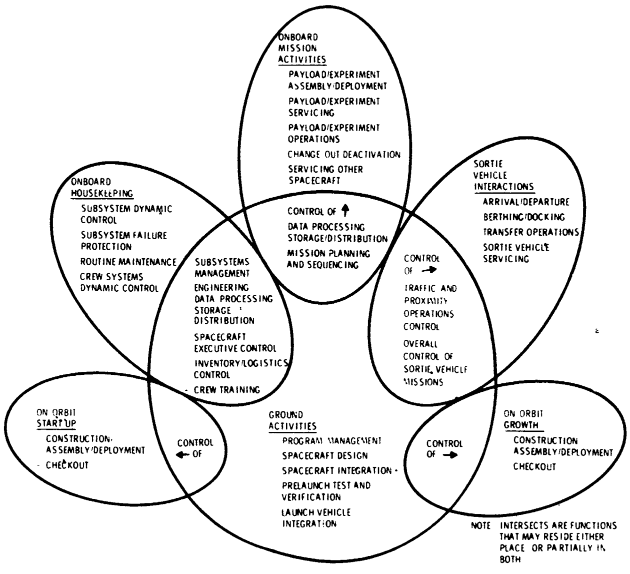

Fig. 3. Functional applications of autonomous systems.

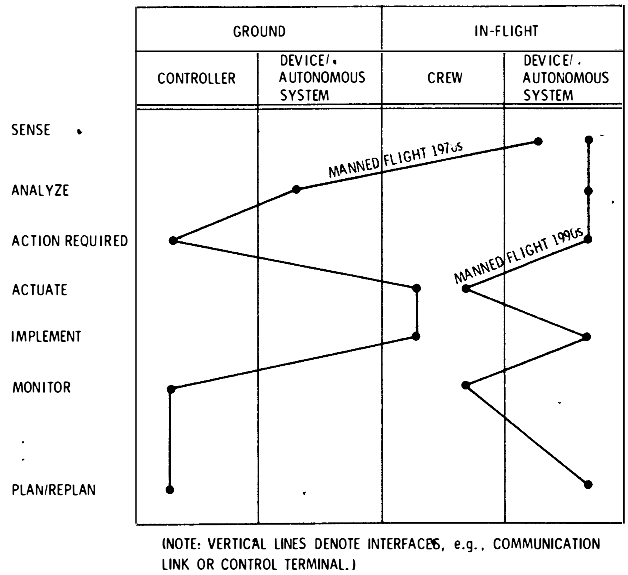

Fig. 4. The concept of functional partitioning.

space platform capable of independent existence on-orbit between visits of a sortie vehicle.

In the category of unserviced space platforms, in particular satellites placed in geosynchronous orbits, long life and reliability are key requirements. In such applications, autonomous onboard control and fault monitoring and recovery systems provide significant advantages in recovery response time, operating cost and efficient use of spacecraft resources relative to continuous ground monitoring; but there is generally some development cost penalty. Long life and reliability are also important in "serviced" space platforms. In addition, to make optimal use of the capability to replenish or repair orbiting platforms, autonomous or automated systems (e.g., robotic or teleoperated systems) will be used to carry out many operations that might be hazardous (such as fuel transfer) or otherwise inappropriate for direct human implementation. Autonomous systems either onboard the platform or the servicing vehicle, or both, are also likely to be employed in the control of close proximity manoeuvring, docking and/or berthing operations because of the short time constant involved.

"Multipurpose" platforms are those that simultaneously support a variety of different instruments and/or experiments and, if serviced, have equipment changes while on-orbit. For these applications, artificial intelligence (AI) systems (e.g., expert systems) will find use in deriving optimal mission plans and sequences and in driving the systems that control the allocation of onboard resources among the missions, instruments and experiments. These sequencing and planning systems are currently beginning to find use on the ground and should eventually move onboard these orbiting platforms.

At least two additional major requirements for autonomous and automated systems arise in inhabited space platforms: assisting in the preservation of crew well-being and maximising human productivity. These two requirements do not necessarily introduce broad new areas of application beyond the three mentioned earlier in this section: control and fault monitoring of spacecraft systems, systems capable of remote manoeuvre and/or manipulation, and AI systems for planning and sequencing. However, inhabited platforms provide the greatest opportunities to explore the synergistic use of humans and machines in the space environment where, in general, autonomous systems can carry out fast occurring, repetitious, monotonous tasks, or tasks requiring continuous attention for infrequent events, or hazardous tasks. This frees the human adaptive reasoning and decision making abilities for unanticipated, experimental and interesting activities.

