Report of the Committee on the Space Station of the National Research Council (1987)

Pages
75

Size
8.5 x 10

ISBN
0309310938

Committee on Space Station; National Research Council

Report of the

Committee on the Space Station

of the

National Research Council

Order from
National Technical
Information Service,
Springfield, Va.
22161
Order No. PB88-126073

NATIONAL ACADEMY PRESS
Washington, D.C.
September 1987

NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Reveiw Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

The National Academy of Sciences is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Frank Press is President of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. Dr. Robert M. White is President of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Samuel O. Thier is President of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Frank Press and Dr. Robert M. White are chairman and vice chairman, respectively, of the National Research Council.

The Committee on Space Station was convened at the request of the President's Assistant for National Security Affairs, the Director of the Office of Management and Budget, the President's Science Advisor, and the Administrator of the National Aeronautics and Space Administration. The study was supported by a contract between NASA and the National Research Council.

Available from:
Committee on Space Station
National Research Council
2101 Constitution Avenue N.W.
Washington, D.C. 20418

Printed in the United States of America

NATIONAL RESEARCH COUNCIL

2101 Constitution Avenue Washington, D.C. 20418

MMITTEE ON SPACE STATION

September 10, 1987

The Honorable Frank C. Carlucci
The Honorable William R. Graham
The Honorable James C. Miller, III
Executive Office of the President
The White House
Washington, D.C. 20500

The Honorable James C. Fletcher
National Aeronautics and Space Administration
Washington, D.C. 20546

RE: Final Report of the National Research Council Committee on Space Station

Gentlemen:

The final report of the Committee on Space Station is enclosed. This report reflects the unanimous views of the Committee members. They have asked me to emphasize the subjects discussed in subsequent paragraphs of this letter.

The Space Station Program will be the most ambitious space project the nation has ever undertaken. It will require tens of billions of dollars over a period of several decades and will absorb much of the energy of NASA for most of that period. It will entwine for many years our space program with those of our international partners, and it will be a highly visible symbol of the American commitment to remain a leader among spacefaring nations.

Thus the Space Station Program must have enduring stable support across administrations, and this support must be generous enough to provide adequate hardware and testing, provisions to ensure that it can be operated safely for decades, and an adequate space transportation system for its deployment, assembly and operation.

The space transportation system has been a major concern of this Committee. The current Space Shuttle is barely adequate for the limited purpose of deploying the Space Station, and it is inadequate to meet broader national needs in space. The Committee recommends in the strongest terms that the Shuttle be upgraded with new improved solid rocket motors, that it be supplemented with expendable launch vehicles, and that a heavy lift launch vehicle be developed for use in the latter half of the 1990s.

The Honorable Frank C. Carlucci
The Honorable William R. Graham
The Honorable James C. Miller, III
The Honorable James C. Fletcher
September 10, 1987
Page Two

The Committee wishes to commend NASA for a number of constructive changes it has made in the Space Station Program during the short course of this study. The study has probably accelerated a process that was and is even now underway. However, it is important to understand that the continuing changes in many parts of the Program reduce the reliability of current cost estimates. The Committee believes that the net effects on costs of these dynamics will be upward. Thus the Committee strongly recommends that NASA prepare a new Space Station Program cost estimate in conjunction with the Program Requirements Review scheduled for early next year. This exercise should address the full range of uncertainties in the current Program, some of which are discussed in this report.

The Committee's findings and recommendations are more fully summarized in Section 2 of the final report.

We would like to thank NASA for its cooperation and support in the conduct of this study. Many demands were placed on NASA personnel, and the Committee appreciates their efforts.

Sincerely,

Robert C. Seamans
Chairman
Committee on the Space Station
National Research Council

ACKNOWLEDGMENTS

The Committee to advise the Executive Office of the President and NASA on the Space Station is an outstanding assembly of individuals drawn from the nation's leadership in space technology, defense, science, management, and cost analysis. Its Chairman, Dr. Robert Seamans, and Vice Chairman, Dr. John McLucas, have provided leadership and wisdom to guide the preparation of this report. All gave their time generously. Over the four-month period during which this report was prepared, the Committee met 20 times in 7 different locations.

In addition, the Committee's staff performed outstandingly. Mr. Archie L. Wood ably led the staff, provided substantive contributions to the analysis, and drafted the report. Dr. David Bodde, who heads the Commission on Engineering and Technical Systems, made time to shepherd the study through all phases from inception through this final report. Ms. JoAnn Clayton and Dr. Richard Obermann contributed to the Committee's analysis and organized its results in addition to arranging the many meetings. Ms. Catharine Little lent the Committee her energy and management talent. Ms. Susan McCutchen and Ms. Faith Pettit deserve special mention for long hours spent in supporting the Committee's meetings and for their skill in preparing the report. The support of the staff of the Aeronautics and Space Engineering Board was also important to the timely completion of the report.

Finally, the staff of the Office of Management and Budget, the National Security Council, the Office of Science and Technology Policy, and especially NASA provided support, encouragement, and information.

We greatly appreciate the efforts of the above persons and the many others who were involved in this undertaking.

Robert M. White
Vice Chairman
National Research Council

Frank Press
Chairman
National Research Council

COMMITTEE ON SPACE STATION

ROBERT C. SEAMANS, JR., Senior Lecturer, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge Massachusetts, Chairman

JOHN McLUCAS, Chairman of the Board, Questech, Inc., McLean, Virginia, Vice Chairman

W. BOWMAN CUTTER, III, Partner, Coopers & Lybrand, Washington, District of Columbia

EARL H. DOWELL, J.A. Jones Professor & Dean, School of Engineering, Duke University, Durham, North Carolina

ROBERT A. DUFFY, Brig. Gen. (USAF, Retired), President (Retired), The Charles Stark Draper Lab., Inc., Cambridge, Massachusetts

HERBERT FRIEDMAN, Emeritus Scientist, Naval Research Laboratory, Washington, District of Columbia

OWEN K. GARRIOTT, Effort, Inc., Houston, Texas (From May 28, 1987 to August 13, 1987)

BENJAMIN HUBERMAN, Vice President, Consultants International Group, Washington, District of Columbia

EBERHARDT RECHTIN, President and Chief Executive Officer, The Aerospace Corporation, Los Angeles, California

DONALD B. RICE, President, The RAND Corporation, Santa Monica, California

IVAN SELIN, Chairman of the Board, American Management Systems, Arlington, Virginia

THOMAS STAFFORD, Lt. Gen., (USAF, Retired), Defense Technologies, Oklahoma City, Oklahoma

LAURENCE R. YOUNG, Professor of Aeronautics and Astronautics and Director, Man-Vehicle Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts

Staff

ARCHIE L. WOOD, Study Director
DAVID L. BODDE, Executive Director, Commission on Engineering and Technical Systems
JOANN CLAYTON, Senior Staff Officer
ROBERT H. KORKEGI, Director, Committee on NASA Scientific and Technological Program Reviews
CATHARINE E. LITTLE, Associate Director, Commission on Engineering and Technical Systems
RICHARD M. OBERMANN, Consultant, The MITRE Corporation
SUSAN R. McCUTCHEN, Administrative Assistant
FAITH L. PETTIT, Staff Secretary

Technical Advisors

VICTOR ANSELMO, The RAND Corporation
EDWARD CRAWLEY, Massachusetts Institute of Technology

Consultants

DWIGHT ABBOTT, The Aerospace Corporation
THOMAS H. KREBS, Tom Krebs & Associates
ROD LOCHMANN, The Aerospace Corporation
AL KOPANIA, The Aerospace Corporation
ALBIN KAZANOWSKI, The Aerospace Corporation
RICHARD PEI, The RAND Corporation
WILLIAM SMITH, The Aerospace Corporation
JAMES STUCKER, The RAND Corporation
HOWARD WEINER, The Aerospace Corporation

CONTENTS

APPENDIXES

LIST OF TABLES

LIST OF FIGURES

PREFACE

In January of 1984, during his State of the Union address, the President of the United States directed the National Aeronautics and Space Administration to develop a Space Station within a decade. The Station was to be permanently manned, and international participation was invited. The NASA estimate for the Space Station for the Fiscal Year 1985 budget was $8.0 billion total costs in 1984 dollars.

Earlier, in May of 1982, NASA Administrator James M. Beggs established a Space Station Task Force that spent almost two years defining the preliminary requirements and developing conceptual architectures. The Concept Development Group of the Task Force produced a "planar" configuration that served as the starting point for the "power tower," the reference configuration used in subsequent Phase B studies by industry. (The Concept Development exercise consisted of a coordinated 12-month study by 12 contractors and all NASA centers.) Starting in 1983, NASA also conducted a number of Space Station user workshops and in April of 1984 the Task Force on the Scientific Uses of the Space Station was created to coordinate input from the U.S. scientific community. The user working groups and the Task Force on Scientific Uses influenced Phase B requirements in such areas as cabin pressure, module location, and truss structure.

