IAC-02-IAA.8.2.04
IAA.8.2. The Architecture of Space: A Multi-Disciplined Approach
Wednesday, October 16, 2002, 2 PM, Rm. 301EF
George R. Brown Convention Center, Houston, Texas

Design of the Space Station Habitable Modules

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53rd International Astronautical Congress
The World Space Congress - 2002
10-19 October 2002/Houston, Texas

ABSTRACT
Design of the crew compartment and modules of the International Space Station originated in the early 1970s and evolved throughout the 1980s. It was influenced by past experience as well as with new and innovative concepts.

This paper traces some of the alternative configurations considered through the Space Station's formulative and early development periods, and provides an overview of some of the trade studies, design and modeling activities and alternative configurations which led to the configuration as it is being flown today.

SPACE STATION CONCEPTS
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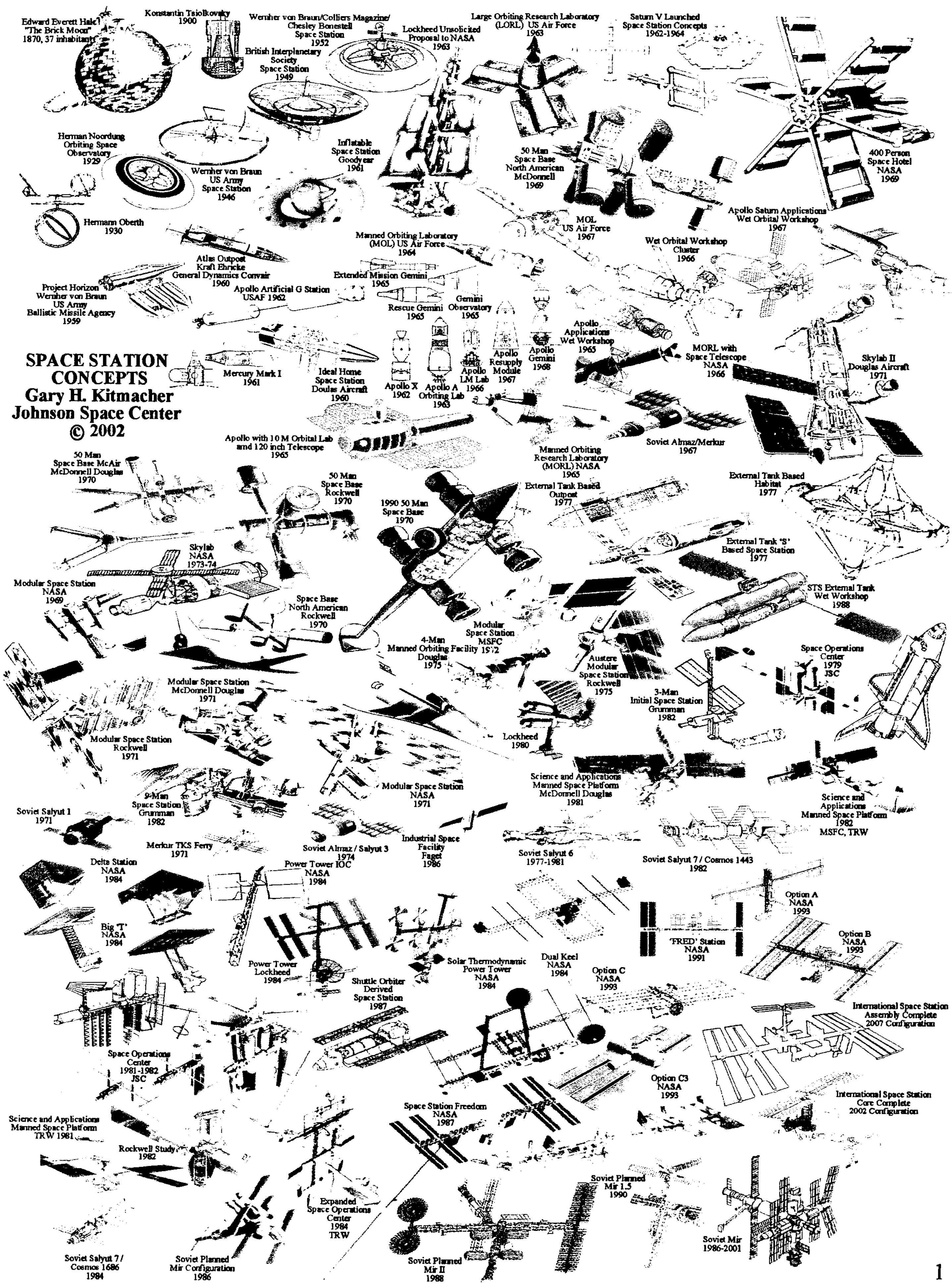

DESIGN OF THE SPACE STATION HABITABLE MODULES

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INTRODUCTION

The International Space Station may be considered one of humanity's greatest international political and technological achievements. However as a result of its complexity, few understand the configuration of the station habitats as they have been designed, and little has been written about the origin and evolution of their design.

100 YEARS OF SPACE STATIONS

The idea of living in space was the very first step in defining what our orbital habitats would look like. The locomotive, hot air balloons, the automobile, the telegraph, the telephone, the electric light, and the camera, were all introduced in the late 1700s and 1800s. This was a great age of impressive engineering achievements and men anticipated even greater inventions. Flight and life beyond our world became a goal. Men looked forward to the invention of the practical spaceship.

More than a hundred different space stations were conceptualized (fig 1) in the more than one hundred years before the International Space Station becoming operational. Several space station designs were developed and manned in orbit by Americans and Russians between the US manned moon landing, and the establishment of the current space station configuration in the late 1980s.

Edward Everett Hale's 'Brick Moon', published in the Atlantic Weekly magazine in 1869, contained all of the basic elements of a space station. It was a man-made structure orbiting the earth, supported life for its crew, and served as a navigation aid for those on earth.

The engineering, design and construction aspects of a space station were first detailed by Herman Potocnik, writing under the pen name of Hermann Noordung, in 1928. His 'Wohnrad' or 'Living Wheel' was the forerunner of a series of rotating wheel-shaped space stations:

> The physical conditions and potentials of empty space are now familiar to us....in order to simplify as far as possible the work to be performed in outer space when constructing this observatory, this working being possible only in space suits, the entire structure including its equipment would have to be assembled first on earth and tested for reliability. Furthermore it would have to be constructed in such a manner that it could easily be disassembled into its components and if at all possible into individual, completely furnished "cells" that could be transported to outer space by means of space ships and reassembled there without difficulty.[44]

The theme of gravity being artificially produced through the rotation of the habitat was carried forward by Wernher von Braun in the 1950s. Willy Ley wrote of it in 1952:

> When man first takes up residence in space, it will be within the spinning hull of a wheel-shaped space station [revolving] around the earth much as the moon does. Life will be cramped and complicated for space dwellers; they will exist under conditions comparable to those in a modern submarine.
>
> The outpost in the sky, which we know to be the first necessity for the exploration of space, will be a self-contained community in which all man's needs, from air-conditioning to artificial gravity, have been supplied.[32]

The rotating wheel was one of several recurring themes that are apparent in a review of the concepts that have been proposed over the decades.

From the beginning, a significant consideration in the design of a space station would be orbiting the maximum habitable volume for the lowest cumulative launch costs.

Two recurring themes developed to reduce launch costs were the use of inflatable fabric structures and the use of spent rocket stage fuel tanks to serve as the habitats.

NASA outlined prospective space stations based on Apollo hardware through the 1960s. Announced formally in 1967, the Apollo Applications Program would focus on the support of long-duration orbital flights in low Earth orbit; the Skylab space station was a direct outgrowth, using a converted third stage of a Saturn moon rocket. Once engineers considered the logistics and crew time required to convert the stage from a 'wet' fuel tank to a dry habitat outfitted with the prerequisite systems, it was determined to be more efficient to develop the fully outfitted workshop on the ground and so the stage was launched without fuel.

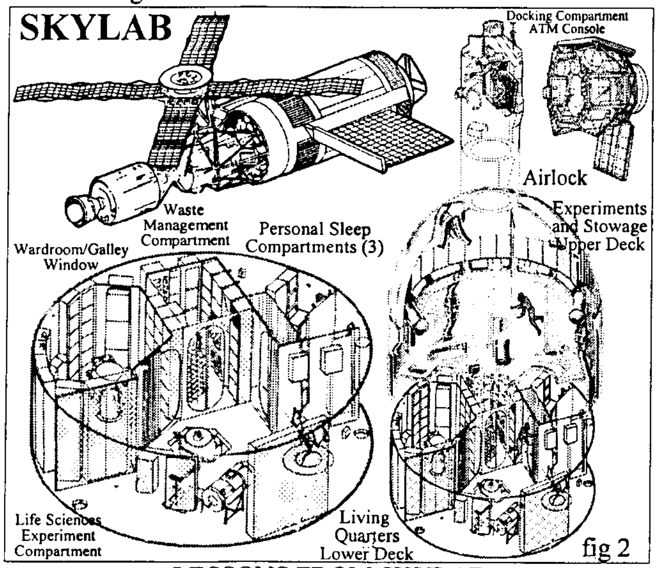


fig 2

LESSONS FROM SKYLAB[60]

The main part of Skylab (fig. 2) was a converted third stage of a Saturn rocket. It was 7 meters in diameter, 39 meters long and provided a habitable volume of approximately 480 cubic meters.