No autonomous systems is actually free of human supervision; autonomous systems do not replace humans in this sense. Rather, they provide much more flexibility for determining the optimal degree, nature and location of human participation in space activities (to be discussed further in the following section).

Figure 3 presents in some detail the functional applications of autonomous or automated systems by broad functional areas. Not all functional applications shown apply to every class of platform, but all would apply to multipurpose, inhabited, serviced, evolving platforms such as the NASA Space Station, which is discussed in the following section.

Note that in Fig. 3 there are certain functional applications that are clearly ground-based and some applications that are clearly on-orbit. Many interesting questions arise, however, when one tries to determine the optimal location or approach to control of on-orbit functions and to the optimal location or approach to functions that may reside either on the ground or onboard or both.

4. ANALYSING APPLICATIONS OF AUTONOMOUS SYSTEMS

As indicated by Fig. 3, many choices face the designers of space platforms with regard to applications of autonomous or automated systems. There are, as yet, no general applicable design methodologies, but there are at least two generally applicable concepts to aid in analysing design problems: the idea of functional partitioning and the idea of applying life cycle cost or life cycle cost-benefit estimation techniques. Each idea is described below.

Functional partitioning is not so much a decision making approach as it is an orderly way of visualising options for supervision and control approaches. Essentially, the approach is to work with the functional requirements associated with the space platform in question. Any given function at the system level, e.g., maintain such and such an orbit and attitude, may be decomposed (admittedly not always with perfect ease) into successively smaller sets, or sets of sets, of subfunctions necessary to carry out the system level

ONE WAY: MINIMIZE ESTIMATED OVERALL LIFE CYCLE COSTS, i.e.,

$$\text{MIN LCC} = \text{MIN}\left\{\sum_{t=1}^{t=IOC}\left[\frac{1}{(1+r)^{t-1}}\right]\left[DC_t(X_{IOC}^{*})\right] + \sum_{t=IOC+1}^{t_f}\left[\frac{1}{(1+r)^{t-1}}\right]\left[DC_t(X_t, X_{t-1}) + OC_t(Y_t)\right]\right\}$$

OR TAKING A BROADER VIEW: MAXIMIZE DIFFERENCE BETWEEN ESTIMATED OVERALL DERIVED BENEFITS AND ESTIMATED OVERALL LIFE CYCLE COST, i.e.,

$$\text{MAX}\left\{ODB - LCC\right\} = \text{MAX}\left\{\sum_{i=1}^{n}\sum_{t=1}^{t_f}\left[\frac{1}{(1+r_i)^{t-1}}\right] \times \left[V_{it}(Y_{it}) - UC_{it}(Y_{it})\right] - LCC\right\}$$

Key

LCC	≡	Overall (present discounted) programmatic life cycle cost
t	≡	Time
IOC	≡	Time increment in which initial operating capability is reached
r	≡	Discount factor (r_i ≡ discount factor for ith-user)
DC_t	≡	Design, development, test, launch, and construction costs (i.e., non-recurring costs in time increment t)
X_t	≡	Set of capabilities/capacities available in time t (e.g., X = X_{power}, X_{data}, $X_{experiment\ pointing}$...)
X^*_{IOC}	≡	Target set of capabilities, i.e., design requirements
OC_t	≡	Operating costs in time increment t
Y_t	≡	Set of resources/services provided in time increment t ($\leq X_t$)
ODB	≡	Overall (present discounted) derived benefits
V_{it}	≡	Value received by user i in increment t
UC_{it}	≡	Costs borne by user i in increment t (including development and operation)

Fig. 5. Decision-making with regard to autonomous systems.

function. At the appropriate level of decomposition, options for subfunction responsibility may be investigated in a manner like that shown in Fig. 4, which depicts four options for each given subfunction: human responsibility or machine responsibility, either onboard or on the ground. Once human responsibilities are determined options for the machine subfunction responsibilities may be investigated (e.g., mechanical controller, dedicated microprocessor or centralised processor).