Systems definition and preliminary design for the Space Station began formally in April of 1985 with eight industry contractors performing 21-month Phase B analyses. Preliminary cost estimates from contractors in 1985 ranged between $13 and $15 billion. These early studies cost approximately $600 million.

In the spring of 1986, the "power tower" reference configuration was modified into a dual keel configuration and formally adopted by NASA at its Systems Requirements Review. In the fall of 1986, NASA's Critical Evaluation Task Force reviewed the dual keel design and made significant changes, e.g., increasing the size of the nodes to accommodate avionics packages slated for attachment to the truss, thereby increasing pressurized volume available as well as decreasing the requirement for extravehicular activity.

1. INTRODUCTION

The Committee on Space Station was formed by the National Research Council, at the request of the Executive Office of the President and the National Aeronautics and Space Administration. The National Research Council was asked to take the President's 1984 decision to develop a space station as its point of departure. Within this context, the Committee was asked to:

- Assess NASA's cost estimates for the Space Station Program.
- Review the mission priorities and user requirements driving the Space Station configuration.
- Examine the configuration proposed by NASA in the context of appropriate mission priorities and user requirements.
- Identify and assess alternatives to this configuration.
- Review the arrangements projected for international participation and assess how these might be affected by alternative Space Station concepts.
- Report on any other matters that would contribute to the development of the Space Station.

The formal Statement of Task is at Appendix 1 to this report. This document called for two reports, one due on June 30, 1987, and the other on September 1, 1987. The June 30 report was submitted on that date. It is at Appendix 2. This is the final report.

The Committee was formed in late April 1987. A chronology of the Committee's major activities is at Appendix 3. A listing of participants is at Appendix 4. A bibliography is at Appendix 5.

The Committee focused on the broader strategic and policy aspects of the Space Station Program, and its findings and recommendations deal with these matters. It was not the Committee's purpose to conduct detailed reviews of many of the complex technical and engineering challenges presented by the Space Station Program.

The remainder of this report is divided into the following sections:

2. **Conclusions, Findings, and Recommendations**
3. **The Space Station Configuration and its Relation to Mission Priorities and User Requirements**
4. **Alternative Configurations**
5. **Space Science and the Space Station**
6. **Space Transportation and the Space Station Program**
7. **The Space Station Test Program and Backup Hardware**
8. **Space Station Cost Estimates**
9. **Management of the Space Station Program**

2. CONCLUSIONS, FINDINGS, AND RECOMMENDATIONS

This section summarizes the most important results of the Space Station study under two headings--"Conclusions" and "Findings and Recommendations." The Committee's conclusions cover broad areas of policy on which the Committee wishes to express itself; its findings and recommendations deal with more detailed issues which are discussed in the remainder of the report.

CONCLUSIONS

The Space Station Program presents a challenge to NASA of formidable proportions. Developing the Space Station, deploying and assembling it in space, and operating it as a multipurpose international research, development, and operational facility must surely rank as the most ambitious and lengthy task NASA has ever undertaken. These tasks will absorb much of NASA's energies for the next two to three decades.

It must be recognized, however, that the challenge is more than NASA's alone. NASA is the architect and program manager, but the commitment is national in character. In pursuing the Space Station Program, the United States is committing itself to a major national project that will of necessity require tens of billions of dollars and take a decade to bring to operational status. Moreover, the Space Station, a key part of our space infrastructure, will require a continuing commitment of support for its operation and evolution.

Space Station deployment and operation depends on its associated space transportation system; the current Shuttle's ability to support the deployment, assembly, and operation of the Station is marginal. Thus, an obligation to improve, maintain, and operate a reliable space transportation capability for the life of the Space Station is an inherent element of the national commitment required for the Space Station Program.

The Space Station cannot be considered a "one administration" program nor can it be developed "on the cheap." The Presidential decision to deploy a permanently manned international space station, if implemented by the nation, should be accompanied by adequate and predictable funding. The Administration and Congress must resolve to make a strong and durable commitment so that the success of the Program is not jeopardized by short-sighted yielding to budgetary and schedule pressures.

The durability of the nation's commitment to the Space Station will be enhanced if there is a clear understanding of what its long-term role is to be. Such an understanding is impossible without defining the long-range goals of the United States in space. The National Commission on Space and NASA have recently addressed these goals in Pioneering the Space Frontier and Leadership and America's Future in Space: A Report to the Administrator, respectively. The Administration should give high priority to this matter to assure that expensive interruptions do not occur in the Space Station Program because national goals to direct its evolution have not been defined.

Beyond its commitment of national treasure, the United States is staking much of its standing as a leader among spacefaring nations on the success of the Space Station Program. The Space Station will be a symbol of the competition in space between the United States and the Soviet Union. Moreover, our international partners--Canada, Japan, and the nations of the European Space Agency--are relying on the Space Station as the foundation for their manned space flight programs. Thus, the United States is undertaking an obligation to them that should entail predictability of support of the Space Station Program, the effective integration of the partners into the development and operation of the Space Station, and the tending of the special international relationships which are an intrinsic part of these long-term commitments.

It would be misleading, though, to think of the Space Station only in terms of its costs and challenges. If the nation develops the Space Station, it would be a visible demonstration of American technological and operational prowess in space. It would establish the permanent presence there of American astronauts and those of our international partners, and it would permit major steps forward in our understanding of man's ability to function effectively in space for extended periods. The Space Station would be a unique laboratory for materials research in microgravity, as well as a test bed for the development of systems for long-duration manned missions in space. In due time, it could become the base for assembly of the next generation of large scientific instruments to observe the universe. It could also become a way station for manned lunar and planetary missions. Indeed, if the United States intends to pursue an aggressive manned space program, a space station is essential to the research, systems development, and accumulation of operational experience necessary for such an undertaking.

FINDINGS AND RECOMMENDATIONS

The Space Station Configuration and Its Relation to Mission Priorities and User Requirements

Findings

- The early scientific and engineering uses of the Space Station are reasonably well understood. No specific defense or commercial applications have been identified.

- The Block I configuration is a satisfactory starting point for the Space Station. It reflects thoughtful compromises among the priorities and the sometimes conflicting requirements of its early scientific and engineering users.

- In the absence of agreed-upon long-term space objectives, commitment to a particular configuration for Block II at this time would be premature. Indeed, the next phase of the Space Station could go in any of several directions.

- There is no intrinsic operational and little scientific relationship between the polar platform (now included as part of the Block I Space Station Program) and the Space Station. Prospective users of the co-orbiting platforms (part of the Block II Space Station Program) are likely to gain few benefits from man tending.

Recommendations

- The Administration should clarify its long-term goals in space before committing the Space Station to a specific evolutionary path beyond Block I.

- Development of those technologies likely to be needed for any evolutionary path, such as solar dynamic power, should be supported.

- The polar and co-orbiting platforms should be evaluated on their own merits, whether or not carried as part of the Space Station Program.

Alternative Configurations

Findings

- None of the alternative configurations for the Space Station examined by the Committee was judged to be as satisfactory as the current Block I configuration.

- Man-tended facilities are not substitutes for a permanently manned station, although they may play a complementary role.

Recommendation

- Block I should be adopted as the initial Space Station configuration.

Space Science and the Space Station(1)

Findings

- Platforms, other than the Space Station, will be needed by space sciences, even after the Station is deployed.

- Devastating blows have already been dealt U.S. space science by the postponement of missions after the Challenger disaster, which followed a decade with very few major space science missions.

- Demands for Shuttle launch services will continue to exceed the Shuttle's capacity. This condition will impact scientific access to space.

Recommendations

- Space science should not be confined to the Space Station. Science requirements should dictate the means of access to space. Space sciences should continue to be supported with dedicated spacecraft and expendable launch vehicles after the Station is deployed.

- Appropriate NASA offices should assure that timely and sufficient investments for Space Station experiments are made.

- In the short to medium term, every effort should be made to increase access to space for scientific purposes. To this end, the on-orbit duration capability of the Shuttle should be increased and expendable launch vehicles should be used for those missions that do not require astronaut involvement.

---

(1) Astronomy, astrophysics, solar system exploration, plasma research, earth observation sciences, and microgravity research in both materials and life sciences are all considered to be part of space science.

Space Transportation and the Space Station

Finding

- The Space Station Program is critically dependent on adequate space transportation for its assembly and operation. Deploying the Space Station with the post-Challenger Shuttle, while not infeasible, will be difficult and risky.

Recommendations

- It is highly desirable that the post-Challenger Shuttle be improved in performance, while maintaining or increasing its reliability level.

  -- Advanced solid rocket motors with improved performance and reliability should be developed for the Shuttle.

  -- NASA should assure high operational reliability and availability for the Shuttle, and should establish operational specifications for Orbiter replacement, spares, accommodation of downtimes, and recovery strategy.

  -- Provision should be made to produce a Shuttle Orbiter, after the Challenger replacement, for delivery before Space Station deployment begins.

