History of
Rocketry and Astronautics

Proceedings of the Eighteenth and Nineteenth History Symposia
of the International Academy of Astronautics

Lausanne, Switzerland, 1984

Stockholm, Sweden, 1985

Tom D. Crouch and Alex M. Spencer, Volume Editors

R. Cargill Hall, Series Editor

AAS History Series, Volume 14

A Supplement to Advances in the Astronautical Sciences

IAA History Symposia, Volume 8

AAS Publications Office
P.O. Box 28130
San Diego, California 92198

Affiliated with the American Association for the Advancement of Science
Member of the International Astronautical Federation

First Printing 1993

ISSN 0730-3564

ISBN 0-87703-374-9 (Hard Cover)
ISBN 0-87703-375-7 (Soft Cover)

Published for the American Astronautical Society
by Univelt, Incorporated, P.O. Box 28130, San Diego, California 92198

Printed and Bound in the U.S.A.

AAS 92-307

Chapter 7

FUNCTION, FORM, AND TECHNOLOGY: THE EVOLUTION OF SPACE STATION IN NASA*

Sylvia Doughty Fries†

Space station designs developed by the National Aeronautics and Space Administration or its contractors since 1960 exhibit a consistent relationship between function, available technology, and form, or configuration. Serious engineering design of space stations, of course, predates the creation of NASA in 1958. Setting aside Edward Everett Hale's fanciful vision in *The Brick Moon* (1869), and the turn-of-the century schemes of Hurt Lasswitz (*On Two Planets*, 1898) and Konstantin Tsiolkovsky, U.S. space station designers could draw upon a rich conceptual heritage reflected in the space station designs of Hermann Oberth (*The Rocket in Interplanetary Space*, 1923; design revised in 1929 and 1957), Hermann Noordung (*The Problem of Space Flight*, 1928), Baron Guido von Pirquet (articles in *Die Rakete*, 1928), H. E. Ross and R. A. Smith (1948), H. H. Koelle (1951) and Wernher von Braun (1952) [1]. For none of these designers was the existence of a manned, permanent station in space an end in itself. Such an achievement was to serve the more enduring purposes of (1) increased understanding of the cosmos through celestial observation, (2) service to Earth-bound humanity through large-scale meteorological observations and global communications, and (3) manned interplanetary exploration through the provision of an Earth-orbiting service and logistics station.

Each of these early designs' configurations was predicated by its several functions. Astronomical and Earth observations required platforms for instruments; scientific research, servicing and manned planetary exploration required a protected environment for human habitation—which, the early designers assumed, meant simulated gravity; and the space station as a whole would require a power source as well as access by Earth-to-orbit and return logistics vehicles. Power would be acquired from the solar rays that warmed the steam boilers on Noordung's "wohnrad," or that were reflected to the Earth in Oberth's 1923 design. Simulated gravity—not necessary for every space station function—was to be achieved through the centrifugal force of rotating elements.

---

* Presented at the Nineteenth History Symposium of the International Academy of Astronautics, Stockholm, Sweden, 1985.

† National Aeronautics and Space Administration, Washington, D.C.

While the number of space station design studies conducted by NASA or its contractors since 1959 easily exceeds a hundred, four examples will suffice to illustrate how the changing functions of a space station, and available or anticipated technologies, have continued to determine the changing forms most characteristic of each design. Our examples will be taken from the pre-Apollo, post Apollo and STS periods in NASA's history.

LANGLEY RESEARCH CENTER AND THE ROTATING HEXAGON: 1959-1962

NASA's engineers at Langley Research Center in Hampton, Virginia—the oldest of the former NACA aeronautical research laboratories transferred to the new space agency—formally launched a study of a "manned space laboratory" (the term was then used interchangeably with a manned space station) in October, 1959. Placing such a laboratory in orbit was conceived "as one of the initial steps in the actual landing of a man on the Moon in 10-15 years." Specifically, a manned orbiting space station would enable the fledgling agency to explore the "materials, structures, control and orientation systems, [and] auxiliary power plants" required for a space station; it would enable study of "means of communication, orbit control and rendezvous;" and finally, it would allow NASA to investigate the necessary conditions of human life and operations in space—to study "the psychological and physiological reactions of man in a space environment over extended periods of time . . . his capabilities and usefulness" and "techniques" for manned "terrestrial and astronomical observations" from space. Joseph A. Shortal of Langley's Applied Mechanics and Physics Division (in which the Langley space station office was located) regarded "the orbiting laboratory as an extension of ground facilities for a broad range of engineering and systems studies," or a research and development laboratory in space [2]. *Developing the technology of long duration manned space flight was a sufficient purpose unto itself.*

By August of 1962 the Langley group was ready to share the results of its work with the young aerospace community. Their principal design requirements were the necessity for rotation to achieve artificial gravity, and for unitized structure, since the station would have to be "carried aloft on a single launch vehicle." Both requirements, however, entailed critical structural and dynamic constraints. Assuming a "range of gravity from 0 to 1 g" for experiments and human livability, a station rotating at an acceptable rate would have to have a radius of 75 ft. A station of that size—too large to be launched, wholly constructed, in any single, conceivable vehicle—would have to be "broken into elements which, when suitably folded or packaged become a reasonably compact payload." Just as rotation would affect the dynamics of a space station, so also would unitized structure impose certain dynamic constraints. The need for launch vehicle and payload compatibility was obvious, lest "the destabilizing aerodynamic moments . . . overpower the control system." Nor could the combined structures' "natural frequencies" be allowed to "couple among themselves or with the pitch frequencies."