Figure 4 is not meant to represent any particular function, but rather to display the general approach and to compare more and less autonomous approaches to a given function. Figure 4 also helps to visualise an important aspect of the approach, i.e. identifying of interfaces. In Fig. 4, a vertical line represents an interface across which information must travel; in the case of the human-machine interface, examples are a cathode ray tube (CRT), annunciator, printer and a keyboard, or an electromagnetic communications link across the ground/in flight interface. While many other criteria must be applied to determine the optimal functional partitioning approach, one important criterion is to avoid proliferating interfaces, for reasons of cost and complexity, particularly in the development, test and verification phases of the platform project.

Although development, test and verification cost concerns are often paramount in the design and implementation of spacecraft projects, more and more attention is being given to the costs and benefits that accrue after the platform reaches the operational stage. Perhaps the fundamental reason for this awareness is that most space platforms are or will be in some sense in the business of providing services to users who often have alternative means for obtaining those services, or are undertaken by agencies whose limited budgets must be balanced between development and operation of the spacecraft and development and operation of systems to utilise platform capabilities. In either case, the idea of applying life cycle cost of life cycle cost/benefit approaches provides a conceptual framework for making general decisions of all kinds, and specific decisions about use of autonomy and automation, in particular, since much of the cost savings and benefit of using autonomous systems appears only in the post-development phases.

Figure 5 presents rather general mathematical expressions of the ideas of minimisation of estimated life cycle cost and maximisation of the difference between life cycle benefits and life cycle costs. While the latter is more satisfying, it suffers from the criticism common to all cost-benefit estimates, i.e., that it is often extremely difficult in practice to estimate future benefits in any quantitatively meaningful way for any new or unique undertaking. Even if quantification is difficult, the cost benefit approach is of considerable heuristic value, particularly if the developer, operator and user are different parties. Finally, while the cost-benefit approach may be better for decision making from a broad point of view, e.g., that of a government agency, the life cycle cost approach (with revenues treated as negative costs) is probably more suitable for a private owner/operator.

Factors that may be investigated using the life cycle cost decision criterion include:

1. Relative importance of operating costs *versus* development costs (*via* discounting).
2. Impact of design decisions on revenues (revenues may be treated as negative costs).
3. Tradeoffs between initial capacity, growth capacity, and level of utilisation (if suitable relationships can be derived among X_t, X_{IOC}, and Y_t).

Factors that may be investigated using the cost-benefit criterion include:

1. User life cycle economics (e.g., user trades between payload development and fee for service costs).
2. Alternative mixes of users and the impact of charge policy thereupon (through investigation of individual user's overall derived benefit and minimum return on investment requirements).
3. Importance of indirect benefits (assuming they can be quantified).

The following simplified example illustrates the use of the life cycle cost and cost benefit expressions:

Assume that an uninhabited, unserviced space platform is in the definition phase. The question arises as to whether or not to develop an autonomous system for onboard control and management of a major spacecraft function, with no change to the platform's operating capabilities. The estimated additional cost of developing and testing this system is ΔDC, occurring in each year of the three-year development, test and launch programme. If the system is developed, estimated savings are ΔOC, occurring in each of the planned ten years of operation as a consequence of reduced need for ground controllers.

Ignoring questions of risk and assuming a zero discount factor, the life cycle cost decision criterion yields the simple and obvious result that the autonomous system should be developed if the following is true:

$$10\ \Delta OC > 3\ \Delta DC \qquad (1)$$

i.e., if the savings in operation costs is greater than the

additional costs of development.

To extend this example to illustrate the use of an alternative cost-benefit decision criterion, assume that there are three potential users of the platform who expect to derive values V_a, V_b and V_cm respectively, from using the platform during each of its ten years of operation. Furthermore, assume that the owner/operator of the platform has an established policy whereby each user must pay an annual fee equal to a fixed fraction (f_a, f_b and f_c, respectively) of the annual platform operational cost. Ignoring risk, assuming a zero discount rate and treating the annual users fees as negative costs, the life cycle cost criterion (which essentially represents the owner/operator's point of view) yields the result that the autonomous system should be developed if the following is satisfied:

$$10\ \Delta OC\ [1 - (f_a + f_b + f_c)] > 3\ \Delta DC \quad (2)$$

i.e., if, first, the user fees do not cover all operating costs and, secondly, the savings in residual (after revenues) operating costs is still greater than the increase in development costs.