  -- Extended duration on-orbit capabilities should be provided on one or more of the Orbiters.

- The nation should develop a heavy lift launch vehicle for use in the latter half of the 1990s to permit the launching of payloads larger than those of the Shuttle and to enhance the robustness of the space transportation system.

- NASA should make plans for eventual logistical support of the Space Station with expendable launch vehicles, as well as with the Shuttle.

- NASA should establish a mandatory requirement for a crew emergency rescue vehicle and should consider its use, on a man-rated expendable launch vehicle, as a backup means of manned access to the Space Station.

Space Station Test Program and Backup Hardware

Finding

- The Committee believes that the Space Station test program and backup hardware policy were inadequately defined at the beginning of its study. It believes that NASA has since made progress in both areas, but NASA must continue development of a test program and backup hardware policy, if it is to improve the resilience of the Program.

Recommendations

- Because of the complex and potentially unanticipated interactions among the Space Station systems, a prototype, as opposed to a protoflight, test program should be employed to the maximum extent practicable.[(1)]

- A centralized Space Station test bed duplicating, to the extent practical, the configuration of the Space Station on orbit should be retained on the ground.

- Each launch package should undergo pre-launch integration, using the Space Station test bed.

- Backup hardware to replace flight equipment that might be lost during the deployment phase should be procured. NASA needs to develop an understanding of contingency scenarios in order to determine the backup hardware required.

Space Station Cost Estimates

Finding

- Analyses by the Committee during the second phase of this study have, on balance, decreased its confidence in NASA's cost estimates, as presented in the Committee's June 30 report. For example, up to $3.9 billion in research and development funds over those noted in its earlier report--almost a 30 percent increase--could be needed to enhance the test program and to buy backup hardware. Additional growth could arise from difficulties not now identified.

---

(1) A prototype program involves the production of two substantially complete sets of hardware--one for ground testing and one for flight. A protoflight program would have only one set used for both purposes.

- The level of definition of the Station operational concept does not permit the estimation of steady state operating costs with much confidence.

Recommendations

- NASA should make a new Space Station Program cost estimate in early 1988. During this exercise, uncertainties such as those in costs of the test program and for backup hardware should be addressed.

- Increased attention should be focused on estimating and controlling Space Station operating costs, so that these costs do not absorb a significant portion of the civilian space budget.

Management of the Space Station Program

Findings

- The management challenge presented by the Space Station Program is at least as critical to the Program's success as its technical challenges.

- NASA has moved to strengthen Space Station Program management, but additional steps are required.

- The Committee is not satisfied that the current arrangements to coordinate the Space Transportation and Space Station Programs are adequate.

- The Committee believes more attention must be paid to managing the operational characteristics of the Space Station.

Recommendations

- NASA management must emphasize that the Space Station Program Director is the principal line manager of the Space Station Program and is accountable for the successful development of the Space Station.

- The Committee recommends that NASA establish a dedicated Space Station project organization that would subordinate all NASA personnel assigned to the Space Station to the Program Director and give the Program Director control of financial and other resources assigned to the Program.

- An improved liaison structure between the Space Transportation and Space Station Programs should be developed as part of the management study called for below.

- An organizational entity, independent of the Space Station development hierarchy, with the ultimate responsibility for operating the Space Station, should be formed promptly to assure greater attention to operations during the design phase.

- NASA should simplify the structure now envisioned for relations between the Station operators and the users of the Space Station.

- A realistic Space Station development budget should be determined and funds provided in a series of multiyear appropriations, thereby giving long-term financial predictability to the Program.

- The Committee recommends that NASA, under the general supervision of the Office of Management and Budget, conduct a study analyzing the Committee's program management recommendations and concerns. A management plan, expressing how NASA intends to respond to the Committee's management concerns, should be developed as part of this study. An assessment of NASA's progress against this plan should be carried out at an appropriate time.

3. THE SPACE STATION CONFIGURATION AND ITS RELATION TO MISSION PRIORITIES AND USER REQUIREMENTS

The Space Station has been divided into two blocks. The first to be deployed, Block I, will consist essentially of a large beam at the center of which will be mounted the U.S. laboratory and habitation modules, the Japanese Experiment Module, and the European Space Agency laboratory module. Eight solar photovoltaic arrays will be mounted on extensions at the ends of the beam, four on each extension, to provide 75 kilowatts of power. Block I would also include a U.S. polar orbiting platform.

Block II would add more power, upper and lower booms, and a servicing facility for satellites and other spacecraft. The booms would be attached to the central beam by two "keels." The Block II booms are intended primarily for attaching payloads that look out into space from the upper boom and down toward the Earth from the lower. Block II would also add a U.S. co-orbiting platform.[1]

Both configurations--the "Revised Baseline" (Block I) and the "Enhanced Configuration" (Block I plus Block II)--include provisions for Shuttle docking and attachment of logistics modules. They also include subsystems such as the environmental control and life support subsystem, the data management subsystem, and other provisions necessary for a viable, productive Space Station. Figure 1 is an artist's rendition of the "Revised Baseline" and the "Enhanced Configuration."

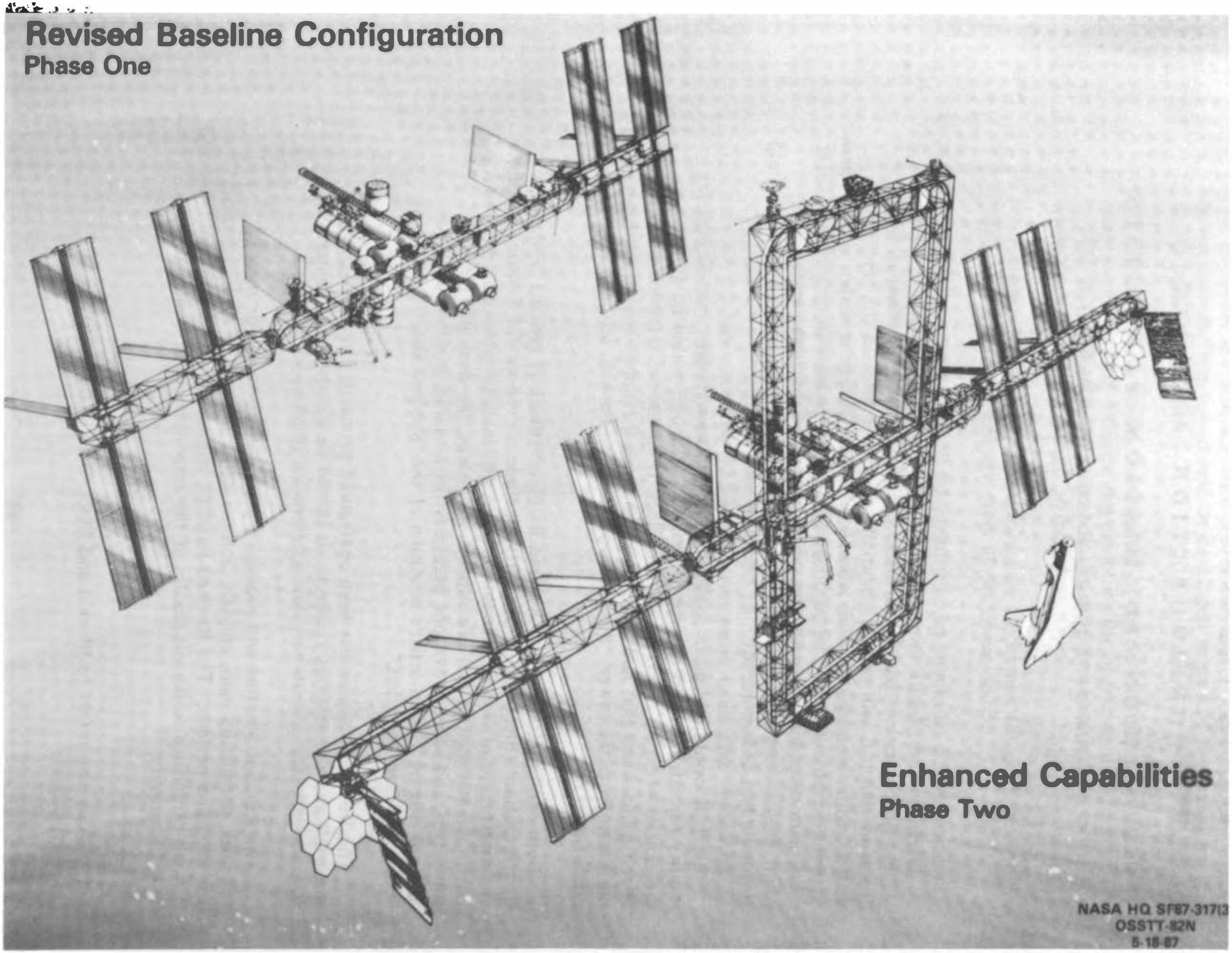
The Revised Baseline has been configured primarily for microgravity materials and life sciences research. It should be a satisfactory materials sciences laboratory, with very low acceleration (microgravity) levels.