Langley's engineers explored six space station configurations (Figure 1): (1) cylinder rotating about an axis perpendicular to the length of the cylinder, with solar panels extended from the cylinder's sides; (2) a cylinder attached by a tether to a terminal stage booster, again rotating about an axis perpendicular to the length of the terminal stage and tethered cylindrical station; (3) a station consisting of *two* cylindrical living modules, about 100 feet apart and extended from either side of a central, 200 foot tubular core having a nuclear power plant at one end and multiple docking facilities at the other (rotation would be about the horizontal axis of the central core); (4) a spoke configuration, with two or more radial habitable elements extending from a central hub, in which rotation would be perpendicular to the vertical axis of the hub; (5) a configuration consisting of two or more habitable modules positioned at the end of spokes extending from a central hub, and with axis *parallel* to the axis of rotation; and finally, (6) the familiar annular "wheel" rotating about the central hub to which it was connected by one or more tubular spokes, and lying "essentially within the plane of rotation" [3].

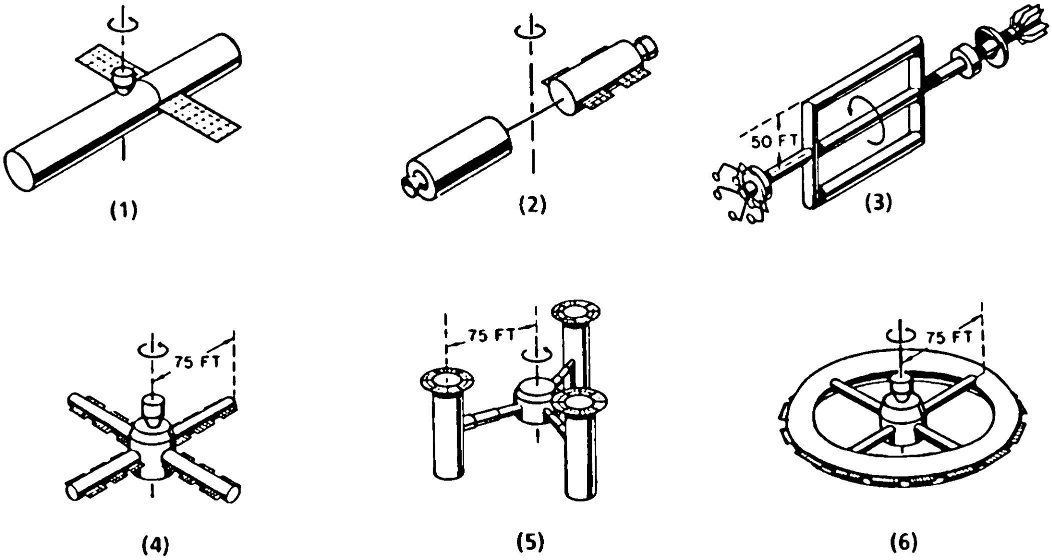


Figure 1 Langley Research Center: Space station basic configurations studied 1959-1962. Source: Langley Research Center, **A Report on the Research and Technological Problems of Manned Rotating Spacecraft.** NASA TN D-1504 (Washington, D.C., August, 1962).

Expected problems with dynamic stability, single vehicle launch and subsequent erection of the launch package, and degrees of movement required for human crews (which could entail the disorienting Coriolis effect) led the Langley team to reject all but one of the candidate configurations—the large annular torus with a radius of 75 ft. Launching such a structure into orbit then determined the special characteristics of NASA's early "wheel." Wernher von Braun had suggested that a toroidal space station could be inflated in orbit; but the Langley group concluded that the station's equipment could not be properly installed in an inflatable structure prior to launch and would have to be stored in a "central hub," to be moved into place once the station was in orbit. The motion thus required, however, would jeopardize the station's stability. If, however, the living and working sections of the station were rigidly constructed, and equipment put into place before launch, the problems posed by the inflatable configuration could be avoided; moreover, a rigid station could be constructed with materials that could provide "adequate protection from the space environment." Even this solution, however, had the defects of its virtues: a rigidly constructed space station would have to be assembled in space. This defect, however, might be minimized if assembly could be automated.

Langley's engineers finally adopted, as the reference configuration for a feasibility study contracted to North American Aviation, an automatically erectable manned orbital space station which, in their view, combined "the best features of the inflatable and rigid space-station concepts, that is, the compactness of inflatable designs and the prelaunch equipment installation features of the rigid designs." North American Aviation, in turn, narrowed the range of conceivable configurations for an automatically erectable rotating space station to three: an annular torus, a hexagon, and a modified hexagon.

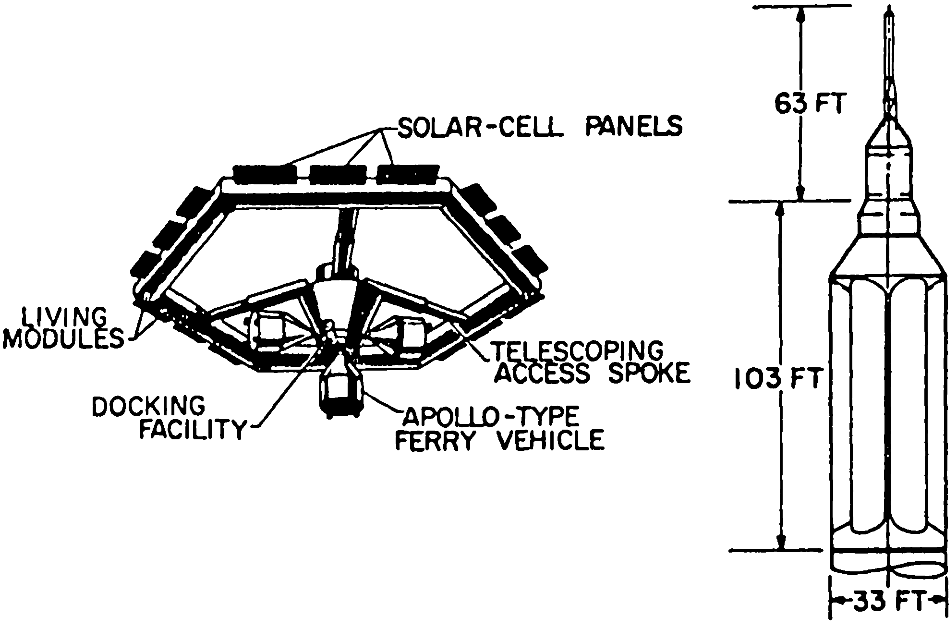


Figure 2 Langley Research Center hexagonal configuration (North American Aviation, 1962). Source: Langley Research Center, **A Report on the Research and Technological Problems of Manned Rotating Spacecraft**. NASA TN D-1504 (Washington, D.C., August, 1962).