From the users' point of view, the autonomous system approach is clearly better, since (assuming no difference in value received or in users' development costs and zero users' discount factors), the overall derived benefits in the case of autonomous system are greater by the following quantity:

$$10(f_a + f_b + f_c)\ \Delta OC \quad (3)$$

i.e., by the amount of reduced users fees the users are required to pay.

Combining the two points of view into the overall cost benefit criterion yields the result that the autonomous system should be developed if

$$10\ \Delta OC > 3\ \Delta DC \quad (4)$$

which is more favourable to the autonomous system approach than is the life-cycle cost criterion alone, and which is the same result obtained when the users were not considered.

More complex results, which do explicitly include user value received, are obtained from the cost-benefit criterion in cases where the operating cost delta leads to a change in the number of identities of users. If, for instance, in the example user C was unwilling to pay the higher user fee associated with the unautomated approach because his derived benefit (value minus cost) was negative, then the cost-benefit decision criterion would include a term involving V_c.

While life cycle cost and cost benefit approaches have much to offer, further work is needed to develop methods of acknowledging the risk associated with including the new and relatively untried technologies associated with autonomous systems in major investments such as space platforms.

5. SPACE STATION AS A DRIVER FOR AUTONOMY IMPLEMENTATION

The NASA Space Station, planned for initial operation in 1992, will begin the transition from today's heavily crew-intensive (ground and orbit crews) operations to an expected era of relative autonomy of space facilities from hour-by-hour ground control.

5.1 Reasons for Autonomy

Relative autonomy of space station operations from direct ground control is desirable for a variety of reasons. First, large, round-the-clock staffing, as practised with the Apollo, Skylab, Viking and Shuttle programmes, is expensive and frequently may impede system flexibility simply because of the need to coordinate large groups of people with diverse, near-real-time responsibilities.

Secondly, indirect staffing associated with mission planning, subsystem support and ground network coordination is also expensive. Such indirect staff levels, which do not include online controllers, are generally much higher than the direct ground control staff.

Thirdly, many functions presently requiring personnel are tedious and really do not make best use of human capabilities either in orbit or on the ground. It is also difficult to keep qualified support personnel motivated to perform over long periods the more mundane tasks presently requiring highly trained individuals.

Fourth, the Space Station will be the most complex space system (in orbit and on the ground) ever constructed. On rare occasions, very rapid decisions might be required to recover from system faults or externally-induced conditions. Contingency responses may have unanticipated consequences, which propogate from subsystem to subsystem. As expereince is gained, artificial intelligence (AI) techniques might be able to establish knowledge-based systems combining the experience of several human experts in ways that will mimic the immediate on-line presence of such experts at all times under certain fault conditions. This might offer safety and mission performance benefits during rapid and unexpected transitions from normal to degraded operating modes, and might additionally assist with management during extended periods of operations degraded by lack of full capability in one or more subsystems.

Fifth, space crews are sometimes bothered, and their effectiveness reduced, by detail-level "control" and direction from ground personnel who are not fully sensitive to prevailing conditions in orbit. Like other workers, orbiting crewmembers generally do not like to be told what to do every minute, even though detailed planning makes an important contribution toward getting the most productive work from scarce resources of crew time and spacecraft services. In the case of platforms with a crew (e.g., space stations), platform autonomy from the ground does not imply full automation of functions, but rather the ability of the crew, with assistance from automated planning tools and other software, to make day-to-day detailed plans for achieving goals and directives sent from the ground. Greater productivity is expected to result from having those who perform the work intimately involved in planning their hour-by-hour schedules and interactions, though some level of ground support is expected here as well as in other activities.

Sixth, as autonomy is increased, reliance on limited communication links between space and ground is reduced, and more capacity of such links may be devoted to payload communication instead of the "overhead" capacity required for facility operations. Periods without communication might be tolerated without disruption of productive operations if a constant stream of uplink commands and advisories are not required for normal activities.

Seventh, as autonomy becomes more commonplace, the operation of numerous platforms simultaneously becomes feasible because skilled personnel might be then employed on a variety of different activities.

In summary, the reasons for increased autonomy may be categorised as reducing costs, increasing achievable productivity and flexibility and increasing safety and system reliability to carry out extended functions.

5.2 "Ideal" Autonomy Guidelines

A fully autonomous space platform is neither achievable nor necessarily desirable. The attribute of autonomy can be

characterised with respect to both a period of time and a set of functions. In order to describe a level of autonomy, one might ask how long a space platform can perform a given function, even in the presence of new and existing faults, without intervention or direction from ground personnel or equipment.