The Revised Baseline will provide a giant step forward for the life sciences, permitting man, animals, and plants to be exposed to microgravity for extended periods. The Revised Baseline will accommodate small animals and a small centrifuge to permit studies of the responses of these animals to variable gravity.

---

(1) NASA also refers to Block I and Block II as Phase 1 and Phase 2, respectively.

FIGURE 1 Revised Baseline and Enhanced Configuration



Photograph courtesy of NASA

However, the Revised Baseline does not provide all that the life scientists may ultimately need. For example, it would be difficult to accommodate large animals and to install a large variable force centrifuge in this configuration. Moreover in the Revised Baseline, life and materials sciences must be conducted in the same laboratories. Adequate isolation can be achieved in the Revised Baseline by engineering and operational measures, but eventually, if the United States decides to undertake long duration manned interplanetary missions, a dedicated life sciences module may be a necessary addition to the Space Station.

The Revised Baseline will provide a good test bed for the development of technologies for extended manned space flight in such areas as environmental control and life support, power, and thermal control.

Because commercial applications of the Space Station have not yet been defined, it is impractical to plan specific accommodations for such applications. However, there is no obvious reason that the Revised Baseline could not be used for a number of conceivable commercial applications.

The Department of Defense has not enunciated specific purposes for which it might want to use the Space Station. Thus, the design of the Space Station has not been influenced by Department of Defense requirements.

The Revised Baseline has only limited capabilities to accommodate attached payloads for earth- and space-directed observations. It has no capability for satellite servicing, construction of large space structures, or for staging manned missions to the moon or to the planets.

The Enhanced Configuration with its servicing facility, the booms for additional attached payloads, and more electrical power would be a more capable Space Station. The servicing facility could be used to assemble some large space structures--perhaps one or more of the next generation of large observatories envisioned for about the year 2000, for example--but the Enhanced Configuration would have to be substantially modified to serve as a transportation node for development of a lunar base or for manned journeys to Mars. The Enhanced Configuration would not remove the constraints on life sciences research inherent in the Revised Baseline.

In conclusion, it is the Committee's judgment that on balance the mission priorities reflected in the Revised Baseline design are reasonable. It is a good compromise among the needs of early users of the Space Station, and it accommodates the framework established for the Space Station by national policy. The Revised Baseline would be a useful productive facility even with the limitations noted and even if further evolution does not occur.

It is not clear that Block II reflects the right priorities for Space Station evolution. The Space Station will be in the wrong orbit to serve as a good Earth observation platform. The most important astronomy and solar system exploration experiments can best be deployed on free flying spacecraft. Thus, the upper and lower booms may not add much to the Station as a platform for science. A strong case has not been made for a satellite servicing requirement. Moreover, other directions of evolution might prove to be more important. For example, if the United States decides to pursue manned planetary explorations in the next century, the addition of a dedicated life sciences module to accommodate a large centrifuge and adequate facilities for animals might be the preferred next step. The adoption of other objectives could lead in quite different directions. Thus, the Committee believes that a commitment to Block II at this time would be premature.

It is important for NASA to continue to study the effects on the Revised Baseline of alternative evolutionary paths. Such studies will suggest what detailed provisions for evolution should be designed into this configuration. It seems highly probable that any evolution beyond Block I will require more power; thus, continued development of solar dynamic power technology, an important element of Block II, is strongly supported by the Committee.

The polar orbiting platform, part of Block I, would be launched from the Western Test Range on an expendable launch vehicle. It would carry instruments primarily supporting the Earth observational sciences. The co-orbiting platform, part of Block II, would be deployed in an orbit close to that of the Space Station. It would carry instruments primarily for space observations.

The Committee finds no intrinsic operational or strong scientific relationship between the Space Station, on the one hand, and the polar orbiting platform, on the other. Moreover, many of the potential users of the co-orbiting platform stand to gain little by man tending. Orbital requirements for astronomy are largely incompatible with the Space Station orbit. Users of the co-orbiting platform would be better served by individual free flyers. Thus, the polar and co-orbiting platforms should be evaluated on their own merits whether or not they are managed as part of the Space Station Program.

Finally, it is important to understand that the Space Station will not be a space system in the usual sense. Instead it will be a research facility in space, and potentially an operational base, that will change and adapt to serve a host of applications that cannot now be foreseen. These characteristics imply, among other things, that national space goals should be defined prior to the development of each later block of the Space Station if expensive interruptions are to be avoided in the Space Station Program.

In summary, the Committee believes that the Revised Baseline--the Block I configuration--is a satisfactory starting point for the Space Station, given the present ambiguity in national space goals. However, it wishes to emphasize that Block I is only a starting point; if the United States is going to remain a leader among spacefaring nations, the Station must evolve to support this role. Lack of consensus on our long-term objectives in space limits the extent to which this evolution can now be foreseen; thus it is too early to commit to Block II. Those technologies likely to be needed in any evolutionary path, such as solar dynamic power, should be supported.

4. ALTERNATIVE CONFIGURATIONS

The Committee examined a number of alternative configurations for the Space Station, including those from which NASA derived the current configuration. The Committee also reviewed proposals by scientists and engineers outside NASA, and examined concepts for man-tended facilities currently under development.

In its study of Space Station configurations, NASA examined a wide range of alternatives for the Space Station--a range that virtually exhausted all fundamentally different possibilities. Alternatives to the current configuration were eventually rejected for such reasons as:

- higher acceleration (microgravity) levels than Block I;
- less desirable orientation relative to the Earth and space;
- more limited access for construction and support; and
- lesser growth potential.

The Committee in its review found no strong reasons to disagree with NASA's analysis of these alternatives.

Proposals from outside NASA have not, in general, been proposals for reasonably complete alternative Space Station configurations. Some deal only, or primarily, with construction systems; others with the size or arrangement of pressurized modules. NASA's current approach embodies some of the basic ideas from the construction system alternatives, and NASA considered many alternative arrangements of modules in its study of alternative configurations. The Committee did not find attractive alternatives to the Block I configuration in proposals from outside NASA.

Finally, man-tended facilities were examined. Such facilities may have important roles to play in Space Station related development and in materials and life sciences research before and possibly after the Space Station is deployed. The Committee encourages NASA to exploit such facilities as appropriate.

However, man-tended facilities do not allow the frequent manned interaction that will be required by a significant number of important experiments. Nor do they provide the long-term exposure of humans to microgravity needed by life scientists. Clearly, man-tended facilities are not substitutes for a permanently manned facility.

In summary, none of the alternative configurations was judged to be as satisfactory as the current configuration.

5. SPACE SCIENCE AND THE SPACE STATION

In the third section of this report, the strengths and weaknesses of the Block I Space Station were discussed. In summary, Block I will provide a good platform for microgravity work in materials and life sciences. However, it is in the wrong orbit for most Earth observations, and many scientific missions in solar system exploration and astronomy cannot be effectively performed in conjunction with the Space Station.

These characteristics of the Space Station clearly imply that other platforms will be needed by the space sciences even after the Space Station is operational. Moreover, expendable launch vehicles will be best suited to launch many of these spacecraft because the Shuttle cannot attain (or can attain only with difficulty) the desired trajectories. Thus, it is important that space sciences not be confined, made hostage if you will, to the Space Station and the Shuttle.

Devastating blows have already been dealt American space science by the postponement of missions after the Challenger disaster, which followed a decade with very few major space science missions. Not only has the launch of many science payloads been delayed, but the lower flight rates now expected from the Shuttle and the existing backlog of non-science payloads will drastically reduce future scientific access to space. Furthermore, the Shuttle will be needed for technology experiments to support Space Station development. These payloads, and demands in life and materials sciences, will keep pressure on the Shuttle for the next several years.

The Committee thus believes that in the short and medium term, every effort should be made to increase access to space for astronomy, solar system exploration, plasma research, and earth observation sciences, to work off the backlogs created by exclusive reliance on and problems with the Shuttle. Given expected Shuttle flight rates and other demands on the Shuttle, expendable launch vehicles will be essential for this purpose.

The productivity of the Shuttle should also be increased. One of the few ways to do this is to increase its capability to remain on orbit for a longer time. The Committee thus believes this is a cost effective way in the near term to enhance access to space for a number of important users. Extended on-orbit duration will also provide greater robustness in the Space Station assembly process. The Committee thus recommends that appropriate modifications be made to one or more of the Orbiters to increase their stay time on orbit from the current level of about one week to about two weeks. This step would make this capability available for those missions on which it is needed.

Finally, Space Station budgets do not and should not include funds for development of the scientific experiments needed to make the Station a productive research facility. However, NASA should assure that timely and sufficient investments for experiments are made in order to exploit the special capabilities the Space Station will offer.