The configuration finally chosen by North American Aviation for systems analysis was the purely hexagonal configuration (Figure 2), which offered the advantages of a wheel configuration and overcame some of the disadvantages of the inflatable torus or modified hexagon, which related primarily to problems of orbital deployment and creating a "launch package" adaptable to the straight-sided launch vehicle. Six rigid cylindrical modules were arranged in a hexagonal shape; every other module (three in all) was joined to the core with a telescoping spoke; and the modules were joined at their ends by a system of six compound hinges devised at Langley, thus avoiding the need for any exposed flexible fabric. Mechanical screw-jack actuators at the six joints would do the job of deploying the space station from launch configuration into an orbital configuration. The hub of the station would incorporate docking facilities for Apollo-type ferry vehicles. The total volume and weight of this proposed space station would be 45,000 cubic feet, and roughly 171,000 pounds, respectively, just under the 210,000 pound then anticipated payload weight capability of the Saturn rocket [4].

1966: A SPACE STATION FOR SCIENCE

By 1966 the value of access to space for research in such scientific disciplines as astronomy and meteorology had been proven, and NASA became more attentive to the scientific disciplines' insistence that their requirements be fully incorporated into planning for the agency's projects and programs. It is clear from the results of NASA's space station studies carried out in 1966, that the agency hoped the scientific community would support continuation of an agency-wide effort to develop a space station. A space station requirements steering committee, headed by Charles J. Donlan and a parallel group to carry out the resulting design work (headed by E. Z. Gray), sought to develop a configuration that would satisfy the numerous and sometimes incompatible requirements of a space station designed to satisfy the needs of a variety of scientific disciplines.

NASA Deputy Administrator Robert C. Seamans had specified that a space station program emphasize "Astronomy, Earth Resources, Meteorology, Biology, Long-term Flight (including aerospace medicine), Research and Development in Advanced Technology and Orbital Operations and Logistics" [5]. However, accommodating the projected research programs for astronomy, Earth resources and meteorology on one station would prove difficult. The telescopes required for the astronomy program (gamma-ray, x-ray, optical and radio telescopes), dictated station deployment above the ionosphere, at a minimum time in radiation belts and maximum time in darkness. They would have to be maintained in an inertial space orientation with a stabilization accuracy of 0.001 degrees, gimbal mounted, and rotating 360 degrees along one axis and +/−40 degrees along the other for as long as 10 hours; that portion of the station upon which the telescopes were mounted could not be rotated. Nor could the instruments for the Earth resources research program be rotated.

At the same time, the full complement of projected, Earth resources instruments would have to be operated in continuous alignment with the local Earth vertical at orbital altitudes of 200 nautical miles or less, and at an orbital inclination of 50 degrees or greater for maximum observation over the entire United States. The space station would have to provide a cumulative pointing and holding accuracy of +/−0.05 degrees and, for a tracking telescope, a pointing accuracy of less than 10 seconds. Similarly the meteorological program, with its photographic equipment, optical and infrared telescopes, spectrometers and radiometers, would prohibit instrument or station rotation and require low-altitude (200 nautical miles), low-inclination orbits, with an instrument stabilization accuracy of 0.05 degrees. Thus the astronomy, Earth resources and meteorological research programs projected for the space station in 1966 imposed design requirements that would be difficult to meet on a single station.

Long-term flight and biological research experiments, on the other hand, imposed no requirements on station orientation or stabilization, while advanced technology research and development could be carried out with both inertial and Earth orientations and 0.1 degrees stabilization accuracy. These programs could be accommodated with nominal zero or 10^{-5} gravity and a centrifuge (for biology and long-term flight experiments). Orbital operations required no particular orientation or stabilization accuracies, and could be conducted in nominal zero gravity.

The Donlan Committee considered two strategies for resolving the problem of integrating a multi-disciplinary research program with varying, and in some instances incompatible, engineering design requirements. One strategy was to attempt to integrate all the projected research programs "into a single, unified research program, and to equip a space station capable of pursuing an entire program." As the committee explored the "unified approach," however, it found that meeting the functional requirements for the entire assemblage of planned research activities would dictate a "big station with both rotational and nonrotational components giving a tendency for the design to be large, and possibly somewhat strained." A second, and favored, program integration strategy identified by the committee was the "group approach," or one in which the entire program was divided "into a sufficient number of parts to separate the conflicting requirement items, and to group together those not in conflict for location in separate modules." Thus the Donlan group arrived at the *multi-station or group concept*, which offers an alternative means of *resolving the requirements conflict by the expedient of physical separation* [emphasis mine]" [6].

If the need to satisfy the scientific disciplines was one critical determinant of NASA's 1966 space station design, the heavy investment being made in the hardware for the Apollo and the Apollo Applications ("Skylab") programs—especially the mammoth Saturn booster with its 285,000 lb. lifting capability—was the other. (The Skylab program, inaugurated in 1965, was itself designed to capitalize on the capabilities of the Saturn launch vehicle and Apollo hardware) [7].