The workshop was divided into two-stories. The entire orbital workshop compartment was inside of a tank originally designed to hold liquid hydrogen; beneath this was a trash storage tank, designed originally to hold liquid oxygen. The two tanks were separated by a trash airlock.

The upper story of the workshop provided a large and open volume. The upper deck contained storage for food, water, clothing, space suits, and experiment equipment. The ceiling of the lower deck was only a little higher than a man's height, and this deck contained the living quarters, consisting of a wardroom with a galley and table for eating and a large window used for formal experimental observations, the waste management compartment or bathroom with a toilet and handwash, a sleeping compartment with three separate private crew bedrooms, and an experiment compartment.

A triangle-grid floor separated the upper deck from the lower, and it was found in other areas of the station interior as well. The astronauts wore shoes resembling running shoes, but could affix one of two types of cleats to the soles. Triangular cleats could interlock in the grid floor. These provided the most secure footing. In some locations, there were small mushroom shaped 'Brownline fittings', posts with a flange, that a special cleat could be easily slipped over, but these did not hold quite so securely.

The experiment compartment was the biggest and most cluttered compartment on the lower deck. While the astronauts could easily float over the bulky equipment, they almost always moved about either sliding sideways and upright, or sometimes walking, holding themselves down by pushing against the ceiling with their hands and arms. There was a reason why the astronauts stayed upright. Though there was no gravity in space the workshop was designed as if there were. There was a definite sense of up and down, what is called a 'local vertical', that was defined architecturally, and the astronauts were most comfortable when they felt that they and the room were oriented in the same manner.

Owen Garriot, the scientist on the second crew, tried walking on the ceiling of the compartment. He found "it gives a very strange sensation ...you see brand-new things...it's a fascinating new room...." Joe Kerwin, scientist on the first crew said that "It turns out you carry with you your own body-oriented world, independent of anything else, in which up is over your head, down is below your feet, right is this way and left is that way..." Bill Pogue, on the last crew, and who served as a consultant to the teams designing the International Space Station modules said that opposing his own personal vertical to the Skylab local vertical was "good for kicks" but that "it was more trouble than it was worth."

The astronauts felt most at home in the shallow space of the living quarters and found that it was easier to get around there than in other parts of the station. They were not as comfortable in the upper story. They preferred being more enclosed, where they were not likely to lose their sense of the local vertical. The astronauts learned to use their eyes to replace their inner ears as the link between their own verticals and the space station's.

In the spacious upper story of the station, they found it was easier to be out of kilter than in the more confining compartments below, but nevertheless there was enough of a definite up and down to be able to orient themselves.

The astronauts treated the upper story as a kind of gymnasium.

Most of the Skylab astronauts recommended that any future space station have ample open interior volume for acrobatics. Ed Gibson, the scientist on the last mission, routinely talked to the ground about new space station designs. He thought that the open space was needed "as a place where people can get away from any claustrophobia they might get in small compartments...at least, I feel that if I were penned up for months at a time it would begin to feel pretty much like a cell".

While the first crew tried running on a circle of water tanks lining the periphery of the upper compartment, ground controllers found this would make the spacecraft unstable, and require extra electrical energy for momentum wheels to maintain the station's orientation. But the astronauts did occasionally make themselves into projectiles. A favorite game was to jump from the lower deck's floor, all the way into the docking module tunnel thirty meters away without hitting anything. There were contests to see who could do the most somersaults. Pete Conrad, commander of the first crew, said that in the upper story, "we never went anywhere straight. We always did a somersault or a flip on the way just for the hell of it."

Mounted atop the forward dome of the workshop was a 5.5 meter long cylinder comprised of two segments, an airlock and a docking module. The airlock at the lower end could be isolated and depressurized, permitting astronauts to leave the station in order to perform space walks without having to depressurize the entire station. At the forward end of the cylinder was a docking port through which the crews entered when they arrived from Earth in an Apollo spacecraft.

Cabinets, consoles and instruments jutted off in all directions from the inside of the cylinder wall. In the docking compartment there was no visual compass, no up and down. Mounted to one side were the main controls for a solar observatory, and partway around the cylinder from there, the main control console for the earth resources experiments but oriented 90 degrees from the orientation of the telescope console. The observatory telescope and earth resources instruments themselves were mounted outside the cylinder on a truss. Most of the astronauts found the docking compartment, and its lack of orientation, disconcerting. They found the location of the control consoles, mounted at peculiar angles to everything else in the station and 30 meters above the floor of the lower deck, uncomfortable. To make matters worse, the Apollo command module, clearly visible at the other end of the cylinder, and in which the astronauts rode to and from the station, had a strong local vertical exactly opposite that of the station's workshop.

Gerry Carr, commander of the last crew and another consultant to the space station design group, said during his mission: "I get...one local vertical...embedded in my mind, and I whistle down the tunnel and into the command module and zing, all of a sudden its upside down". Bill Pogue said "Well, all I gotta say is, if you are looking for a very good example of how not to design and arrange a compartment, the docking adapter is the best example...every time I think about how stupid the layout is in there I get all upset."

And to exacerbate this, the location coding, numbering system inside the docking compartment was chaotic. Pogue said "locatability is so bad it almost looks like you had to go out of your way to design it that way..."

A strong recommendation was made by most of the Skylab crews that for future stations a consistent local vertical should be maintained within any compartment with a contiguous field of view. But Ed Gibson said he thought "the lower decks of the workshop wasted a lot of space....the docking compartment is more efficient", but even he had difficulty finding things when he went in there.

From 1973 to 1974, Skylab hosted three crews of three men each for mission durations of approximately 1, 2 and 3 months, respectively. Several of the crewmembers served as consultants to NASA and its contractors in designing the new space station.

SPACE TASK GROUP

As the moon landing mission of Apollo 11 was taking place in the summer of 1969, President Nixon directed a Space Task Group to define the goals of a post-Apollo space program. They reported that:

> ...our horizons and our competence have expanded to the point that we can consider manned bases in earth orbit, lunar orbit or on the surface of the Moon; manned missions to Mars; and space transportation systems that carry their payloads into orbit and then return and land as a conventional jet aircraft.[51]

An integrated set of major new elements that would satisfy the criteria of the Space Task Group included a Space Shuttle to reduce the costs of transportation to and from orbit, and:

> A space station module that would be the basic element of future manned activities.... The space station will be a permanent structure, operating continuously to support 6-12 occupants... The same space station module would provide a permanent manned station in lunar orbit from which expeditions could be sent to the surface.[51]

The report called for a space station to support the Mars landing goal. Life sciences research on the effects of long durations in isolation and weightlessness on human physiology and psychology was a prerequisite to sending people to Mars. A detailed study of biomedical aspects of flights lasting 500-600 days would be required. New highly reliable life support systems, power supply systems enough to support man on a Mars expedition would need to be developed and tested.

In response, NASA commissioned studies by both McDonnell-Douglas and North American Rockwell, to develop proposals for the configuration (fig 3) of the space station. Large diameter monolithic modules (fig 3A,B) based on both the second and third stages of the Saturn V moon rockets, having diameters of 7 and 10 meters, respectively, were the first considered.

A space base (fig 1) could be created by joining small, Shuttle-launched space station modules. This base would be a laboratory, occupied by 50-lOO men, where a broad range of physical and biological experiments would be performed. A much larger 400-man 'space hotel' (fig 1) could be assembled from 18 modules. Smaller clusters of the modules could serve to support continued lunar exploration and as the core habitat for Mars-bound astronauts. These modular station studies formed an important basis for today's Space Station.

From the beginning, it was recognized that the station would have to provide a habitable and livable environment for its crew, an 'engine room' of support systems, and a distribution system for power, data, and fluid resources. Whole modules carrying complements of integrated experiments would be launched to the station, operated for a period, and later returned to earth via the Shuttle. One study looked at operating an integrated research module from the Space Shuttle in lieu of an orbiting Space Station to attach to.

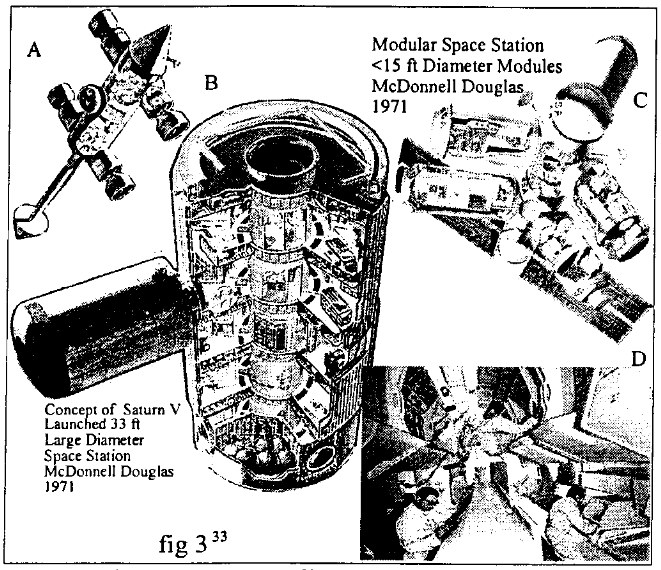


fig 3[33]

Even as the contractor studies were ongoing, Saturn rocket production was permanently being suspended. The Space Shuttle became NASA's top priority. Space station studies were redirected towards concepts in which reduced size modules could be carried inside the proposed Shuttle's payload bay. These 4.5-meter diameter modules might then be clustered in orbit to provide the same functional capability as the large modules (fig 3C).