A set of "ideal" autonomy periods, an implementation philosophy and related architectural guidelines were drafted by members of the Space Station Autonomy Working Group (AWG), an arm of the NASA Space Station Task Force, during the latter part of 1983. While these design targets are not achievable given the technology expected to be available at the time of design "freeze" in 1987 or 1988, they might be considered as indicative of the trends to be expected over the first decade of Space Station operations.

An underlying desire of the goals and architecture proposed by the AWG was to make the Station independent of "marching armies" of large number of ground controllers involved in hour-by-hour decision making. Based on this and operational considerations set by other working groups, three distinct periods of Station autonomy from the ground were specified for normal operations:

1. Ninety days without Space Transportation System (STS) revisit.
2. Five days without routine space station ground support.
3. Twenty-four hours without any communication with the ground.

These specifications do not mean during normal operations that STS revisits, routine ground support or communications with the ground will be carried out no more frequently than indicated; they do mean that the system is to be designed, to accommodate these maximum intervals without interruption of normal operations. The 90-day specification was a programmatic requirement not set by the AWG. The five-day specification was meant to allow for the longest holiday weekends for ground controllers. The 24-hour specification was intended to keep congested communications (especially *via* the Tracking and Data Relay Satellite (TDRSS) from becoming a major bottleneck in operations, and to force designers and planners to think of how to make decisions and to conduct normal operations without consulting with the ground about every small action.

Further, these autonomy periods refer to facility operations and not to all customer payload operations. For example, during observation of a unique solar event occurring on a weekend, discussions between ground-based investigator team and cognisant crewmembers would not be precluded as part of normal operations. Likewise, the installation of a massive payload module need not occur at a resupply interval. Some facility operations will generally be required to support such customer operations, though the philosophy goals A, B and F (see below) were intended to obviate the routine need for facility ground controllers being on line at such times.

Lacking defined customer requirements for the Space Station, autonomy goals were written in terms of facility (i.e., non-payload) operations, though there will always be links between facility operations and payload activity (as in an office building where heating, air conditioning and lighting utilities are operated based on customer schedules and control inputs).

5.3 Autonomy/Automation Philosophy

The AWG autonomy goals were as follows:

a. Subsystem and system monitoring and control will be performed onboard.

b. Systems monitoring and control will be automated.

c. Fault detection and isolation will be an automated function for all subsystems.

d. Redundancy management, including reconfiguration, will be performed automatically onboard.

e. Reverification of system and subsystem elements will be performed automatically onboard.

f. Near term (i.e., next one to three days) operations planning and scheduling will be performed onboard.

g. The degree of automation will increase as the Space Station matures and new technologies become available.

h. Collection and analysis of trend data will be automated onboard.

i. The Space Station Polar and Coorbiting Platforms shall have at least the same degree of automation onboard as the manned station itself.

These goals were written with the intent to avoid specifying how they might be achieved, other than recognising that their realisation requires extensive use of automation to enable many facets of autonomous operation aboard the Space Station.

A closely related set of Architectural Guidelines was also drafted, as follows:

1. Automated fault detection, isolation and recovery will be carried out giving highest priority to crew life support and primary mission objectives.
2. Automated systems architecture is distributed and hierarchical.
3. Fault detection, isolation and recovery is accomplished at as low a level as possible in the hierarchy.
4. The required fault tolerance capabilities may be accomplished using either fault tolerant computers or appropriate network approaches, or both.
5. Architecture shall facilitate development and test of individual subsystems independent of other subsystems.
6. Architecture should minimise subsystem interactions at all levels of architecture. Where interaction is required, it shall be performed at the highest feasible level.
7. Only processed results will routinely progress upward through the hierarchy. Lower level data will be accessible at higher levels when required.
8. Architecture will allow manual intervention in all automated processes. Appropriate safeguards should be provided to prevent inadvertent or unauthorised disabling of essential automated processes.

5.4 Realisable Autonomy Evolution

While not all the stated functions listed on the autonomy/automation philosophy can be performed aboard the Space Station when it begins operating, it will be important to

design the facility so that these functions can be made autonomous later. Studies have begun to determine what types of scarring are required in the initial station to assure that the hardware and software employing new and emerging technologies used to implement autonomy can be retrofitted into the system, when available, with a minimum of disruption and expense. There are important issues of standardisation of hardware and software, communications protocols and allowances for subsystem capacity growth that are expected to have a significant effect on Space Station design activities over the next three years.