6. SPACE TRANSPORTATION AND THE SPACE STATION PROGRAM

SPACE TRANSPORTATION FOR DEPLOYING THE SPACE STATION

From the inception of the Space Station Program, the Shuttle has been the sole means of space transportation contemplated for Station deployment and support. This has resulted in a Space Station design constrained by the Shuttle cargo bay dimensions and the Shuttle's weight-lifting capacity. These constraints have increased the difficulty of satisfying user requirements in a number of ways. For example, module size limitations have led to intense competition among the users for pressurized volume in the modules. In addition, sharing of modules by life and materials sciences, for example, has exacerbated the problem of assuring adequate isolation of experiments from each other. Moreover, dimensional constraints have limited the size of scientific apparatus (for example, centrifuges for the life sciences) available to the users. These Shuttle-associated constraints are likely to be even more confining when the Space Station begins to evolve in the latter half of the 1990s to support more ambitious manned space endeavors.

The deployment process and the operational concept also have been influenced by the lack of other means of space transportation. For example, use of the Shuttle will require substantial levels of extravehicular activity and on-orbit outfitting of the laboratory and habitation modules. The constraints imposed by the Shuttle have become more restrictive as Shuttle capabilities have been reduced, first by shortfalls from original specifications and later by the modifications required after the Challenger accident.

The Committee believes that deployment of the Space Station with the post-Challenger Shuttle--the Shuttle that will be available after the current round of modifications are complete--while not infeasible, will be difficult and risky. For example, NASA has estimated that the orbital life of the first two elements of the Space Station, in the event of failure of the Station reboost system, would be only about 20 days. This means that if the reboost system fails, the Station orbit would decay within about 20 days and the deployed elements of the Station would be lost. This vulnerability is not acceptable and must be corrected.(1) To deploy Block I with the

---

(1) One way to reduce the vulnerability of the Station to orbital decay would be to reduce the payload weights of the first two Space Station launches

post-Challenger Shuttle would require about 18 flights, and as indicated earlier, it would require a large amount of extravehicular activity and on-orbit outfitting of the U.S. modules. Thus, the Committee believes that improved space transportation is needed for a sound Space Station Program. Two means are currently available--improving the Shuttle and developing a heavy lift launch vehicle.

The Shuttle would be improved primarily by providing new solid rocket motors with increased performance and reliability. The development of these motors is estimated by NASA to cost about $0.8 to $1.6 billion in 1988 dollars.

Two approaches to acquiring a heavy lift launch vehicle were examined by the Committee. One approach would use a new cargo canister and existing Shuttle components--solid rocket boosters, two or three used main engines, their supporting structure and plumbing, and the Shuttle external tank. The main engines of this Shuttle-derived vehicle would not be recovered after launch.

The other approach would be to use a vehicle, independent of the Shuttle, from the joint NASA-Department of Defense Advanced Launch System Program. The objective of this program is to develop, by about 1998, a heavy lift vehicle with greatly reduced recurring costs. For this effort to be able to support the Block I Space Station Program on anything similar to the current schedule, an interim advanced launch vehicle would be needed.

---

carried out by the post-Challenger Shuttle, thus permitting the Shuttle to place these payloads in higher orbits. However, probable weight growth in Space Station components would exacerbate the problem, and NASA indicated in its presentations to the Committee that these two payloads could not be significantly reduced.

Subsequent to the Committee's completion of its work, NASA indicated that it was exploring ways to reduce the weights of these payloads. Preliminary studies suggest that reductions might be possible that would permit the post-Challenger Shuttle to place the first two payloads in orbits high enough to eliminate their vulnerability to early orbital decay.

However, relatively low orbital decay times in the event of reboost failure (on the order of 50 days) persist throughout most of the assembly sequence. This condition illustrates the relatively narrow margins that exist during the deployment of the Space Station with the post-Challenger Shuttle.

The costs of achieving the reductions in the first two payloads would include one more Shuttle flight to carry up the equipment removed from the first two flights, about 10-15 more hours of extravehicular activity, and some redundant guidance, navigation, and control equipment. Even if such reductions eventually prove to be practical, the Committee believes that its recommendations on improving the Shuttle and developing a heavy lift launch vehicle (presented in subsequent paragraphs) are still valid.

The NASA estimates in Table 1, on the next page, compare the alternatives in a number of dimensions, assuming operations according to plan and no launch failures.

These estimates show that an Improved Shuttle would result in the following improvements over the post-Challenger Shuttle alternative:

- Orbital life of the first Space Station element deployed, with reboost failure, would be increased from about 20 days to about 240 days, enough time to get a Shuttle to the Station before the Station's orbit would decay.[(1)]

- A 40-hour reduction in extravehicular activity required to deploy Block I.

- Less on-orbit outfitting of the laboratory and habitation modules.

- A reduction in the number of flights required to deploy Block I of about four.

An improved Shuttle would also increase the probability of deploying the Space Station without a Shuttle standdown--partly because of the fewer number of flights required and partly because an Improved Shuttle should be more reliable.

The greater Shuttle payload capability, which would be available on every Improved Shuttle flight, would support heavy payload missions other than deployment and operation of the Space Station. This capability would also increase the overall productivity of the Shuttle by 25 to 30 percent for those missions that would otherwise be limited by Shuttle payload weight capability.

Table 1 also shows how a heavy lift launch vehicle would affect the measures discussed above if it were available on the Block I schedule. On most measures, it gives greater improvement than the Improved Shuttle. Moreover, if a heavy lift launch vehicle were available for launch of the first elements of the Space Station, full operational capability of the Station could be achieved 12 to 18 months earlier.

However, heavy lift launch vehicles would require remote docking capabilities earlier than would otherwise be required, and remote docking would complicate on-orbit Space Station assembly operations. Remote docking would also require orbital maneuvering vehicles or automatic docking systems to assist in maneuvering the large payloads brought up on the heavy lift vehicles.

---

(1) The orbital decay times throughout the assembly sequence are, in the main, markedly better with the Improved Shuttle than with the post-Challenger Shuttle.

TABLE 1

Estimated Effects of Alternative Space Transportation Systems on Block I Space Station Deployment (NASA Estimates)

	Space Transportation Alternatives			
	Post-Challenger Shuttle	Improved Shuttle	Post-Challenger Shuttle and Heavy Lift Vehicle	Improved Shuttle and Heavy Lift Vehicle
Orbital Life of the First Two Payloads (days)				
with No Resupply (1)	>360	>15,000	>15,000	>15,000
and with Reboost Failure (2)	22	240	>240	>240
Extravehicular Activity Required (man hours)	156	116	98	100
On-Orbit Outfitting				
Laboratory Module	47%	33%	0%	0%
Habitation Module	18%	0%	0%	0%
Total Number of Flights to Full Operation Capability	18	14	12	11
Shuttle Flights	18	14	7	7
Heavy Lift Flights	0	0	5	4
Remote Docking Required	No	No	Yes	Yes
Flight on which Permanently Manned Capability Achieved	9	7	8	7

---

(1) The numbers on this line are measures of the time available to replenish the reboost systems.

(2) The numbers on this line are the orbital decay times if the reboost system fails and is not repaired.

NASA estimates that a Shuttle-derived heavy lift launch vehicle and its associated support facilities could be developed for about $1.1 to $1.7 billion (in 1988 dollars), and it could place payloads on orbit with recurring costs per pound roughly comparable to those of the Shuttle. However, it is presently unclear what additional uses such a vehicle would have after the four or five flights needed for deployment of the Block I Space Station because it is likely to face competition from a more economical vehicle from the Advanced Launch System Program.

On the other hand, the Committee does not believe that an interim vehicle can be depended on from the Advanced Launch System Program on schedules roughly consistent with Block I Space Station deployment.

The Committee concluded from this analysis that the Improved Shuttle is the preferred way to enhance the space transportation system at this time, and that the United States should move promptly to acquire capabilities to launch larger payloads than even the Improved Shuttle can accommodate.

Thus, the Committee strongly supports NASA's plans to develop an advanced solid rocket motor and other appropriate components that would enhance both the performance and reliability of the post-Challenger Shuttle.

The Committee wishes to emphasize, however, that the gains discussed above will be achieved in the Space Station Program only if the weights of Space Station components are strictly controlled and if the performance improvements estimated for the Improved Shuttle are largely realized. Significant degradations in either of these two estimates or in Shuttle reliability would swiftly erode the most important gains for the Space Station Program.

The Committee also recommends that the nation start now to escape the constraining effects of the Shuttle on future space programs by developing a heavy lift launch vehicle for use by the latter half of the 1990s. Such a vehicle would remove the dimensional and weight constraints imposed by the Shuttle, thus increasing the options available for evolution of the Space Station, and it would provide a hedge, albeit late, against diminished performance of the Improved Shuttle and weight growth in the Space Station.

A heavy lift launch vehicle would provide other benefits, namely:

- an option to pursue more aggressive lunar and planetary exploration programs, such as the Mars sample return missions;

- the ability to launch payloads that would otherwise be manifested on the Shuttle, allowing the Shuttle to be dedicated to crew-intensive and Shuttle unique missions; and

- a stronger U.S. position vis-à-vis the Soviet Union for possible future cooperative space ventures.