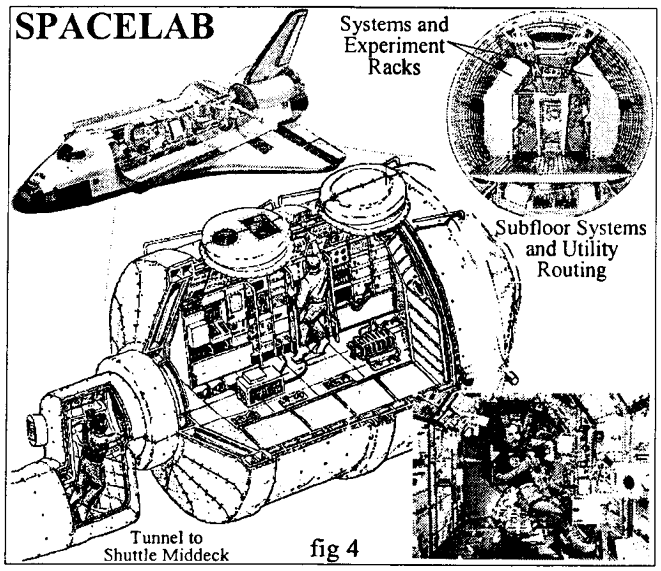


fig 4

SPACELAB

In 1971 it became clear that budget constraints would prevent NASA from moving forward with both Space Station and Space Shuttle. The integrated experiment module concept offered a means to use the Shuttle to house an orbiting laboratory until a Space Station was available. In 1973, an agreement was reached with the European Space Agency to develop the Spacelab (fig 4).

Spacelab modules included the pressurized laboratory and a tunnel to gain access to the module from the Shuttle's crew compartment. The pressurized laboratory could be flown either as a short module, with only a single cylindrical segment mainly containing systems support hardware, or a long module with a forward segment contained the supporting systems and the second segment provided working laboratory space. A sub-floor provided volume for systems and utility routing to floor-mounted equipment racks.

The modules depended upon the Shuttle to provide housing for the crew and were parasitic off the Shuttle, requiring resources such as power, thermal control, and breathing air.

PRELIMINARY SPACE STATION DESIGN STUDIES

While NASA's manned space efforts were focused on the development and testing of the Space Shuttle in the mid-1970s, some long range planning efforts continued, considering adaptation of the Spacelab modules to minimal man-tended or permanently manned orbiting habitats.

Several contractor proposals were focused on the assembly and lay-out of Shuttle-launched modular space stations. Space station functionality would be driven by user requirements. A small crew would be able to support research experimentation, as was being planned for Spacelab. A larger crew and a larger station was required to support assembling and servicing of large spacecraft as was being openly discussed.

The development of orbiting stations was still seen as a critical element in developing a large-scale orbital infrastructure. The Space Operations Center (SOC) (fig 5) concept would permit astronauts to service earth satellites that in turn would be used extensively for environmental monitoring, science missions, communications, and to prepare lunar and planetary mission vehicles. There were discussions about large Solar Power Satellites that would collect solar radiation as electricity and then microwave power to the ground. Orbiting astronauts would be required to assemble and maintain the satellites. Increasing space flight traffic was anticipated with as many as fifty Space Shuttle missions each year foreseen.

A modular approach considered the use of Spacelab-sized modules that could support the habitation of four crewmen; additional modules would provide dedicated volumes for systems placement or other functions, such as scientific research. Typical initial crew size studied was 3 or 4 using 2 or 3 modules. Over periods ranging from five to twenty years, the station size would grow to serve between 9 and 12 astronauts.

Module arrangement was given early consideration. Initially it was proposed that common diameter modules be launched, with lengths dependent upon Space Shuttle

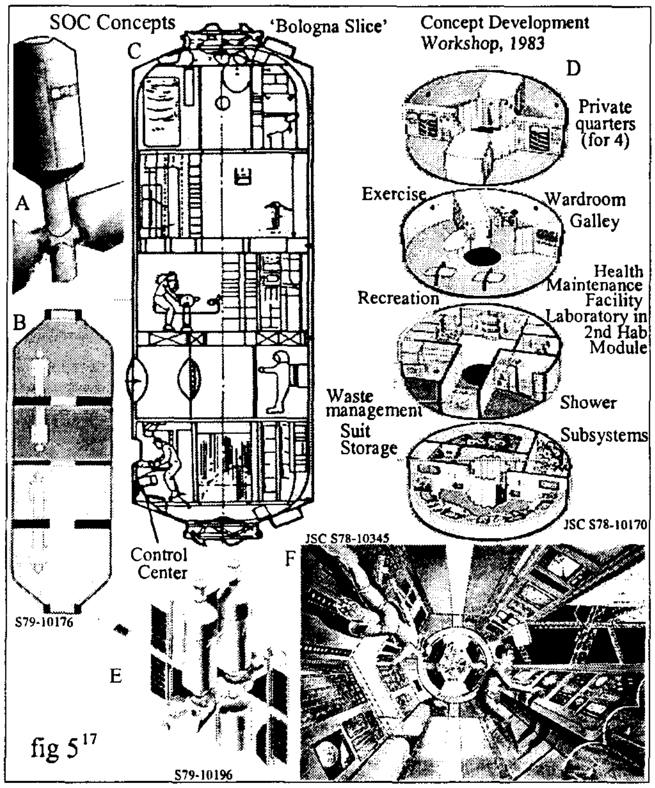


fig 5[17]

launch capabilities. A central berthing module (fig 6) could provide an adequate number of berthing ports to place several habitation, systems or experiment modules later. Concerns arose over this configuration. It was pointed out that this configuration would limit options on crew movement or mission continuation in the case of the central module being lost. It was recommended to place the modules in a configuration that would permit multiple exits from any module, and that the loss of any one module not prove a constraint to access to any other module.

SPACE STATION TASK FORCE

A Space Station Task Force was established in 1982. Design activities were halted temporarily as emphasis was placed on requirements definition. Crew size at the start would be 2-3 crewmembers; 8 at the time of Initial Operational Configuration (IOC), and growth in a subsequent phase to 12 to 16 people. Module lengths would be no more than 9 meters. As always, the Shuttle's payload bay would constrain diameter to less than 5 meters. Normally a 90 day logistics/resupply cycle would be accommodated. A 'safe haven' would always be provided in the case of any module being lost because crewmembers would only be able to leave the station when a Shuttle came to retrieve them. Shuttle flight rates would permit a pick-up within a matter of several weeks in the case of a significant anomaly.[4]

POWER TOWER AND COMMON MODULES

Through 1982 and 1983, a Concept Development Group (CDG) evolved a definitive set of design parameters. It resulted in a 'design reference configuration'; labeled the 'Power Tower' (fig 7); it was a 400 foot trusswork tower with massive solar panels grouped at one end on a crossbeam over 300 feet wide. The Power Tower would depend on the gradient in gravity between the earth-pointing end and the space pointing end to provide stabilization, thereby reducing fuel demand.

All of the other components including habitable modules, work areas, maintenance complex, docking modules and a satellite service area were attached to the central truss. One end would point toward Earth and the other would point into space for astronomical research. Five pressurized modules would accommodate a crew of six people. The habitable modules would be oriented towards earth, maintaining a relatively constant orientation.

Four modules would have identical exterior configurations and they were referred to as 'Common Modules' (fig 6). Berthing ports would be located on each end, and radially in four locations around the perimeter of each module cylinder. The modules would

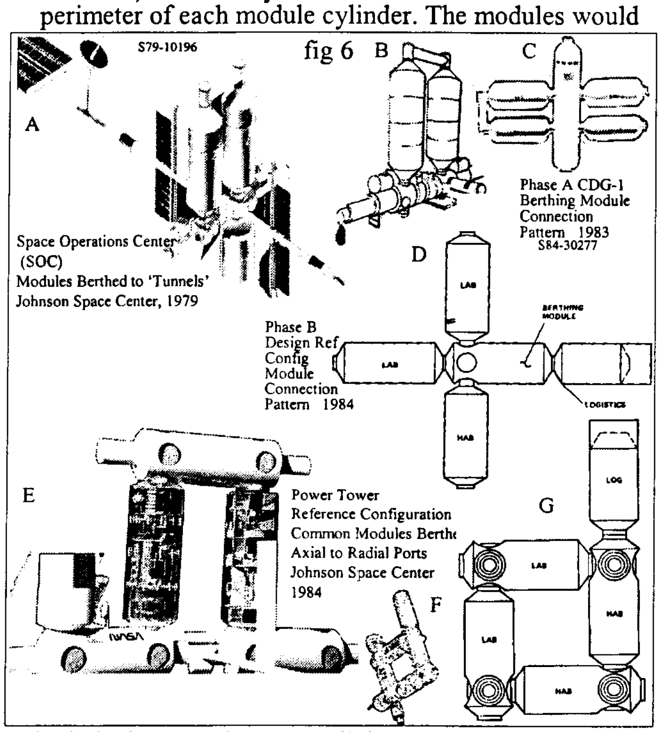


fig 6

be linked, one end to one radial port, in a square pattern, (fig 6f,g) permitting access to other locations in the case that any one module became inaccessible. Two modules would be for laboratory work, and two would share the functions of habitability and command.

A fifth module would be stripped down to reduce mass and serve as a logistics carrier. One logistics module would be left at the station for storage, but would be replaced periodically by the shuttle carrying logistics to and from earth. This configuration went forward as the baseline 'reference configuration' in 1984.