The design work for the space station suggested by the Donlan committee's study was carried out at NASA's George C. Marshall Space Flight Center (MSFC). Twin stations, each dedicated to three scientific disciplines with compatible functional requirements, was MSFC's response to the "group approach" solution proposed by the Donlan committee for the incompatible requirements of a multi-purpose space station. Each zero-g station, which could be fitted to the top of the Saturn IV-B stage, would contain within it three 22' in diameter and 7' wide doughnut shaped experiment modules (or "cans") dedicated to a single discipline. Similarly configured modules would house each station's subsystems and living quarters for its nine-man crew (Figures 3 and 4). Both stations could orbit at altitudes of 260 nautical miles, since none of the initial experiments required geosynchronous or higher orbits. Each station could be deployed in the orbital inclination best suited to the disciplines being served by it. While Earth resources and meteorology would require high inclination—ideally polar orbits—the "heavy energy cost" for "initial launch and logistic flights" suggested a reduced inclination of 55 degrees, which would still allow major land masses to be covered. The second station, serving astronomy, could be space fixed and orbited at an inclination of 28.5 degrees which, approximating the latitude of the launch site at Cape Canaveral, would enable launch vehicles to take advantage of the Earth's natural orbit for orbital placement, and thus considerably reduce the energy requirements (and costs) of logistic flights. The dual station concept, with three modules in each, would thus enable each research discipline (astronomy, Earth resources, meteorology, biology, advanced technology R&D and long term flight biomedical and behavioral research) to have a dedicated module.

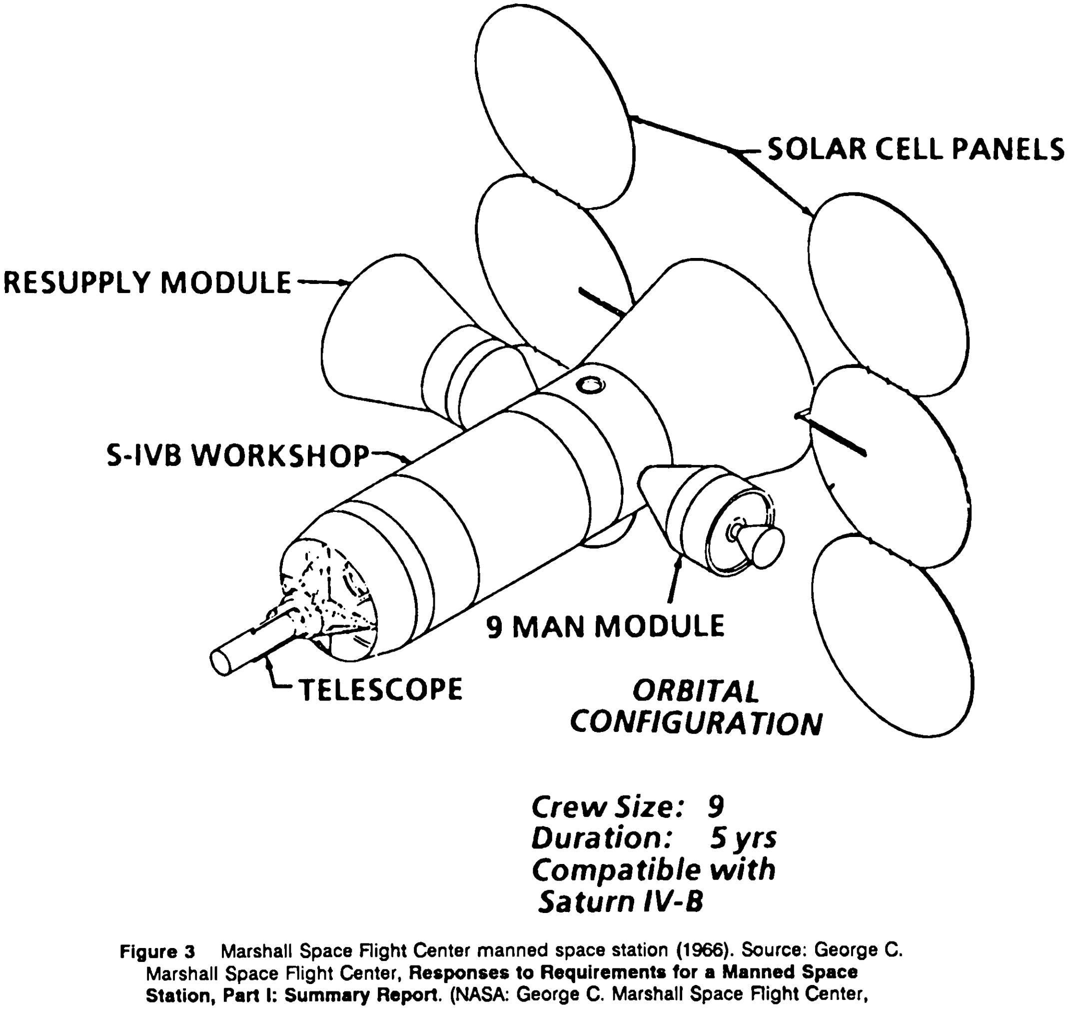
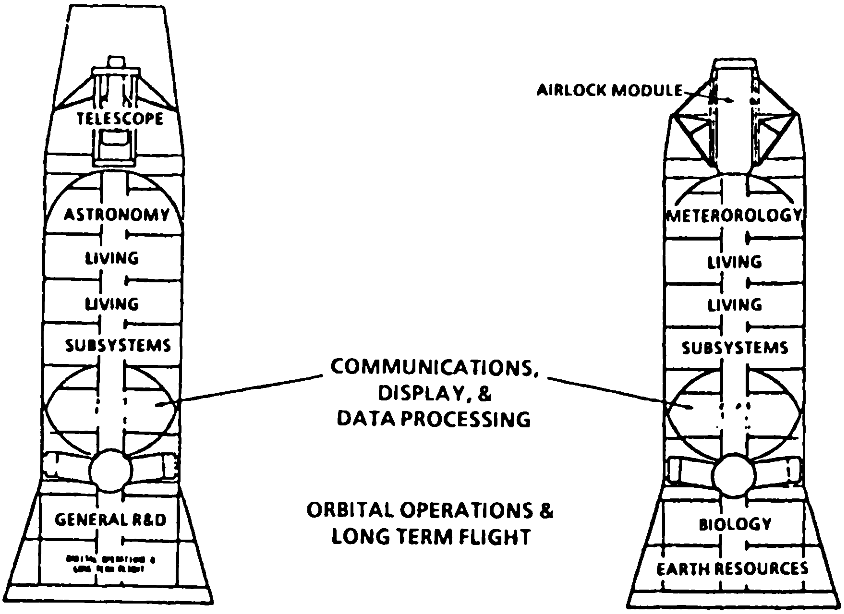