Finally, a heavy lift launch vehicle would increase the robustness of the U.S. space transportation system as a whole, a matter of substantial importance in its own right.

OTHER SHUTTLE-RELATED MEASURES

The Committee believes that the nation must realize that the Shuttle Orbiter fleet is likely to continue to suffer occasional attrition. It is dangerous and misleading to assume that there will be no losses and thus to fail to plan for such events. For example, if the Shuttle resumes flying in late 1988, about 90 flights could occur by late 1996 when Block I will be nearing completion. If the probability of damaging an Orbiter beyond repair on any single Shuttle flight is 1 percent--the demonstrated rate is now one loss in 25 launches, or 4 percent--the probability of losing an Orbiter before Block I is complete is about 60 percent. Put another way, we should expect to lose an Orbiter--not necessarily with accompanying loss of life--about once every 5-8 years, if the single flight loss probability is in the range of 1 percent to 2 percent.

To accommodate this likelihood, production of the first Orbiter after the Challenger replacement should be planned for delivery before Space Station deployment begins.

It is noteworthy that NASA does not have quantitative estimates of important probabilities such as that for loss of an Orbiter or that for loss of a Shuttle payload. At a somewhat more detailed level, NASA does not have quantitative reliability models of important Shuttle components such as the solid rocket motors. Recognizing the difficulty of making accurate quantitative reliability estimates, the Committee nevertheless believes that NASA should develop reliability and safety models for the Shuttle and other major space transportation systems, and for the Space Station itself. The models should be quantitative and based first on theory and then on empirical data as the latter are acquired. These models should be used to assist in improving reliability and safety, in prediction of losses, and in development of replacement and logistic support strategies.

CREW EMERGENCY RESCUE AND SPACE STATION LOGISTICS SUPPORT

As noted earlier, the Space Station Program is totally dependent on the Space Shuttle for crew transfers to and from the Station. A "safe haven" approach has been envisioned for use during Space Station emergencies with rescue, if required, effected by the Shuttle. However, as the Challenger accident has shown, Shuttle downtimes can be very long. Thus, the Committee strongly believes that there is a mandatory requirement for a crew emergency rescue vehicle.

NASA is currently considering what capabilities, if any, such a vehicle should have in addition to those essential to crew rescue. The crew emergency rescue vehicle could eventually be part of a backup means of manned ascent to the Space Station, using a man-rated expendable launch vehicle for propulsion. Such a backup capability would hedge further against problems with the Shuttle and should be considered by NASA in defining the crew emergency rescue vehicle.

The Committee also recommends that NASA plan to provide limited logistics support to the Space Station, using existing or planned types of expendable launch vehicles, to back up the Shuttle.

SUMMARY

In summary, there are a number of actions that need to be taken to make the space transportation system more robust. With respect to the Shuttle, it should be improved in performance and reliability, it should be given an extended on-orbit duration capability as noted in Section 5, page 18, and the Shuttle Program should be funded for an additional Orbiter replacement beyond the Challenger replacement. Beyond assuring an adequate Shuttle launch capability, the nation should initiate development of a heavy lift launch vehicle, and NASA should provide the Space Station with the means for logistics resupply using existing and/or planned expendable launch vehicles. NASA also should provide a reliable non-Shuttle derived rescue capability for the Space Station.

7. THE SPACE STATION TEST PROGRAM AND BACKUP HARDWARE

When the Committee's Space Station study began, NASA indicated that it intended to use a "protoflight" approach to testing. NASA said that it would produce one set of hardware that would first be used for ground testing and qualification; this hardware would then be refurbished and used to build the Space Station. In short, the test hardware would become the flight hardware. The justification for this policy was to reduce the cost of the Space Station Program, but in the form described by NASA, it would have had a number of undesirable consequences. These in part led to the Committee's concerns, expressed in the June 30 report, about integration and backup hardware. In the second phase of the study, NASA dispelled many of the Committee's concerns on this issue:

- NASA now indicates that, with a few exceptions, it will produce two substantially complete sets of Space Station hardware--one for ground functional and qualification testing and one for flight.

- Individual subsystems will be fully integrated, tested, and qualified using dedicated qualification test hardware.

- The laboratory and habitation modules will also be integrated and qualified, using refurbished qualification-test subsystem hardware.

- Flight elements, consisting of the hardware intended for flight, will be assembled, checked out, and acceptance tested on the ground before flight. These accepted flight elements will then be disassembled only as necessary to prepare them for launch and acceptance tested in the launch configuration.

The Committee supports this "modified prototype" approach and believes the following additional steps are essential for an adequate ground test program and adequate backup capability:

- A centralized Space Station test bed, duplicating, to the extent practical, the configuration of the Space Station on orbit, should be retained on the ground. This test bed could consist of refurbished qualification test equipment and backup hardware. In the judgment of the Committee, its possible cannibalization in the event flight equipment is lost is an acceptable risk.

- Each launch package should undergo pre-launch integration, using the Space Station test bed. This process should detect problems on the ground that might otherwise occur on orbit.

- Backup hardware to replace flight equipment that might be lost during the deployment phase should be procured. This hardware should supplement the initial spares planned for the deployment phase. Should this equipment not be needed in Block I, it would be available for evolution of the Space Station; thus, little of it should ultimately be wasted. In order to determine what backup hardware to procure, NASA should develop a good understanding of contingencies that could result in loss of equipment.

8. SPACE STATION COST ESTIMATES

An assessment of Space Station cost estimates was the focus of the Committee's June 30 report. During the second phase of its study, the Committee gained further insights into these estimates. On balance, these insights decreased the Committee's confidence in the earlier estimates.

- First, the Committee notes that the Space Station Program is still in flux. A number of changes occurred in the Space Station Program during the short course of this study. These include such matters as the test program, crew rotation plans (discussed below), reduced commitment to the current Block II (the features of which were part of the baseline program until just prior to the study), and replanning of the deployment process as problems with space transportation have become more apparent. Other changes are almost certainly underway, and they are likely to continue for some time, with net tendencies to increase costs (or alternatively to reduce performance).

- Second, the Committee conducted a detailed review of the cost model used at Marshall Space Flight Center and the application of this model, both at Marshall and at Headquarters. The results of this review reduced the Committee's confidence in the cost estimates for Space Station hardware under the control of Marshall.

- Third, the test program initially characterized by NASA as "protoflight," when studied in detail, was shown to be in fact more nearly a "prototype" test program. The Committee commends NASA for adopting the more conservative test program. NASA has said that its cost estimates provide for the additional hardware implied by this change. But program level guidance to the Centers for the cost estimating exercise leading to current NASA cost estimates clearly called for estimates based on a protoflight policy.(1) Thus, the

---

(1) The General Accounting Office, in a contemporaneous study, developed the same finding. See "Space Station National Aeronautics and Space Administration's 1987 Cost Estimate," (Fact Sheet for the Chairman, Committee on Science, Space, and Technology, House of Representatives), Appendix I, p. 6.

Committee is concerned that current estimates do not cover all of the hardware needed for the test program now evidently planned by NASA.

- The Committee remains strongly convinced that the Space Station Information System is not well defined, nor is the related automation and robotics strategy for the Space Station. This has implications for the confidence that can be placed in both the development estimates and the estimates of operational costs.

The Committee reviewed the operational concept for the Space Station. Much good work has been done on this concept, but the level of definition of the concept does not permit the estimation of steady-state operating costs with much confidence. The Committee believes that it is important for NASA to give increased attention to this area, because high Space Station operating costs could potentially absorb a significant portion of the civilian space budget. Moreover, this matter is of great concern to our international partners who, properly, are being asked to defray part of these costs. Their space programs are smaller than ours, and unanticipated operating costs could have relatively more serious implications for their programs than for ours.

A significant part of total operating costs after the Space Station reaches full operational status will be incurred for crew rotation and logistics support. During the course of the study, NASA revised its planning from eight Shuttle flights per year to five for these purposes. This reduction stems directly from crew rotation considerations. When the Committee was first briefed on crew rotation plans, NASA intended Space Station tours of duty to be 90 days. With eight Space Station crew members, eight Shuttle trips per year, rotating four astronauts each trip, would be needed. By increasing the planned stay time to 180 days, the number of Shuttle flights required would be reduced to four. NASA now intends to fly five crew rotation flights per year. This is one more than needed for a 180-day stay and would provide some flexibility in logistics operations.

The Committee has no definitive reasons to doubt that such long stay times can become standard practice, but notes that insufficient medical and psychological data are now available to the United States to provide high confidence that such practices can be employed. NASA's plans provide for gradually increasing crew stay times, while such data are being collected, to insure that astronauts are not endangered during the testing period.