Two basic orientations (fig 7) for the common module interiors were studied. First was the 'vertical' (fig 7h,11) orientation, where modules were divided into decks in 'bologna slice' fashion. This was similar to the Skylab configuration. 'Longitudinal deck' architectures had the orientation of the 'floor' parallel with the module cylinder (fig 7B). This arrangement was similar to the Spacelab module.

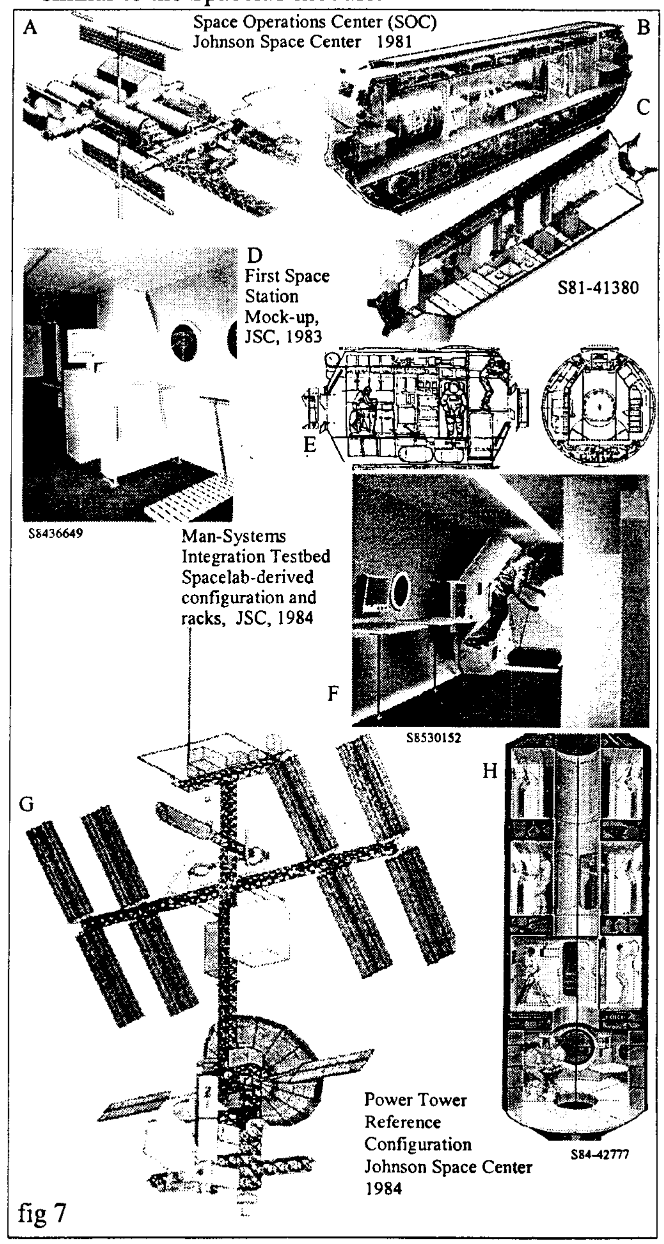


fig 7

The module orientations were compared using factors such as pressure shell access, surface area and volume requirements of utility distribution networks, equipment accessibility, volumetric use, environmental control and distribution, maintenance, human factors, and ground requirements including accessibility for training and for launch preparation.

The 'vertical' arrangements were volumetrically efficient and provided the best access to environmental distribution systems. The configuration had the advantage of permitting normal 1-G access even when placed in the Shuttle's payload bay on the launch pad. From a human factors standpoint, orientation, up and down, of the crewmember could be consistent within each module, but would change as the crewman moved from one module to another around the corners of the rectangular group of modules. Another alternative looked at using more structurally rigid bulkheads that would serve as a common mounting floor for two adjacent decks; this would require a change in orientation every time a crewman would go from one deck to another (fig 5B). The division into multiple decks resulted in the interior being visually confining.

The 'longitudinal' deck arrangement would make access in the module after assembly or mounting in the Shuttle more difficult, but would permit a larger internal apparent volume. By placing the floor of each module in the same direction, it would be possible to maintain a consistent orientation from one module to the next.

While manufacturers agreed that either vertical or longitudinal internal orientations could be built and could house the requisite systems, there was uncertainty with respect to the total quantity of systems hardware that would be required and the resulting available free volume.

In 1984, agreements with the European Space Agency (ESA) and the National Space Development Agency of Japan (NASDA) resulted in each agency signing up to provide their own laboratory modules. Additionally, small logistics carriers provided by the Japanese would be launched either on Shuttles or on Japanese unmanned rockets.

DUAL KEEL

In 1985, the NASA centers began a two-year long 'Phase B' study period. Several contractors, including Rockwell and McDonnell Douglas for JSC, and Boeing and Martin Marietta at MSFC, were selected to participate. The goal was to fully develop design concepts that would allow NASA to move towards a definitive station configuration, and which would also permit contractors to bid to develop the hardware systems during Phase C/D.

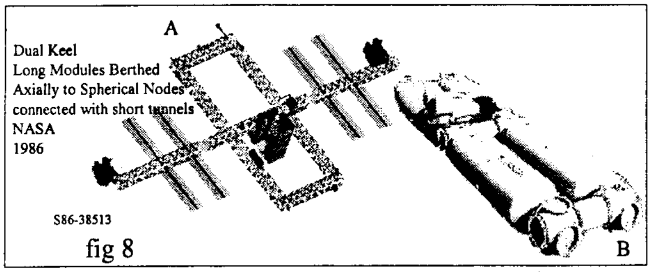


fig 8

Payload models studied during Phase B showed significant requirements for earth and deep space viewing, and for the reduction of vibrations in order to support micro-gravity materials processing experiments such as crystal growth. The payload requirements were being extrapolated in part from the expansion of payload activities being conducted on the Space Shuttle during this time period.

In looking at the overall station configuration's ability to meet the requirements, dynamic models of the Power Tower showed that the crew, located in modules at the end of the long central truss, would induce vibration, amplified by the long moment arm of the vertical truss and reducing the quality of the environment required for materials processing research. A need was also defined for substantially larger platforms than the Power Tower afforded, in order to permit the attachment of externally mounted payloads looking towards both earth and space.

The Power Tower configuration was revised to the 'Dual Keel' (fig 8). In the revised configuration, at the ends of two parallel earth pointing trusses, there would be platforms for both earth observation and space observation payloads. A long truss would cross through the center of the parallel trusses, with solar arrays at either end and with the habitable modules located at the center, close to the center of mass to reduce vibrations, suspended from the crossbeam.

MAN-SYSTEMS

In 1983 an organizational change was made that would emphasize the importance of the design of the space station habitat. A crew station development group had been part of the Johnson Space Center's Engineering Directorate almost since the inception of the manned space program. As habitability would be more critical in a long duration space station, management decided a group focused primarily on hardware would not pay adequate attention to the man-machine interface. They established a Man-Systems Division within the Life Sciences Directorate in order to ensure increased emphasis.[13]

The Crew Station Branch within the Man-Systems Division took the lead for development of the station module architecture with the stated goal of 'enhancing human productivity and reducing the need for later design changes'.[38] A Crew Interface Panel set to work on the development of a low fidelity mock-up to identify the volumetric requirements and placement relationships between key systems.

Man-Systems initiated the development of three sets of requirements. The Space Station Habitability Requirements documented environmental and habitability requirements and considerations. The Man-Systems Architectural Control Document established the architecture and system/subsystem requirements. The Man-Systems Integration Standards provided design considerations, requirements and example design solutions.

The Man-Systems Division would come to have a significant role in the definition of the Space Station and particularly the module architecture. From the outset the influence of the group made its way into program requirements:

> Habitability...is concerned with providing a Space Station facility that...provides a comfortable, functionally efficient habitat.... Attention must be given to the morale, comfort and health of crews....the "Habitability Architecture" design concerns are mainly with respect to the fixed architectural elements of the Crew/Space Station interfaces such as the (a) geometric arrangements of compartments (b) the interior appointments, decoration...(c) provisions for work or duty stations and off-duty stations (d) stowage and retrieval provisions, privacy, (e) traffic patterns, (f) displays, and (g) access and egress provisions.
>
> The success of an extended mission on a Space Station depends on the crew being an integral part of the interior design.[38]

Through the termination of the Freedom Program in 1993, 'Man-Systems' was recognized as one of nine primary systems of the Space Station, along with Electrical Power, Data Management, Thermal Control, Communications, Guidance, Extravehicular Activity, and Environmental Control.

Man-Systems was responsible for overseeing the development of the end-to-end architecture within the manned modules. Architectural parameters were defined to include orientation, movement of personnel, viewing, design of work locations, nomenclature and markings, human interfaces to displays and controls, human/computer interaction, and facility management. Man-Systems was also responsible for the end-to-end definition, design, functionality, and hardware development for fifteen subsystems: Crew Quarters, Restraints and Mobility Aids, Operational and Personal Equipment, Portable Emergency Provisions, Integrated Workstations, Galley/Food, Personal Hygiene, Illumination, Wardroom, Stowage, Housekeeping/Trash management, Interfacing Partitions and Structures, On-Orbit Maintenance, Inventory Management, and Crew Health Care, which in turn was comprised of Health Maintenance, Exercise/Countermeasures, and Environmental Health.