It is anticipated that the areas of short-term fault management and short-term operations planning will be among the first to employ advanced autonomation in such a way as to increase station autonomy from continuous ground control and oversight. Over time, continuous subsystem management will become more and more autonomous, with some subsystems leading others in the implementation of autonomous control. Nearly all subsystem areas have today received some consideration for onboard control and management employing artificially-intelligent (AI) knowledge-based expert systems. Somewhat more effort has gone into the consideration of AI techniques for scheduling tools, environmental control and electrical power subsystem management than into other areas, but all critical functions appear amenable to a substantially increasing level of autonomy aboard the Space Station as the facility and its payloads evolve.

In terms of Fig. 4, we might expect early fault analysis and recovery, as represented by 2nd. & 3rd. functions listed in the left column, to be performed onboard in the presence of a time-crucial fault. During early operations, such analysis and recovery would be monitored and cleared by some combination of ground controllers and flight crewmembers, while later operations might involve only flight crewmembers and subsequent reports to the ground as confidence is gained.

Some amount of planning might be undertaken onboard during early operations by crewmembers using AI planning tools, though much of the planning is still expected to take place on the ground. Monitoring is likely to be the next functional area moved onboard, followed by the more complex aspects of planning and replanning. In what is perhaps an oversimplification, we might imagine the analogue of today's commercial aircraft, where the flight crew has instructions to fly passengers between two different airports during a particular period of time, but the crew does not report nor receive instructions regarding operation of the landing gear, power settings, control surfaces, meal service and so on. The crew does report and receive instructions regarding takeoff, landing and various waypoints, but these involve complex system level interactions with other aircraft, ground facilities and navigation constraints. One can imagine a station crew being given a set of experiment objectives to be performed over a period of several days, but where, having principal investigators onboard with a large suite of automated equipment and planning tools, only occasional interaction with ground personnel is required.

It is important to draw the distinction between autonomy for basic facility operations, such as life support and electrical power generation, and for payload operations, such as for materials processing or remote sensing. A major objective of advanced automation and autonomy is to allow the crew to devote nearly all their time to valuable payload operations instead of housekeeping. While facility operations might best be at once autonomous and automated for reasons of economy of crew time and ground operations expenses, it might, at the same time, be best to have certain payload operations monitored and controlled by the crew, or even by persons on the ground because of complexities or the expense of automating a nonroutine function.

5.5 Cost/Benefit Viewpoint

As described generally in Section 4, various options for Space Station autonomy can be examined from a life cycle cost or cost/benefit point of view. While highly accurate numerical prediction of costs and benefits will not be possible within 1985, it might be possible to apply semiquantitative techniques to determine the relative economics of making life support fault management functions, rather than electrical power fault management functions for instance, autonomous at initial operational capability (IOC). In fact, such decisions might have to be made early in Space Station development given the limited resources that will be available for technology development leading to initial operations.

Alternatively, it may be possible to assess whether either the planning function or the subsystem monitoring function should be placed onboard early in the programme, again assuming that funding limits programme managers to the selection of one or the other technology for development emphasis over the next three to five years. In fact, analysis of costs and benefits both with respect to individual technologies (which could be applied to several subsystems) and with respect to subsystem or system level functions (as in the life support *vs* power example above) can be employed to select the most fruitful areas of autonomy development given constrained initial costs.

5.6 Technology Stimulus Viewpoint

Another point of view may be obtained by examining the externalities or benefits beyond the Space Station Program. Some technologies required for Space Station autonomy might be more applicable in terrestrial situations than others. It was the intent of the US Congress in directing NASA to perform a study of advanced automation applications for the Space Station Program to stimulate those areas of technology development that would prove to be of greatest benefit to the US industry.