Tables 2 and 3 present revised estimates paralleling those in the Committee's June 30 report. The estimates from the June 30 report are shown in the left column for comparison. The tables include costs only for Block I, and the revised estimates are stated in both 1984 and 1988 dollars. The Committee used NASA's inflation factors to adjust the 1984 estimates. The major changes in these tables are:

- Increased costs for the test program to reflect the change from "protoflight" to "modified prototype." As pointed out earlier, NASA argues that its program has not changed and that its earlier estimates

TABLE 2 (1)

Block I Space Station Research and Development Cost Estimates (2)
(Billions of Dollars)

	June 30 Estimate BLOCK I (1984 Dollars)	Revised Estimates BLOCK I (1984 Dollars)	Revised Estimates BLOCK I (1988 Dollars)
Phased Approach--Block I (3)	$12.2	$12.2	$ 14.6
Flight Telerobotic Servicer	0.3(4)	0.3(4)	0.4
Crew Emergency Rescue Vehicles	1.5(5)	1.5(5)	1.8
Test Program Enhancement	--	0.0-2.5	0.0-3.0
Backup Hardware	--	0.2-1.4	0.2-1.7
Total Research and Development	$14.0(6)	$14.2-17.9(6)	$17.0-21.5

(1) All estimates in this table, except for that for Test Program Enhancement, are NASA estimates. They do not include international partners' costs.

(2) The estimates in this table include funds for Space Station that are in (or would be added to) NASA's Research and Development account. This account pays for hardware and services purchased from contractors by NASA, e.g., for the development and production of Space Station flight hardware, ground support and test equipment, software, and the integration of Space Station systems. The Space Station R&D account does not cover other costs such as construction of Space Station facilities, launch services, salaries of NASA personnel working on the Space Station Program, and operational costs.

(3) The phased approach would deploy Space Station in two blocks. Block I, the "Revised Baseline," in NASA terminology, would consist of the U.S. laboratory and habitation modules, the two laboratory modules from Japan and the European Space Agency, 75 KW of photovoltaic power and other supporting systems and structures.

(4) These funds are in NASA's financial plan.

(5) Development and procurement of two vehicles; funds are not in NASA's financial plan. Source of this estimate is testimony of the Director, Space Station Program Office, before the House Subcommittee on Space Science and Applications, April 8, 1987. He stressed that this estimate is highly uncertain because of the early state of crew emergency rescue vehicle definition.

(6) In addition to these costs, NASA has planned "transition definition" studies--early conceptual studies of Space Station evolutionary possibilities--in the amount of $0.2 billion, during the development and deployment of Space Station.

TABLE 3 (1)

Estimated Total Costs to Develop and Deploy Space Station
(Billions of Dollars)

	June 30 Estimate BLOCK I (1984 Dollars)	Revised Estimates BLOCK I (1984 Dollars)	Revised Estimates BLOCK I (1988 Dollars)
Total Research and Development (from Table 2)	$14.0	$ 14.2-17.9	$ 17.0-21.5
Elements Essential to Space Station Carried in Other NASA Accounts (2)			
Space Transportation (3)	1.5	1.2-1.5	1.4-1.8
Operations Prior to Full Operational Capability	3.0	3.0	3.6
NASA Personnel (Direct & Indirect)	2.2	2.2	2.6
Related Facilities	0.2	0.2	0.2
Shuttle Mods for Space Station	0.1	0.1	0.1
Extended Duration Orbiter	--	0.1	0.1
Estimated Total Space Station Program Costs	$ 21.0	$ 21.0-25.0	$ 25.0-29.9

---

(1) All estimates in this table are NASA estimates. They do not include international partners' costs. No operating costs after full operational capability are included in these estimates.

(2) The elements of cost listed below are covered in other NASA accounts, except for modifications to the Shuttle to permit it to berth at Space Station; Shuttle modification costs will eventually appear in the Space Transportation Program, not in Space Station estimates.

(3) Estimates reflect prices charged to the Department of Defense for Shuttle launches. This is a readily available approximation of the price of Shuttle launch services, and is one measure of the opportunity costs associated with Space Station uses of the Shuttle. Low end of range, 15 Shuttle flights; high end, 19.

cover the equipment and testing now planned. The Committee had an independent estimate made of these effects, based on assumptions that NASA's current estimates are for a protoflight program and that the program is in fact prototype. This independent estimate totals $2.5 billion in 1984 dollars. Table 2, therefore, shows a range for test program enhancement of from $0.0 to $2.5 billion. The true cost probably will lie between these two values.

- Cost of backup hardware. NASA has not settled on a policy for the procurement of backup hardware. A policy of acquiring only minimal amounts of backup hardware would reduce lead times for the longest lead time elements of the Space Station so that they would not pace the resumption of deployment after a launch system standdown. NASA estimates that this policy would cost about $0.2 billion. Alternatively, enough equipment could be procured, in addition to the already planned purchase of spares, to provide a complete "ship-set" of Space Station hardware. This policy would cost about $1.4 billion, according to NASA estimates. This range--$0.2 to $1.4 billion--is shown in Table 2.

It should be stressed that the tables do not include the costs for advanced solid rocket motors, heavy lift launch vehicles, and any expendable launch vehicles that might ultimately be required.

The Committee notes that Table 2 indicates that there could be up to a $3.9 billion increase, almost 30 percent, in Space Station research and development costs, over those identified in the Committee's June 30 report, for backup hardware and test program enhancements alone.

In view of the continuing uncertainties surrounding Program costs, the Committee recommends that NASA prepare a new cost estimate as part of the Program Requirements Review which will occur early in 1988. NASA already has the services of its Program Support Contractor and at that time will have definitive contracts with its prime contractors. These circumstances will provide a far better framework for arriving at estimates in which more confidence can be placed.

These new estimates should cover all costs of the Space Station Program, generally as outlined in Table 3, and they should specifically address the test program and backup hardware uncertainties discussed above, as well as the impact of changes to the transportation system. The Space Station impact on the overall NASA budget should also be examined. Once these new Space Station estimates are made they should be documented, controlled, and updated on a continuing basis in response to engineering economic studies of the Space Station Program.

9. MANAGEMENT OF THE SPACE STATION PROGRAM

This report has emphasized the magnitude of the technical challenge presented to NASA by the Space Station Program. The Committee believes that management of the Program represents an area of equal risk to the successful development and deployment of the Space Station. Accordingly, high priority must be placed on enhancing and supporting Space Station Program management.

STRENGTHENING PROGRAM MANAGEMENT

NASA is to be commended for the steps it has already taken in this direction. In the spring of 1986, the Administrator of NASA asked General Samuel C. Phillips, former director of the Apollo Program, to review Space Station organization and management. In response to the recommendations of his committee, NASA:

- Established a Space Station Program Office, independent of the Centers.

- Selected a Program Support Contractor to assist the Space Station Program Office.

- Altered work assignments among NASA Centers to increase Program efficiency.

- Formally subordinated the Station project managers at the NASA Centers to the Space Station Program Director.

- Developed enhanced planning and documentation systems for the Space Station Program.

The resulting more centralized arrangement is clearly more appropriate to the challenges of the Space Station Program than its predecessor, a "lead-center" structure. However, it does not go far enough; the following additional measures are needed:

- NASA management must emphasize that the Space Station Program Director is the principal line manager of the Space Station Program and is accountable for the successful development of the Space Station. He must be equipped with authority commensurate with this accountability.

- The Space Station Program Office must be continually supported and reinforced by senior NASA management. There are likely to be tendencies for control of the Space Station Program to move away from the Program Office to the NASA Centers. Such diffusion of influence would be highly inappropriate for the Space Station Program. Reinforcement can come from support to the Program Office on such issues as timely authorization of adequate staff, the extent of the Station Program Director's authority over Station project managers at the Centers, and establishment of the Program Office's role in the decision-making structure for the Space Station. In this latter regard, the Committee welcomes the revitalization of the Management Council, with the Space Station Program Director as a full member.

- NASA has made commendable progress in rationalizing the allocation of responsibilities among the five Centers most heavily involved in the Space Station Program. Nevertheless, provision for integration and test, and component flows among Centers remain too complex. The Committee recommends that this matter be addressed in the management study recommended below.

Even these actions may not be sufficient to ensure that the Space Station Program can be properly managed in NASA. The Committee thus recommends that NASA establish a dedicated Space Station project organization that would subordinate all NASA personnel assigned to the Space Station development program to the Program Director and give the Program Director control of financial and other resources assigned to the Program. This authority would extend into the Centers, placing Center personnel assigned to the Space Station Program under the line authority of the Space Station Program Director.

The Committee recognizes that such arrangements would depart significantly from current "matrix" management practices in the Centers. However, the Committee believes that the importance, size, complexity, and duration of the Space Station Program fully justify such new arrangements.