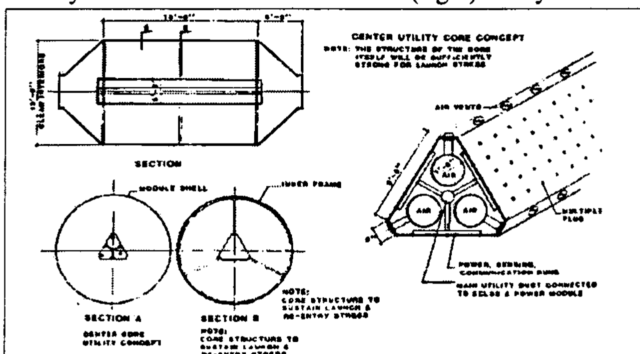
MODULE ARCHITECTURE

In order to ensure longevity, to enable evolution over the planned 30+ year design life, and to control costs during development, common denominators for station systems were defined to be reconfigurability and maintainability. The modularity of components, the ability to replace obsolete or malfunctioning elements was critical.

For the module interiors, trade studies looked at a building block approach and considered the most efficient block size. At one end of the spectrum was the potential to change out entire modules; at the opposite, small modular elements, the size of Space Shuttle lockers (2 cu ft) were studied. The ability to remove and replace whole modules inside of a cluster and joined at both ends would prove difficult. Locker-sized compartments would be adequate for most stowed crew equipment, but would prove too small for most systems hardware. Refrigerator-sized packages were deemed to be the most likely solution for housing most major systems hardware.

A concern since the beginning of the mid-1970s station studies was the ability to deal with orbital debris or micro-meteorites. Increasing orbital traffic and the models that showed that most orbital debris resulted from the break up of orbiting satellites and rocket stages indicated the need to anticipate significantly greater amounts of shrapnel in the decades ahead. The orbital debris would penetrate a module, depressurize it, and render it uninhabitable. This dictated easy access to the vehicle pressure shell. This would in turn require systems hardware to be packaged in such a way that pressure shell access could be assured in a short amount of time.

Several conceptual designs looked at concentrating the utilities and systems into the center of the modules. In a study of the 'Center Service Core' (fig 9) the systems



Conceptual Design Center Utility Core

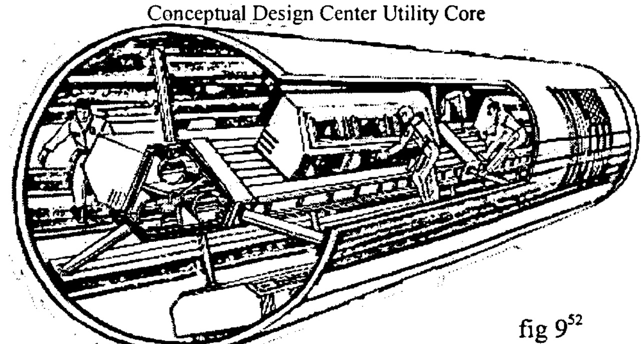


fig 9[52]

hardware was limited to a 1.5 meter wide zone down the length of the module, with another 1.5 meters on either side allocated to crew living and working volume. The design was described as being:

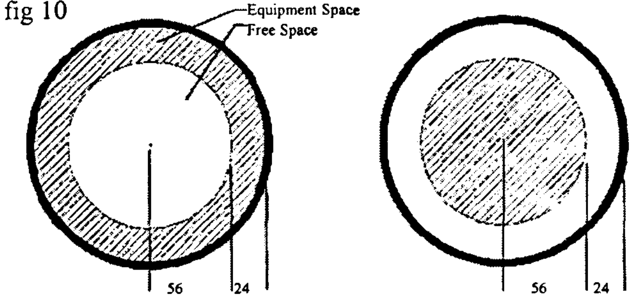
> similar to a modern office building...which concentrates the mechanical, utilities, and circulation in a service core located in the center of the building with large continuous office space surrounding the core....
>
> The Service Core concept promotes efficient servicing of the station in orbit and provides reasonable access to the utility volume while on the ground prior to launch....
>
> The utility runs such as air ducts, electrical, etc., occupy in an efficient manner the volume created by the curved interior wall joint with the straight floor and ceiling. The concept creates enhanced adaptability and flexibility for equipment maintenance and repair.[52]

A similar concept was proposed and a medium fidelity mock-up of the configuration constructed by Rockwell International. The 'Center Core's' (fig 12) key advantage was identified to be the concentration of service functions to a small volume, while enhancing access to equipment and maintaining an open work or habitation volume.

A related concept, developed by John Frassanito and the Man-Systems Division was the 'center beam' (fig 13) , in which the utility runs and structural attachments were confined to a beam running through the center of the module, and wedge shaped equipment containers and compartments for people were suspended between the beam and the module shell. Almost all of the interior outfitting would be modular packages and mounted to the center utility run.

If the space station modules were divided based on functionality - some to provide habitability and others to provide housing for systems hardware, then such concepts might work. But if systems hardware and habitable volume were to share the same module, then such concepts would work best for volumes with larger cross-sections, like a large diameter space station module. A comparison of the amount of volume available for hardware centered in a narrow cylinder, such as a 4.5 meter diameter space station module, shows the narrow dimensions of the remaining open volume. Figure 10 compares the same volume of hardware, in one case

fig 10



EQUIVALENT EQUIPMENT VOLUMES (64 CU FT)

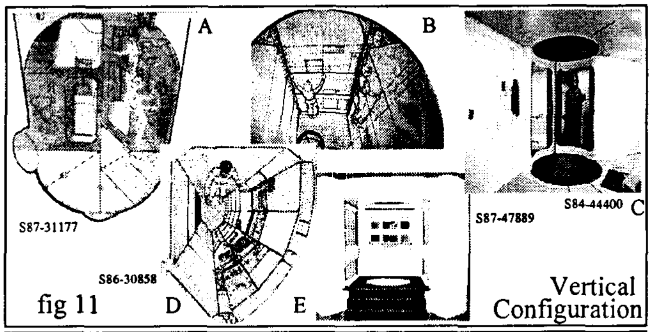


fig 11 Vertical Configuration

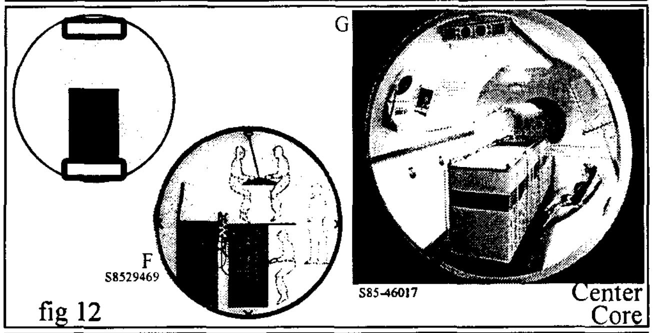


fig 12 Center Core

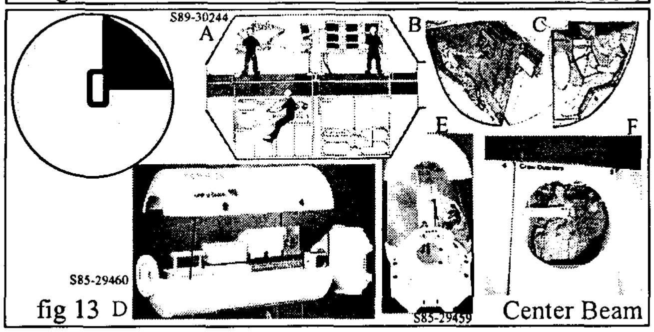


fig 13 D Center Beam

located around the periphery of the cylinder, and in the second case, centered in the cylinder. Generally, the larger the volume and the diameter, the more flexibility there would be.

Two Phase B configurations, developed by Grumman and McDonnell-Douglas, took the approach of equipment mounted on the cylinder periphery. Grumman's 'loft' (fig 14) configuration had equipment in wedge shapes at the four corners, resulting in an x-shaped cross section for the habitable volume. There would prove to be an inadequate volume for systems hardware in this approach, though from a human factors standpoint the open volume was desirable. McDonnell-Douglas (fig 15) had two sizes of equipment packages, lining the walls and ceiling. Utility runs ran the length of the floor and ceiling. While both of these architectural concepts were more reasonably balanced with respect to the proportion of systems hardware to open volume, neither made a point of placing the systems hardware into modular racks for removal and replacement or for pressure shell access.