Figure 3 Marshall Space Flight Center manned space station (1966). Source: George C. Marshall Space Flight Center, **Responses to Requirements for a Manned Space Station, Part I: Summary Report**. (NASA: George C. Marshall Space Flight Center, November 4, 1966).



Crew Size: 9
Duration: 5 yrs
Orbit: Low Earth (260 NM)
Inclination: 28 1/2 degrees

Crew Size: 9
Duration: 5 yrs
Orbit: Low Earth (260 NM)
Inclination: 55 degrees

Figure 4 Marshall Space Flight Center dual manned space station concept (1966). Source: George C. Marshall Space Flight Center, **Responses to Requirements for a Manned Space Station, Part I: Summary Report.** (NASA: George C. Marshall Space Flight Center, November 4, 1966).

The need for artificial gravity was among the most problematic of all space station design considerations. The Marshall group found that most experiments required 10^{-5} gravity or less or were gravity independent, and that, therefore, neither station required rotation; those few experiments requiring artificial gravity could be accommodated with a centrifuge. NASA's Manned Spacecraft Center (MSC) in Houston, which worked on the technical systems "applicable to any space station configuration," was unwilling to proceed on the assumption that a manned, orbiting space station would not require artificial gravity for its manned elements [8]. Nonetheless NASA accepted the biomedical findings of the Skylab program as sufficient evidence that man could live and work without artificial gravity for limited periods (about 90 days), if not permanently, in space [9].

SPACE CONSTRUCTION BASE

In 1969, NASA management decided to phase out production of the Saturn V and to emphasize development of the Space Transportation System (STS, or "Shuttle"). Making use of remaining Saturn and Apollo hardware, the agency launched in 1973 Skylab, a manned "workshop," which remained in orbit for three years. By the spring of 1975, NASA once again began to take a serious look at space station design. Studies during the 1970s had emphasized use of the STS as the launch vehicle, modularity based on Shuttle-launched Research Applications Modules (RAM's) under study since 1972, and a much expanded view of the possible functions of a space station. Space Station, now beginning to be conceived as a multipurpose orbiting facility, would be used not only for science, but for commercial space manufacture and such space-based operations as assembly of large structures in orbit. In 1976 NASA awarded contracts to McDonnell Douglas Astronautics Co. and Grumman Aerospace Corporation to carry out parallel space station systems analysis studies. "'Space base,' rather than 'science requirements,' would 'drive configuration design'" [10].

The concept of a space base, in turn, was "driven" by the same cost-consciousness with NASA that led to the abandonment of the large Saturn booster and development of the Shuttle. The operational costs of individual space missions had been among the largest of the entire space program, and the space station concept advanced by McDonnell Douglas in its 1976-1977 study was calculated to achieve the most "cost-effective" approach to future space activities. A space station "facility" was needed "to provide the economies associated with long duration manned mission in Earth orbit." Such a facility should, moreover, be designed to grow from a modest Shuttle-tended construction base to a permanently manned structure based on the Shuttle-Spacelab program [11].

In carrying out its study, McDonnell Douglas was also guided by the 1975 "Outlook for Space" report prepared by an *ad hoc* group at the request of NASA Administrator James C. Fletcher. The "Outlook" report's strong emphasis on terrestrial applications and human benefits was translated into three principal areas of space activity, for which a space station system would provide unique and substantial support: *space construction* (satellite power system, nuclear energy, Earth services, and space cosmological R&D, such as the construction of a large microwave telescope), *space manufacture* (micro-processing), and *support* (cluster support system, depot, multidiscipline science laboratory, sensor development and living and working in space). Given the "energy crisis" of those years, development of a satellite power system—by which solar energy could be transmitted to Earth through microwave systems—seemed to hold out special promise.

The space station concept which McDonnell Douglas developed to satisfy these objectives was a modular concept which would provide power, space construction facilities, and habitability and sub-system support for the crew and operations; McDonnell Douglas named the concept a "space construction base." Furthermore, the concept was designed to be evolutionary, that is, an initial base could "grow" from a basic station and construction base intermittently manned and tended by the Shuttle (which would provide crew and operations support) and joined by a "strong back" truss beam to a permanently manned construction base using Spacelab and additional mission hardware. A key element in the permanently manned base would be the "construction shack," a module that would "replace the [Shuttle] Orbiter in providing habitability support for the crew for extended-duration activities," and to which Spacelab modules could be berthed as necessary (Figure 5). Power, logistics and fabrication and assembly modules fitted with mobile cranes, which could be added incrementally as needed, would complete the "evolutionary" station designed to support an initial crew of seven [12].