An example illustrating this difference in terrestrial applicability may be found in the area of robotics, where local, artificially intelligent manipulators aboard a Space Station or associated vehicle could reduce the need for teleoperation from the ground or extravehicular activity (EVA). In space, the mechanics of robotic manipulators are substantially different from the mechanics of terrestrial robots in industrial environments. While terrestrial robots can take advantage of the power-to-volume ratios available with pneumatic or hydraulic actuators, electrical actuators must generally be used in space and with a different set of lubricants and design specifications than on the ground. Therefore, spaceborne manipulator hardware might find limited application on the ground. On the other hand, for many servicing tasks in space, the simultaneous, coordinated action of two manipulator arms is often desirable, just as would be available with a crewmember. Such coordinated robot action is rare today, except in simple situations, and its application is restricted mainly by the unavailability of software algorithms required to coordinate the simultaneous motions of two arms in close proximity. Any such algorithms developed for space application are likely to be insensitive to the actuation mechanism (e.g., electrical motors *vs* hydraulic pistons) and might, therefore, find a significant terrestrial application in such a function as a complex assembly over a short production run.

6. TECHNOLOGIES FOR SPACE PLATFORM AUTONOMY

Part of the Autonomy Working Group (AWG) activity

TABLE 1. Consensus List of Important Autonomy Technologies.

Artificial Intelligence
- Learning Expert Systems (Ground)
- Learning Expert Systems (Onboard)
- Expert Systems
- Explanation Mechanism
- Fault Detection, Diagnosis, and Recovery Software
- Fault Recovery Software
- Planning and Scheduling Software
- Subsystem Monitoring Software
- Symbolic Processor (Onboard)
- Power System and Load Management

Control Techniques
- Adaptive
- Distributed Parameter
- Hierarchial
- Multivariable
- Nonlinear
- Optimal

Data Storage
- Archival Storage (Onboard)
- Mass Storage (Onboard)

Fault Tolerant Computing
- Architecture
- Data Transfer (Onboard)
- Data Transfer (Between Station and Ground)
- Mass Storage (Onboard)
- Processors (Onboard)
- Software

High Order (Procedure Oriented) Language (HOL or VHOL)
- Reprogrammable Onboard Procedures and Software
- Software

High Speed Computing
- Data Bus (Onboard)
- Memory (Onboard)
- Memory (Ground)
- Processors (Onboard)
- Processors (Ground)

Crew-Machine Interface (part of HOL)
- Text Generation
- Natural Language Annunciation
- Natural Language Understanding

Robotics
- Dextrous Manipulators
- Image Understanding
- Pattern Recognition
- Teleoperation*
- Telepresence*
- Dextrous Arm
- Intelligent Manipulation
- Intelligent Mobility

Simulation Techniques
- Analysis Tools
- Integrated Design

Very Large Scale Integration/Very High Speed Integrated Circuits
(VLSI/VHSIC)

* Within the categories of teleoperation and telepresence, no distinction was made between short-range control, where the communications link introduces no significant time delay, and long-range control, where one or more signal hops to geostationary satellites may introduce significant and varying time delays into the control loop. While short-range control has been demonstrated frequently, long-range control still carries significant technical risk for early implementation.

noted in Section 5 resulted in the identification of a set of advanced automation technologies required to implement the "ideal" autonomy philosophy. This broad set of technologies is listed in Table 1. Based on this list, an informal survey was made of members of the AWG and others in aerospace automation fields to determine which technologies offered the greatest productivity benefits and cost impact, as well as which were achievable for design selection at the initiation of detailed station design and fabrication, expected to start in 1987. Finally, respondents were asked to assess whether ongoing developments outside the Space Station programme were sufficient to bring each desirable technology to a sufficient level of maturity within the desired time period. Based on these responses, three technology areas emerged most often as being candidates for development impetus provided by the Space Station effort. Three areas were as follows:

1. Artificial intelligence: Expert Systems and Processors.
2. Fault Tolerant Computing.
3. High Order (Procedure Oriented) Languages.

All of the technologies noted in Table 1 were considered to be important, but the above selection was made on the basis of achievable maturity before the IOC design freeze and on the basis of required attention from the Space Station Program itself. Some technologies were more important when viewed from a cost reduction point of view while others stood out from the point of view of productivity improvement. The three areas cited above were prominent in either case, though all selections should be considered in light of the fact that the survey was small and informal. A different selection might also be made for a different type of space platform.

The Congressionally-mandated Space Station Automation Study, now in progress, involves NASA, industry and academic assessments of automation requirements, benefits and priorities. The study was due to result in the delivery of an automation plan for the Space Station Program to Congress and the Space Station Definition Phase contractors on 1 April 1985. Parts of this plan will address both the economics specific to the Space Station Program and the externalities introduced by the consideration of industrial and quality-of-life benefits stimulated and catalysed by programmatic emphasis on autonomy and advanced automation.