These architectural studies were critical in identifying the attributes of the module interiors that would permit the design to meet the requirements of reconfigurability and

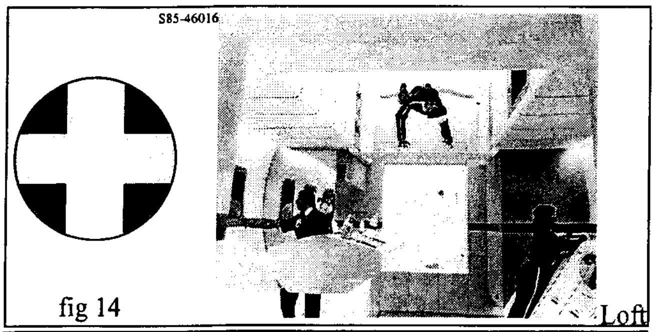


fig 14

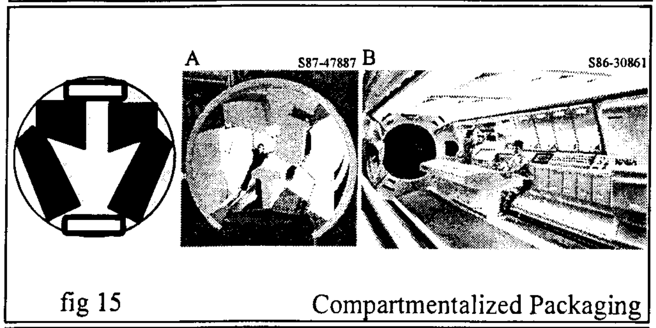


fig 15 Compartmentalized Packaging

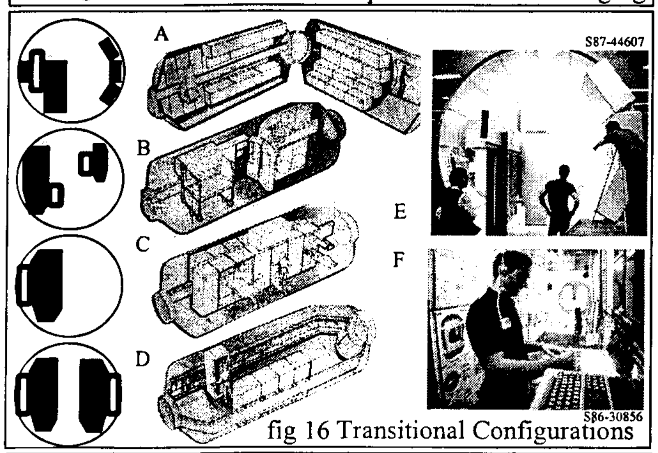


fig 16 Transitional Configurations

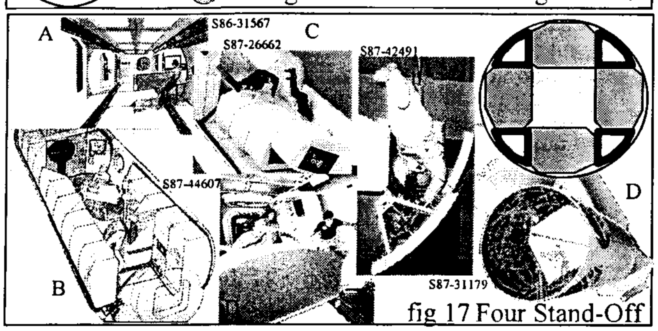


fig 17 Four Stand-Off

maintainability while still promoting habitability, but none was deemed to have met all of the requirements.

Several elements of the different concepts were integrated by Man-Systems to develop the configuration that would ultimately be built. (fig 17).

In the 'four stand-off design', equipment would be located around the module periphery. Utility runs would be consolidated into relatively compact areas located at the'four corners'. Like in Spacelab, systems equipment and compartments would be housed in refrigerator sized modular racks.

Roughly rectangular shaped racks would fit into the volumes between the stand-offs (fig 17). The rectangular solid would be easiest for systems developers and manufacturers to work with. Cross sections of the wall, floor and ceiling racks would all be common. Utility connections between the utility runs and the racks would be made only at the base of each equipment rack so that most racks could fold away from the module wall for rapid access to the pressure shell. Modeling determined the required size for the corner utility runs. Tests were run to establish that, even in the case of a depressurized module, a fully suited crewmember would have adequate access to nearly all module areas (fig 17E). Racks were sized so that they could be carried through hatches and rotated for passage.

MODULES, TUNNELS AND NODES

Early space station concepts had been for 'common modules' to be built according to a 'sausage factory' approach akin to building airliner fuselages. Module cylindrical structure could be turned out and cut to length; the modularity of hardware racks would permit the addition of whole outfitted modules to the station at relatively low marginal costs, once the basic design was in manufacture. But the Phase B space station studies were now aiming towards fewer modules. Program costs were estimated based on systems mass and complexity, and only a small number of copies of systems hardware components would be built. Systems and humans would share a common volume.

As systems volume requirements were being defined, a higher proportion of systems hardware to free volume was anticipated than for the Spacelab. The relative amounts of volume to be allocated within the modules for different functions were developed and compared.

One-third of each module's pressurized volume would be required for airlocks and for hatch storage and passage between modules, so it was recommended that airlocks be placed externally and that radial berthing ports not be incorporated into each module's structure.

This left the only connecting ports at the module ends and necessitated the development of a concept for connecting 'nodes', the purpose of which was to house hatches and berthing ports to link the modules.

As the elimination of the four radial hatches and berthing ports in each common module reduced mass in the modules, the modules could be lengthened. Larger modules meant that the number of modules could be reduced. One module would be required as a habitation module and one as a US laboratory module.

Tunnels would be located in place of two parallel US common modules in order to maintain the rectangular configuration required to provide a safe haven or emergency response capability. (fig 18)

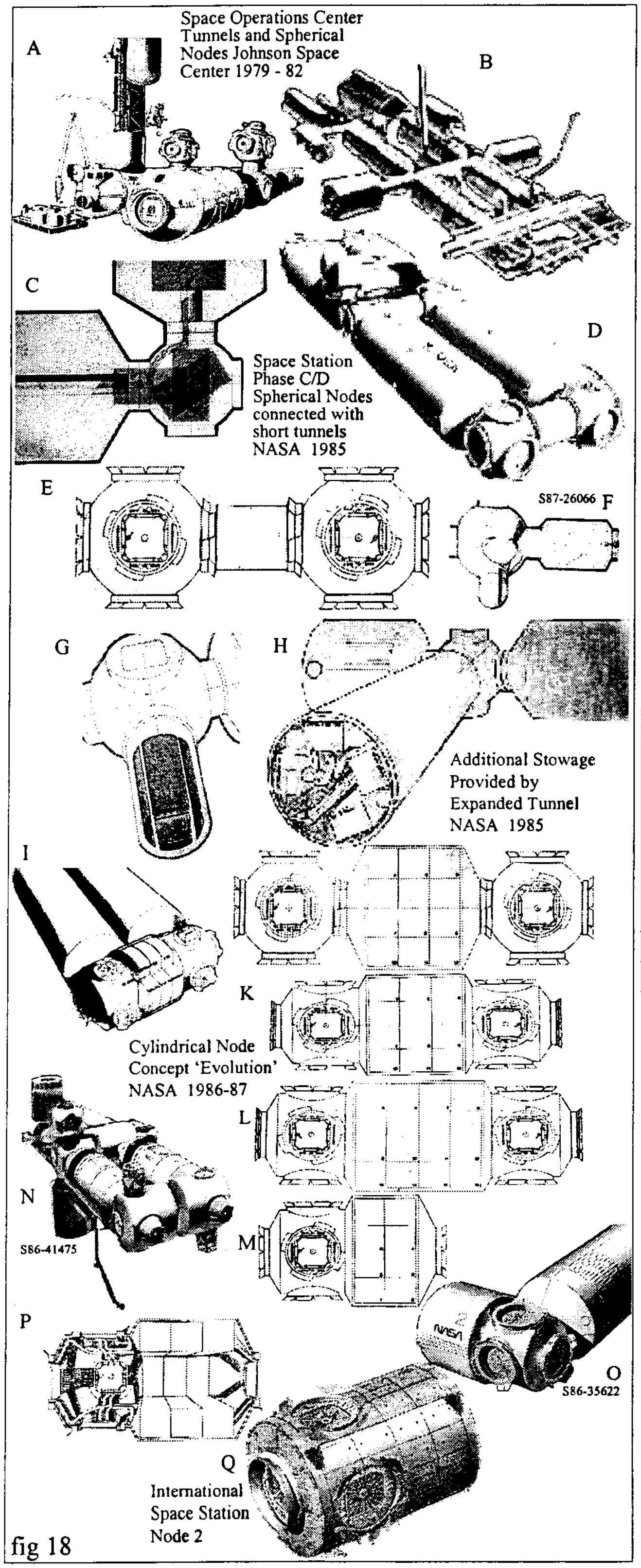


fig 18

Use of the tunnels for passive functions, such as stowage, was studied (Fig 18H). The tunnels had little internally mounted hardware and so were not densely packed; therefore expansion of their diameter to the limitations of the Shuttle was proposed. As the tunnel diameter approached the diameter of the connecting nodes, it was proposed to unitize the nodes and tunnels, eliminating two berthing ports and hatches and reducing the mass, complexity and total cost (Fig 18 J-M). The single cylindrical 'node module' could be long enough to accommodate a limited amount of storage or systems hardware, but due to the mass of the berthing rings, hatches and any internal systems, the length would have to be considerably shorter than the primary modules.

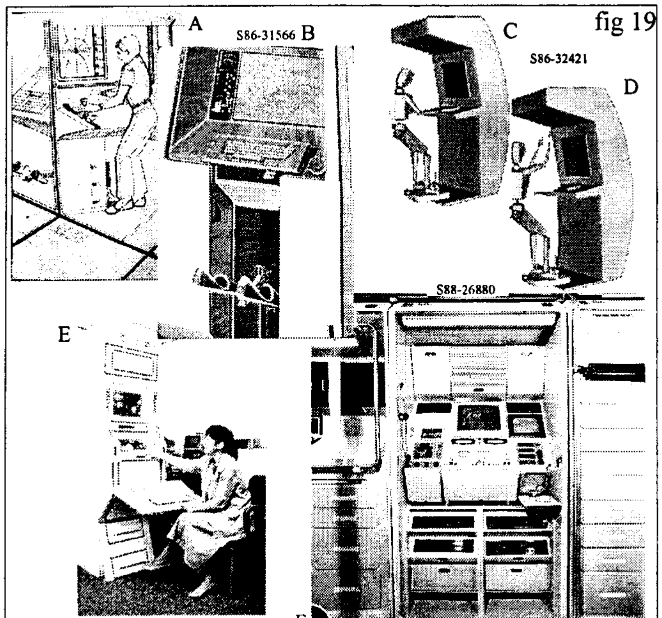


fig 19

WORKSTATIONS AND WINDOWS

At the time that the Space Station architecture was being developed, from the 1970s through the early 1980s, computers were just making it into mainstream everyday life on earth. Many expected that a central computer in space station would serve as the primary command and control 'console', analogous to the Space Shuttle orbiter flight deck or the Skylab's telescope mount console. A small team of Man-Systems scientists and engineers set about defining the requirements and operational and physical parameters for computer-based workstations. Requirements for operations and hardware were defined, designs (fig 19) considered and evaluated using the anthropometric evaluations. First low fidelity mock-ups and then high fidelity mock-ups were built and evaluated.