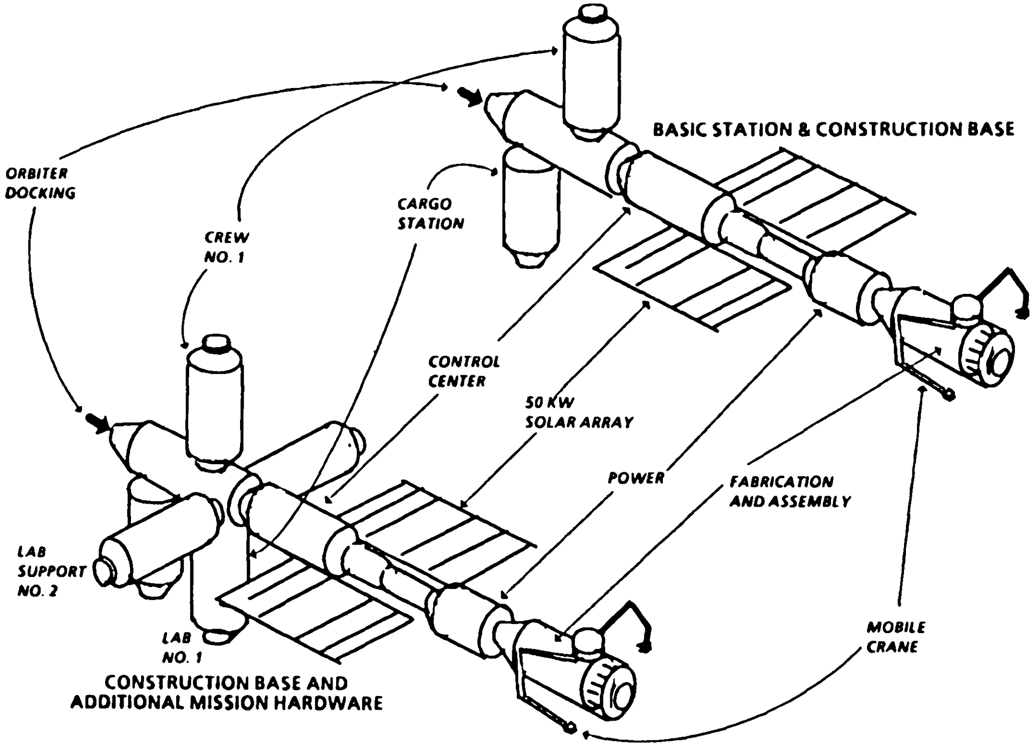


Figure 5 Initial construction base, McDonnell Douglas - 1976. Source: McDonnell Douglas, **Space Station Systems Analysis Study, Part I: Final Report Executive Summary**. September 1, 1976, p.29.

A "POWER TOWER" IN SPACE

Concepts developed by McDonnell Douglas and Grumman Aerospace (not detailed here) provided the foundation for the reference configuration which NASA used when the agency again approached industry for space station design proposals in 1984. Mission analyses studies contracted by NASA to eight aerospace firms in 1983 concurred in concluding that an evolutionary space station "architecture" comprised of a combination of manned and unmanned elements, tethered or free-flying in various orbits, and serviced by a station in low-Earth orbit, provided the best means of achieving a truly multi-purpose, long-term national capability at lowest cost. Such a concept would reduce the cost of continuous, routine space operations by allowing for on-orbit servicing and maintenance, thus reducing the need for ground-based maintenance of a growing inventory of "high value space assets." Moreover, a space station conceived as a multi-purpose architecture of discrete elements would not only enable transfer of payloads from low Earth to geosynchronous orbits by orbiting transfer vehicles, serviced by the station, but provide as well in-orbit utilities (e.g., power, data management, thermal control, course pointing, and communications) [13].

NASA's 1984 space station reference configuration, unofficially dubbed the "power tower," was one of a number of configurations explored during the past three years by NASA and the aerospace industry (Figure 6). The configuration got its name from the graceful 450-foot long skeletal truss structure—three times as long as the diameter of Langley's hexagon—designed to orbit the Earth with its main axis perpendicular to the Earth's surface, achieving stability through gravity gradiance. Attached to and serviced by the "power tower" would be a common set of modular elements, which could be arranged in various ways to meet different design requirements. Those elements include pressurized modules, articulated solar-inertial power generation devices, and assembly hardware connecting modules and power devices, and supporting externally mounted systems, payloads, and facilities." Also essential to its design is the space station's capability for on-orbit proximity operations such as remote maintenance, servicing, checkout and retrieval for orbiting unmanned platforms.