7. CONCLUSIONS

The complex space platforms orbited before the end of the century will have the potential of operating much more autonomously than have spacecraft in the past. Emerging advanced automation technologies afford numerous opportunities for moving subsystem – and system-level functions from the ground to onboard equipment or crewmembers. The reasons for desiring increased platform autonomy may be categorised as reducing cost, increasing productivity and flexibility, and as increasing safety and system reliability in carrying out intended functions.

By examining options for functional partitioning between spacecraft and the ground, and between personnel and

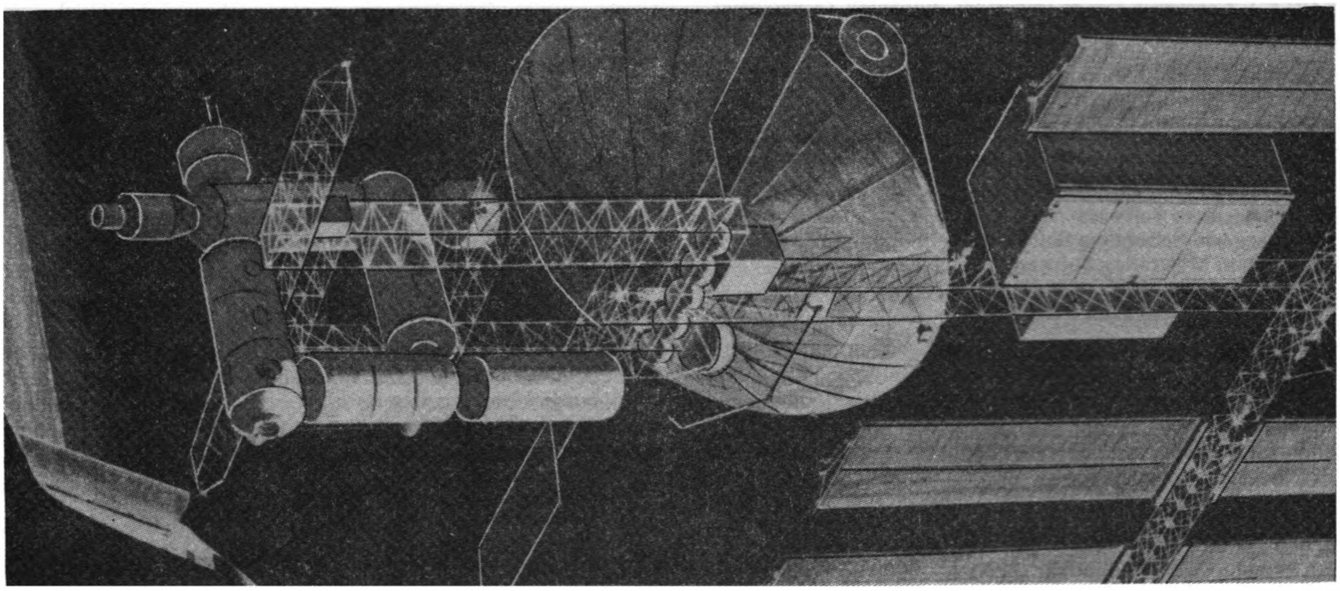

Fig. 6. NASA's Space Station Program will be a major application of autonomous systems. NASA

machines, designers can become aware of the options for increased space platform autonomy. These options can be evaluated on either a life cycle cost basis, or on a life cycle cost/benefit basis, though rigorous numerical comparisons are restricted by the low accuracy of predicted costs and values for new activities and new approaches to solving design problems.

A broad base of technologies contributes to the advancement of space platform autonomy, falling into the categories of artificial intelligence, fault-tolerant computing, procedure oriented languages, robotics and teleoperation, control techniques, data storage and transfer, high speed computing, crew/machine interfaces and other areas. Some technologies will likely require specific programmatic emphasis to achieve maturity by any particular date, while others are being vigorously developed for applications outside the space platforms arena.

Analysis of autonomy options is of major importance for the most complex space platforms yet conceived: the US Space Station planned for initial operations in 1992. In addition to the cost and benefit evaluations, which may be made from the point of view of any particular platform programme by itself, the US Congress has directed that the development and application of advanced automation techniques for the Space Station be evaluated from the point of view of terrestrial benefits for industry and mankind.

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