A space station 'flight deck', providing external viewing together with controls and displays for system operations

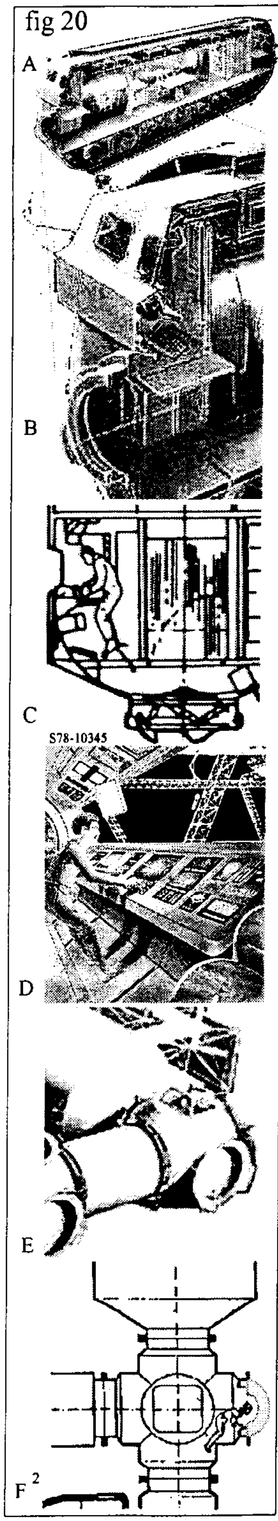


fig 20

was a concept developed at the time of the Space Operations Center (SOC). A primary SOC mission was defined to be operations with other spacecraft, and external viewing in conjunction with spacecraft maneuvers and operation of robotic manipulators would be prime requirements. SOC concepts showed control stations with windows either in the module end or cylinder side.(Fig 20 A-D)

On Skylab the astronauts had experienced control stations using only televisions for viewing such as the telescope mount console, and they had also used a large window located in the wardroom, mainly for observing the earth.

Al Bean, commander of the second mission, enjoyed working at the telescope console that had TV's to show telescopic images of the sun; he felt that the telescope console was "the only time you really have sort of by yourself... you come up here and spend two or three hours and its really pleasant..."[60] Bean and the other astronauts liked watching the sun, giving them something important and useful to do, operating the instruments, controlling the orientation of the spacecraft and telescope. Since they were often looking for the unanticipated, they also had some independence in the operation of the system. The instruments and their operation were complex, and so it was a challenge. While the operations at the console included spacecraft maneuvering, the operations were in support of research and not rendezvous or maneuvering of other spacecraft, extravehicular 'spacewalks', or assembly and repair operations.

The Skylab astronauts spent considerable time at the wardroom window, observing and photographing the earth. Both activities were reported to be the most enjoyable time spent in orbit.

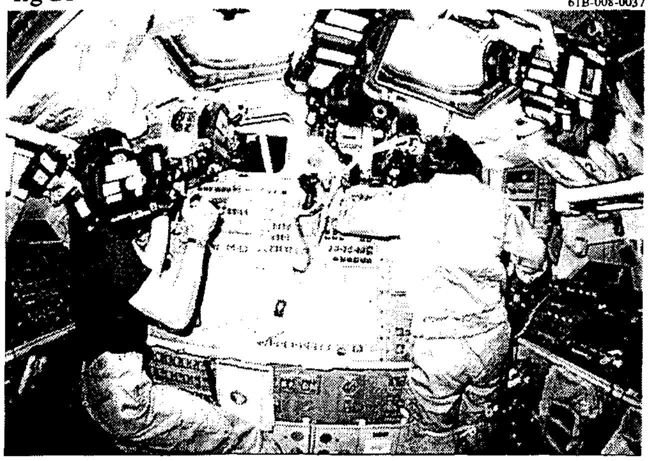
There was considerable disagreement in the first year of the Space Station Program over the necessity of any windows and 'windowed workstations'. Many of the scientists and engineers focused on computer-based operations felt that direct viewing would be unnecessary. A primary argument was that due to the size and complexity of the station, viewing of specific activities would in many cases not be possible. An interesting perspective came from some in the engineering/structures community, who believed windows to add a new, heavy, expensive and unnecessary factor which would compromise the safety of the pressure vessel.

Astronaut Gordon Fullerton expressed the viewpoint of the flight crew very simply: 'give me a window and binoculars any day over a high tech solution'. [61]John Young, as Chief of the Astronaut Office, defined the requirements in detail:

> ....the space station is a facility whose crew has to perform a wide variety of functions with equipment ...on it or in its vicinity....an example might be the station keeping of an orbital platform controlled from the station...[using] the station manipulator and while an extravehicular activity crew....functions that will need to be guided or controlled from the station: rendezvous, station-keeping, approach, docking, transfers from other platforms to/from station, attitude control, manipulator system use, extravehicular construction, repair, refurbishment, refueling, antenna orientation, solar power orientation, radiator orientation, damage control operations such as fire or leak location and isolation....
>
> It has been suggested that all these functions can be easily performed in the station's one great unified data processing system by people using their own individual personal computer workstation. This is an unreliable and unsafe idea....
>
> In order to accomplish the command and control of the Space Station, each Habitability Module...must have a suitably isolated and properly partitioned Operations Center. This Operations Center...should allow direct vision, windows or portholes...of structures, extendadable appendages, vehicle approach paths, and station-keeping sectors....Television or fiber optic are not suitable substitutes for direct vision....[58]

In developing the initial detailed design of a windowed workstation, the aft flight deck of the Shuttle Orbiter, used for the operation of its robotic arm, the management of spacewalks, and the orientation and control of the Shuttle during dockings, served as an inspiration (fig 21).

fig 21



One of the first designs detailed was modeled after the orbiter's aft flight deck (fig 22 c,f).

The name 'windowed workstation' proved cumbersome and once the idea appeared to be finally sold, the small module with the windows was named the 'Cupola', after the elevated and windowed section of a railroad caboose.

Many configurations were modeled and evaluated (Fig 22 A-J). Size was a primary factor. Would it need to hold one or two crewmembers, or more? Would the crew need to be fully enclosed, or only their heads and shoulders ? Would computer, controls and displays be permanently mounted, or temporarily placed? The size and the shape of windows was another important consideration. Would the best viewing be in one or two primary directions, or in all directions ? In the end, the cupola design today (Fig 22 K-L) is essentially as was proposed by the space station contractor, McDonnell Douglas, in 1987.

EPILOGUE

Almost as soon as the space station design was settled upon, the influences of budgetary cutbacks began to have effects on the configuration. Station Program Manager, John Aaron, frequently would initiate development meetings saying, 'we need to keep it capable of performing the same functions, but it needs to be cut back'. The upper and lower keels meant as the scientific equipment mounting platforms, were cut-off and this left only the long central truss.

The station configuration initially baselined as the Phase C/D contracts were signed had a US laboratory Module, a habitation module, four 'resource nodes', two Cupolas, two airlocks, plus the European and Japanese laboratory modules. Over the period of the next five years a series of redesigns left the station with the US laboratory, one airlock, and one node of the original design all to be built by the US. Another node, extended in length to accommodate more racks, and a single cupola would be built by the Europeans.

The logistics module, also being built by the Europeans, was stripped of systems and mass until it could no longer be left in orbit, eliminating the planned storage area. The module would now have to be carried to the station and returned on the same shuttle flight.