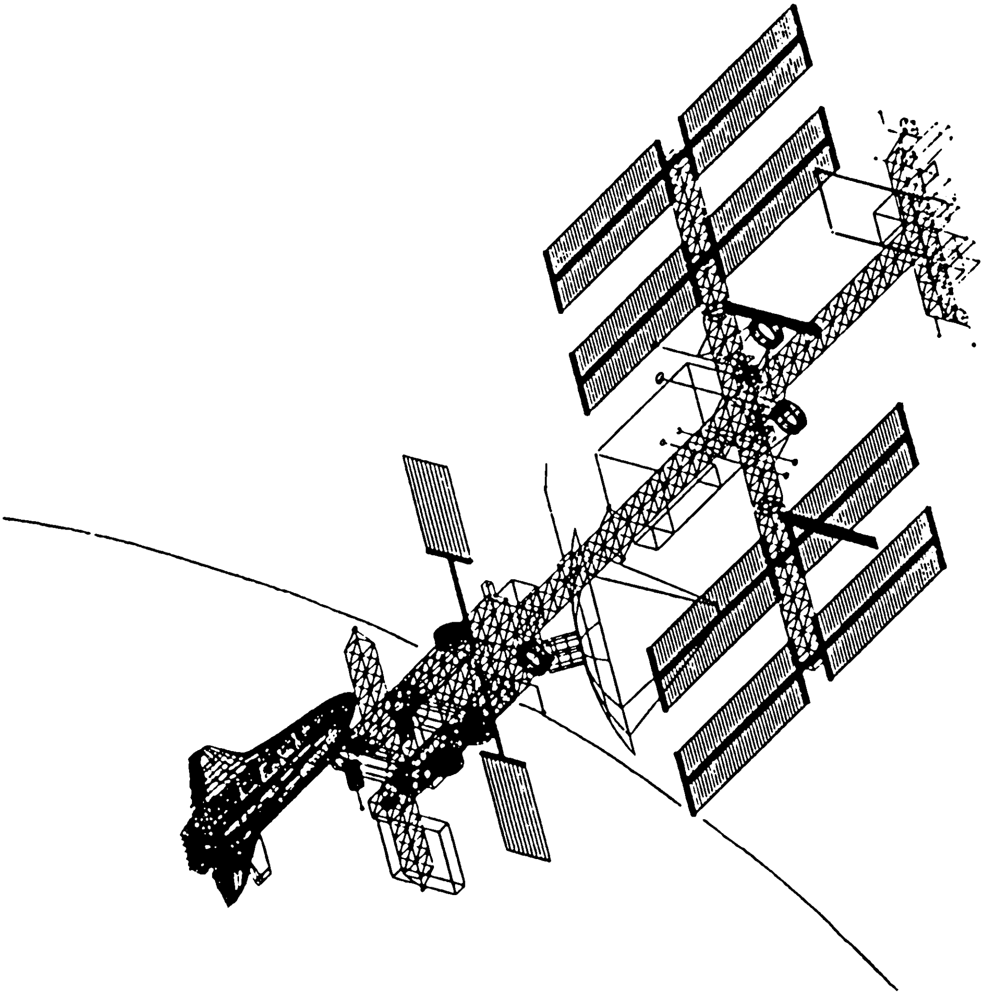


Figure 6 NASA Space Station "Power Tower" Reference Configuration (1984).

The design offered an elegant solution to a basic problem of accommodating both astronomy missions—with their sensitive pointing and stability requirements—and manned laboratory and orbital servicing operations, which entail considerable dynamic disturbance. Instruments for celestial observations would be mounted on the heavenward end of the "tower," while laboratory modules, service sheds and docking ports would be located at the "lower," or Earthward end. The total space station system architecture included co-orbiting and polar-orbiting unmanned platforms for Earth and celestial observations at inclinations of 28.5 degrees and 98.2 degrees [14].

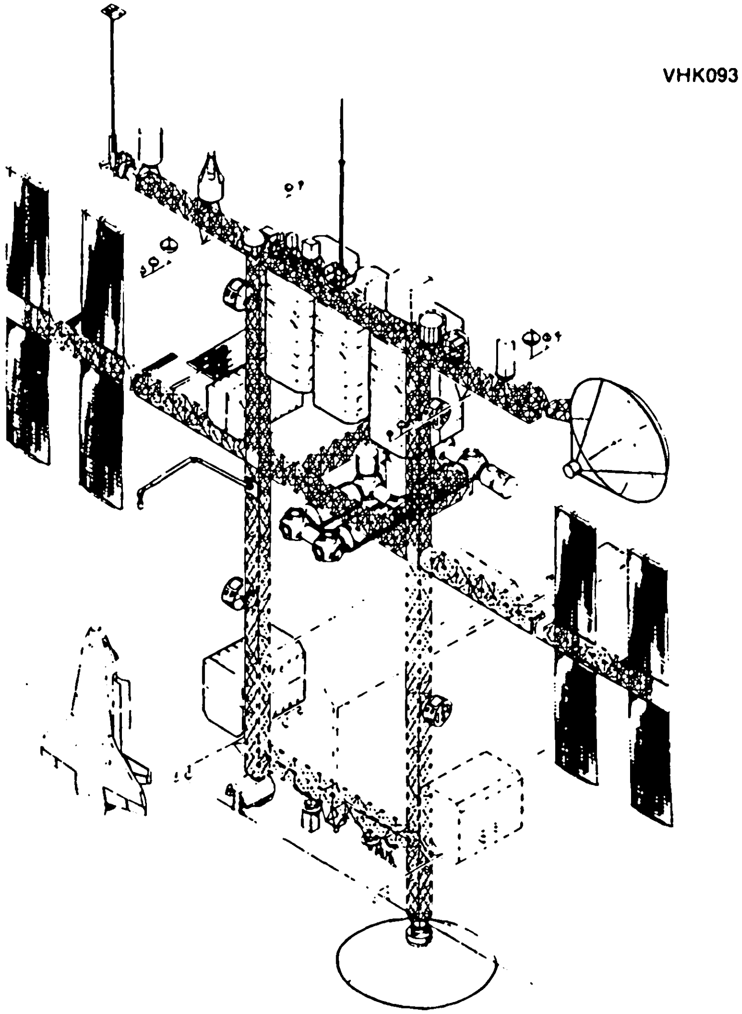


Figure 7 Dual keel space station.

In the fall of 1985 the NASA Space Station program office's "requirements update review" process resulted in a change in the space station's basic configuration from the "power tower" to the "dual keel," a double-truss version of the 1984 configuration foreshortened to a length of 297 feet. (The inclusion in the over-all space station concept of two unmanned orbiting platforms at 28.5 and 98.2 degrees remained unchanged.) The revised configuration offered advantages which would render the space station more useful to anticipated users of a micro-gravity laboratory environment, *viz.*, a larger area to which micro-gravity payloads could be attached, and the placement of micro-gravity payloads closer to the station's center of gravity to achieve a more perfect zero-gravity environment. Shifting the substantial mass of laboratory and living modules closer to the station's center of gravity would, however, have destabilized the power tower which was intended to maintain stability through gravity gradiance. Thus the original lengthy truss structure, with payloads for celestial observations placed at its heavenward end, was foreshortened to minimize natural instability. Even so, the "dual keel" space station will require a more powerful attitude control system to maintain a perpendicular orientation (Figure 7) [15].

SUMMARY

The evolution of space station forms, or configurations, developed by NASA and its contractors in the aerospace industry since the agency's beginning, exhibits a continual adaptation to changing functional requirements and changing technological capabilities. The transitions from the orbiting R&D laboratory designed by Langley Research Center and North American Aviation, to the space station for science of 1966, and from the "space construction base" of 1976 to the "dual keel" station of 1985, represent an expanding notion of the purposes of a space station. These purposes have extended from an orbiting technological research center to a scientific laboratory in space, to a space station that served not only those functions, but provided as well a multi-purpose space facility adaptable to a wide array of possible space operations and missions. Of the many technological developments which helped to determine the configurations of each particular space station, two are paramount. First, the realization (from the experience of the Skylab program) that for limited periods of about 90 days human crews would not require artificial gravity offered the possibility of "manning" a space station without rotation. Secondly, NASA's decision in 1968 to abandon the costly Saturn vehicle in favor of the reusable Space Transportation System provided not only a relatively cost-effective means of rotating crews and expendable supplies, but of using the Shuttle orbiter itself as an element of a space station which could be constructed incrementally on orbit from a modest initial "space base" to a multi-purpose space "architecture" providing an evolutionary, long-term national capability in space.

ACKNOWLEDGEMENTS

In addition to the authors of those reports and studies upon which this study draws, the author is indebted to Lee D. Saegesser, Nathaniel B. Cohen, Philip E. Culbertson, John D. Hodge, A. Michal McMahon and Russell I. Fries for assistance in preparing this essay. Any errors are the author's, while the views expressed therein are not necessarily the views of the National Aeronautics and Space Administration.

REFERENCE NOTES

1. John W. Massey, "Historical Resume of Manned Space Stations." Report No. DSP-TM-9-60. Army Ballistic Missile Agency, Redstone Arsenal, AL, June 15, 1960; Frank H. Winter, "Observations in Space, 1920s Style," *Griffith Observer*, June, 1982; Frederick I. Ordway, III, "The History, Evolution, and Benefits of The Space Station Concept," XIII International Congress of the History of Science, Moscow, August, 1971; Ron Miller, "Evolution of the Space Station," *Science 83* (October 1983); Wernher von Braun, "Crossing the last Frontier," *Collier's* (March 22, 1952).
2. Memorandum for the Associate Director, Langley Research Laboratory, from Beverly Z. Henry, Jr., October 5, 1950. Edward H. Kolcum, "NASA Explores Space Station Problems" *Aviation Week*, June 26, 1961, pp.89-93.
3. Langley Research Center, *Report on the Research and Technological Problems of Manned rotating Spacecraft*, NASA TN D-1504 (Washington, D.C., August, 1962), pp.1-5, 10-11.
4. *Ibid.*, pp.10-17.
5. "The Needs and Requirements for a Manned Space Station," Volume I: Summary Report, Prepared by the Space Station Requirements Steering Committee, NASA (Washington, DC., 1966).
6. *Ibid.*, pp.68-69.
7. Marshall Space Flight Center Space Station Working Group, "Responses to Requirements for a Manned Space Station and the Evolution of a One-Year Space Station," Part I: Summary Report, NASA (George C. Marshall Space Flight Center, November 4, 1966), Part I, sections 3.0-3.0.3.
8. "Preliminary Technical Data for Earth Orbiting Space Station," NASA (Manned Spacecraft Center, November 7, 1967), Vol. I: Summary Report, Section 4.1.1.9.
9. The Apollo Applications Program is detailed in W. David Compton and Charles D. Benson, *Living and Working in Space: A History of Skylab* NASA SP-4208 (Washington, DC, 1983). See especially pp.149-150, 339-342.
10. John H. Disher, NASA director of advanced programs, quoted in *Aerospace Daily*, September 13, 1976, p.54.
11. McDonnell Douglas, *Space Station Systems Analysis Study: Final Report*, Part 1, Vol. 1, Executive Summary (September 1, 1977).
12. McDonnell Douglas, *Space Station Analysis Study*, Part 2, Vol. 1: Executive Summary; Part 3, Vol. 1: Executive Summary (February 28, 1977).
13. *Space Station Needs, Attributes, and Architectural Options: Final Study Report*, Summary Briefing. McDonnell Douglas Astronautics Co., (April, 1983); *Space Station Needs, Attributes, and Architectural Options Study: Final Review/Executive Summary.* Martin Marietta Aerospace (April, 1983); *Study of Space Station Needs, Attributes & Architectural Options: Final Briefing.* General Dynamics, Convair Division (April, 1983); *Space Station Needs, Attributes, and Architectural Options: Final Study Report, Summary Briefing.* Lockheed Missiles & Space Co., Inc. (April, 1983); *Space Station Needs, Attributes, and Architectural Options.* Summary: Final Briefing. Grumman Aerospace Corporation (April, 1983); *Space Station Needs, Attributes and Architectural Options Study: Final Review, Executive Summary Briefing.* TRW Space & Technology Group (April, 1983); *Space Station Needs, Attributes and Architectural Options Study: Final Executive Summary Briefing.* Rockwell International Corporation (April, 1983); *Space Station Needs, Attributes, and Architectural Options Study. Final Report, Final Briefing.* Boeing Co. (April, 1983).

14. "Space Station Definition and Preliminary Design: Request for Proposals," National Aeronautics and Space Administration (Washington, D.C., September 15, 1984), Section C.

15. "Space Station Program Definition and Requirements," JSC 30000 (National Aeronautics and Space Administration, Washington, D.C., October 15, 1985), Section 3; Revised by Level B Space Station Control Board Directive No. BJ 020117, October 17, 1985.