The length of the primary US modules was an area of some discussion and concern from the time of the source boards that evaluated the proposed Phase C/D configurations, and even before the conclusion of the source board it was anticipated that both the Laboratory and Habitation modules would need to be shortened to meet Shuttle launch capabilities to an orbit of 200 miles or more. The reduction in the number of modules eliminated the figure '8' or racetrack configuration of

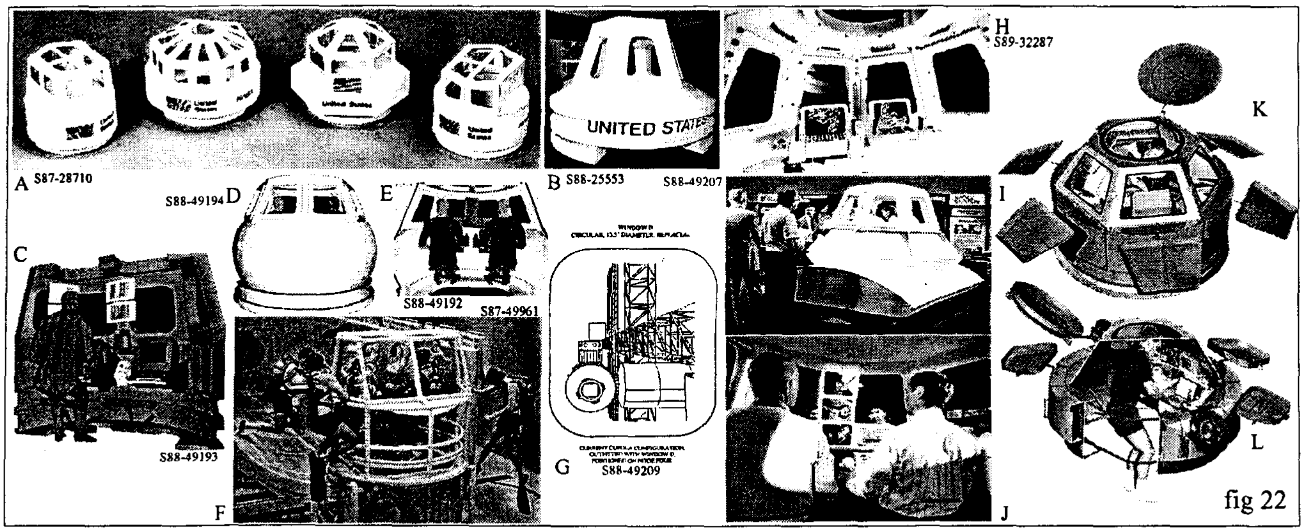


fig 22

modules (Fig 23). A crew rescue vehicle would take care of emergencies requiring the evacuation of crew. This was a direct outcome of the Challenger tragedy of 1986 which grounded the Shuttle fleet for just less than 2 years. 'Safe haven' requirements could be reduced.

In 1993, Russian habitation, service and airlock modules were added to the mix. These were left over from the Soviet-planned Mir 1.5. Together with the US lab and node, three crewmen have been accommodated. As of the current time (2002) discussion is still ongoing about expansion of the crew to six. Expansion of the crew size would require additional habitation resources.

The fate of the Habitation Module, which was a primary focus of the station and particularly the Man-Systems design effort over many years, is uncertain. While the basic shell was completed at the same time as the Laboratory Module, no further outfitting or integration was ever completed as a result of funding. There have been discussions and negotiations to have a hab module developed by an international partner. While consideration has been given to the use of the original module shell, most recently plans have considered the use of a lengthened node.

SUMMARY

The development of the architecture and configuration of the International Space Station modules and crew compartment extended over a long time period and was based on a very comprehensive set of requirements and analyses. Many different habitat architectures were considered. In the end the architecture that was adopted was based upon a compromise of launch vehicle capabilities, system requirements, past experience, human factors and political considerations, but the basic internal architecture of the habitable modules as established in the two years prior to the Station contract signature has remained fairly constant.

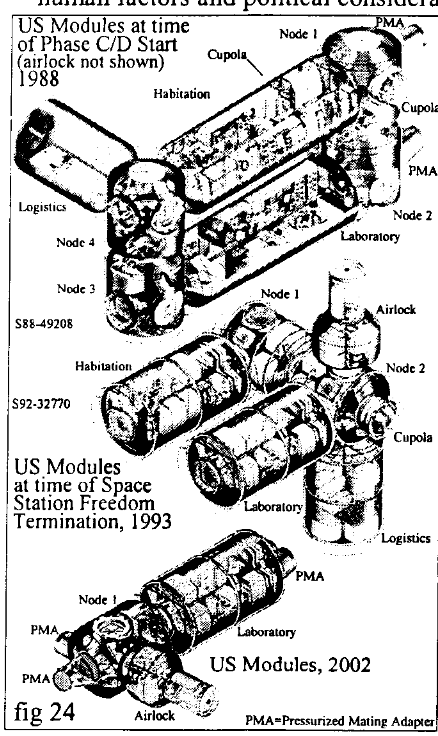


fig 24

In the future, the International Space Station module design may be used for habitats going to the moon or planets (fig 25), though most recent design efforts have focused on use of an inflatable fabric module in order to gain living and working volume without incurring additional cost in mass.

Consideration of a wide variety of module configurations was important in developing an innovative but practical architecture for the International Space Station.

The design concepts and architecture promise to be an important consideration in how crews live and work in space for decades to come.

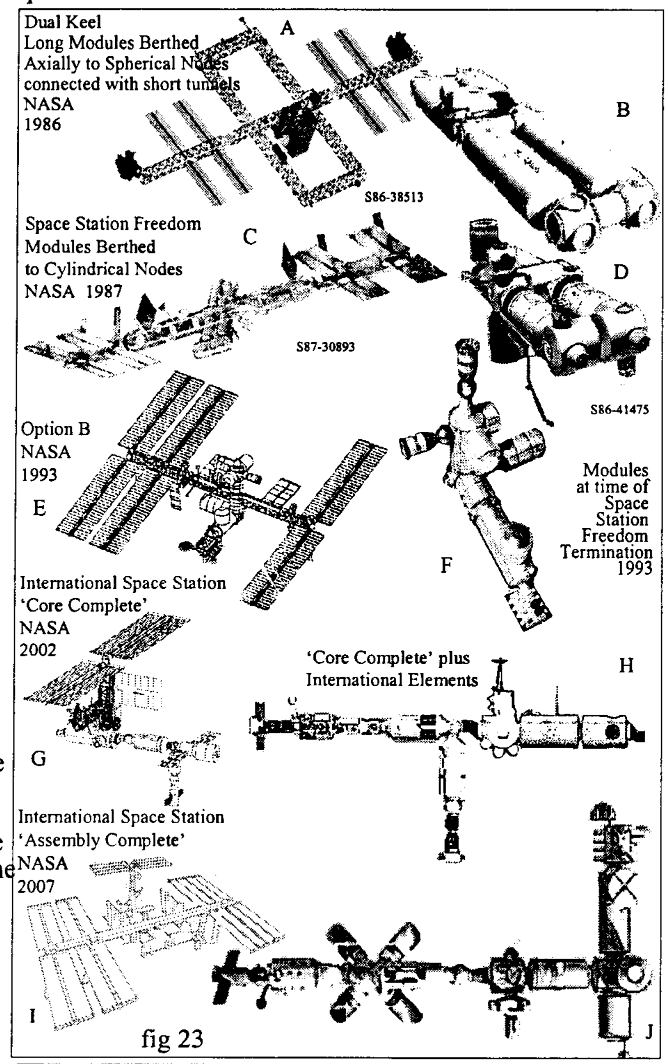


fig 23

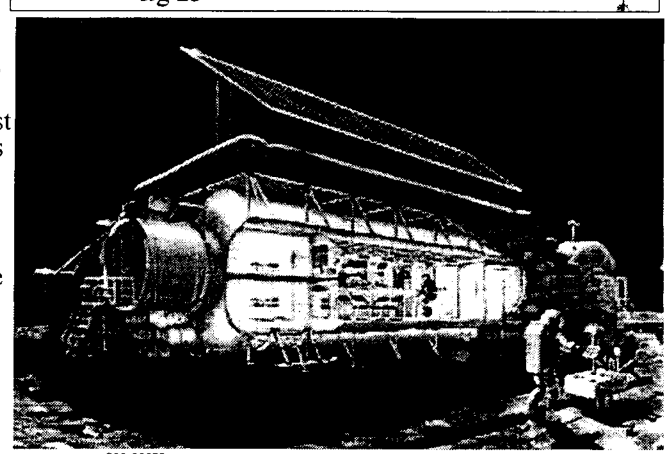


fig 25 S89-20093

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PHOTOGRAPHS

I have attempted to use the images produced at the time of the design process and where possible have provided the NASA S- numbers. In many cases, images came from personal files and were never placed in the NASA photo system. Many images have been modified to highlight important features.

ACKNOWLEDGEMENTS

This paper would not have been possible without the contributions of the men and women of NASA and their supporting contractors. The development of the space station module design can be looked upon fondly as a high point in our careers.

Additionally the following individuals provided important contributions in the form of their recollections and information:

Jay Cory — Bill Langdoc
Max Faget — Chuck Wheelwright
Malcolm Johnson

Frances Mount, PhD, her recollections and insights and the documentation she had carefully selected and saved from over two decades of work in this area were indispensable.

Any mistakes are those of the author.

Gary H. Kitmacher
(seen here with astronaut Paul Scully Power in the Vomit Comet)

Gary Kitmacher is from NASA's Johnson Space Center in Houston Texas. Mr. Kitmacher serves as the Space and Life Sciences manager for space flight safety and supports Space Station and Shutte missions and commercialization initiatives.

Mr. Kitmacher has served in several capacities since coming to the space center in 1981.

- During the Shuttle-Mir program; he was the US manager responsible for the last Mir module, Priroda, and directed integration and operations on Mir. He led US efforts to develop, certify and and integrate systems and payloads on Mir. One of the systems developed at his direction is the logistics system now in use for International Space Station.
- Previously he worked in the commercial Spacehab program and managed the STS-60/Spacehab 2 mission.
- During the design and definition stage of the Space Station, he was the Man-Systems system architectural control agent and later applied this experience to the design of manned moon and Mars habitats, rovers and landers.
- In 1985-86 he served as the subsytem manager for Space Shuttle Crew Equipment and Stowage.

Mr. Kitmacher has masters and bachelors degrees in Management, Geology, Astronomy and Education and is an Adjunct Professor in the University of Houston School of Business teaching a course in the commercialization of space technology.

Mr. Kitmacher is married. He resides with his wife and daughters in Houston, Texas.

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