SPACE STATION OPERATIONS MANAGEMENT

As pointed out elsewhere in this report, planning has not gone far enough to permit a confident estimate of Space Station operating costs. Moreover, the Committee is not satisfied that operational considerations will be given sufficient priority. An organizational entity, independent of the Space Station Program development hierarchy, with the ultimate responsibility for operating the Space Station, should be formed promptly.(1) (NASA appears to

---

(1) This entity would not obviate the need for operational expertise within the Space Station Program Office.

be taking steps in this direction.) This entity should be located at a Center where much of NASA's operational expertise resides. One of the entity's important roles during development should be to promote those characteristics in the Space Station that will make it economical and practical to operate. This entity should not have veto power over decisions of the Space Station Program Director, but it should be sufficiently independent that it can create constructive tension between itself and the Space Station Program Office to assure that its views are taken into account.

NASA should simplify the structure now envisioned for relations between the Space Station operators and the users. The Space Station will be a tightly constrained facility with more demands on it than can be satisfied. In such an environment, the burden should be placed on the user communities, insofar as possible, to set priorities and allocate the capabilities of the Station, consistent with national priorities and objectives.

COORDINATING THE SPACE TRANSPORTATION AND SPACE STATION PROGRAMS

As this report underlines, space transportation is of crucial importance to the Space Station: the deployment of the Station will require a large fraction of the Shuttle's capacity, and other resource tradeoffs between the Station, the Shuttle, and other launch systems will inevitably arise. Moreover, the Space Station cannot be developed, deployed, and operated without risk of significant setbacks, especially regarding the space transportation system. Although the Space Station Program has as an objective a "permanent manned capability," this capability will be permanent only to the extent that the supporting transportation system remains operational. In an important sense, the Station and its supporting transportation system comprise a larger system that arguably should be under a single manager. The Committee recognizes, that until problems in the Shuttle are corrected, such a consolidation would not be in the best interest of either the Shuttle or the Space Station. However, the Committee is not satisfied that the current liaison structure is adequate to deal with the critical issues at this interface. This issue should be addressed in the management study recommended below.

FINANCIAL PLANNING FOR THE SPACE STATION PROGRAM

As the Committee pointed out elsewhere in this report, the Space Station Program is extraordinarily complex, and unlike other space systems, the Space Station will become a facility that will be operated for decades. In some ways, it will be similar to the research base at Antarctica or to an oceanographic research vessel. It differs from these in that it will evolve and change, perhaps radically and in unanticipated directions, as it adapts to new uses.

The Space Station is planned to be developed over a decade and subsequently managed over a 30-year period. Ideally, a realistic development budget should be determined and funds provided in a series of multiyear appropriations, thereby giving long-term financial predictability to the Space Station Program. NASA's obligation would be to manage the Program on a multiyear basis within this budget envelope. Eventually, the Space Station should not be defined as a project, but as an ongoing facility from which separately-funded research and other missions would be carried out; it should then be funded on a predictable long-term basis the way analogous facilities are. The Committee thus recommends that multiyear appropriations be provided to make financing of the Space Station more predictable.

PREPARING A MANAGEMENT PLAN FOR REVIEW BY THE OFFICE OF MANAGEMENT AND BUDGET

Resolution of the management issues discussed above is of sufficient importance to the success of the Space Station Program that follow-up is justified. The Committee thus recommends that NASA, under the general supervision of the Office of Management and Budget, conduct a study analyzing this Committee's program management recommendations and concerns. This study should result in a plan expressing how and to what extent NASA intends to respond to the Committee's management concerns. The Office of Management and Budget should evaluate NASA's progress in implementing this plan approximately nine months after its submission.

APPENDIXES

APPENDIX 1

STATEMENT OF TASK

The purpose of the Committee on Space Station (COSS) is to advise the Executive Office of the President and the National Aeronautics and Space Administration (NASA) on the design and development of an orbiting space station. The Committee is to review space station development in light of national space priorities, the functions and performance required to meet those priorities, the phasing of specific capabilities and interaction with foreign nations. Where appropriate, alternatives to current proposals should be identified and addressed.

The study will be divided into three phases. Phase 0 will be a learning and information gathering process. Phase 1 has two distinct components. The first is a critical review of: mission priorities currently assigned the space station; functional and performance requirements; the proposed phasing of specific capabilities; and the rationale for design choices. The second component is a critical assessment of NASA cost estimates. The COSS will neither form cost estimates of its own nor attempt to replicate NASA's cost estimates. Instead, it will: review methods used by NASA; identify key assumptions underlying the cost calculations; and assess the risk that some of these assumptions will not be realized and the implications for space station timing, performance, and cost. Where appropriate, alternative methods and assumptions will be suggested. Phase 1 is to be completed by June 30, 1987.

Phase 2 concerns long-term requirements and alternatives. The COSS will:

(a) Review longer-term space station requirements, emphasizing scientific goals, technology development missions, commercial uses, national security purposes, and space infrastructure requirements, to include transportation and communications.

(b) Identify attractive alternatives to the configurations identified in Phase 0 and assess their evolutionary capabilities and capacity to meet the desiderata outlined in (a).

(c) Based upon (b), assess the potential costs associated with these additional capabilities, or savings associated with reduced or postponed requirements, including considerations of changing program content and schedule.

(d) Review the projected arrangements for international participation in the space station project and suggest how alternative space station concepts could influence this.

(e) Complete Phase 2 by September 1, 1987.

The COSS will submit two reports to the Executive Office of the President (National Security Council, Office of Management and Budget, and Office of Science and Technology Policy) and to NASA. The first will be a letter report due June 30 and will include Phase 1 work. The second letter report will be due September 1 and will include Phase 2 work as well as any other observations the Committee believes to be relevant.

In addition to the specific charge, the COSS should report any other observations and recommendations it believes would contribute to national space station development.

NATIONAL RESEARCH COUNCIL

2101 Constitution Avenue Washington, D.C. 20418

COMMITTEE ON SPACE STATION

APPENDIX 2

June 30, 1987

The Honorable Frank C. Carlucci
The Honorable William R. Graham
The Honorable James C. Miller, III
Executive Office of the President
The White House
Washington, D.C. 20500

The Honorable James C. Fletcher
National Aeronautics and Space Administration
Washington, D.C. 20546

RE: June 30 Report of the National Research Council Committee on Space Station

Gentlemen:

The Committee on Space Station was asked, first, to assess NASA's cost estimates for the Space Station Program and, second, to examine Space Station mission requirements and alternative configurations. This report covers the Committee's current findings on the acquisition cost estimate for Space Station and summarizes some broader issues that will be addressed in the second phase of the study.

The Committee's line of departure for its review of Space Station cost estimates was the Space Station Program recently proposed by NASA. This program was estimated to cost $14.5 billion, in 1984 dollars. Subsequently, a similar but phased approach was proposed; the first phase has been approved by the President. This approach is currently estimated by NASA to cost $16.0 billion, also in 1984 dollars. The first phase would cost $12.2 billion; the second, $3.8 billion.

The Committee took as givens for its cost review such elements of the Space Station Program as the configuration of the Station and its components, the program schedules and plans for space transportation, manning the Station, and rotating Station crews. However, the Committee plans to examine the uncertainties implicit in some of these elements. These uncertainties could substantially affect schedules and costs of the Space Station Program. They will be treated more completely in the second phase of the study.

The Committee offers the following preliminary findings relating to the cost estimates for Space Station:

a. Cost estimates for the hardware components vary in quality from some that seem quite supportable to others that are less so. Overall, the uncertainties associated with the hardware cost estimates are characteristic of these for other large aerospace systems at the same early stage of definition. This implies that the current cost estimates for some hardware components may be exceeded for reasons that cannot now be foreseen.

b. Software cost estimates depend on the unit costs of developing "source lines of code" and the amount of code that must be developed. The Committee is comfortable with NASA's estimates of unit costs for developing code, but feels that the amount of code that must be produced may have been underestimated. This uncertainty in software cost stems from the preliminary state of definition of Space Station information systems.

c. Space Station is an extraordinarily large and complex system. It cannot be fully integrated on the ground and must be transported into space and assembled on orbit in 29 packages--18 packages for Block I and 11 packages for Block II. The size and weight of these packages is limited by the payload volume and lift capacity of Shuttle. These limitations increase the on-orbit assembly and checkout required, much of which must be done by astronauts during extra-vehicular activity. The management of Space Station integration is made more difficult by the complex interfaces among the four NASA Centers doing the bulk of the work on Space Station, and especially those between Johnson and Marshall. The integration challenge presented by this combination of factors is unprecedented.

Technical problems with systems integration are unlikely to be discovered until relatively late in the development cycle when they are costly to rectify. Schedule slippages resulting from delays associated with these fixes can themselves be a source of additional cost. NASA's most recent and relevant experience is with the Shuttle; however, Space Station integration is different from and more complex than Shuttle integration. Thus, the experience with systems integration of the Shuttle is not likely to be a reliable guide to integration of Space Station. The Committee believes that systems integration is a principal source of uncertainty in current cost and schedule estimates.

d. NASA's $16.0 billion cost estimate for the phased approach includes $3.8 billion for program-wide contingency reserves. These reserves are currently retained at the Space Station program office level; no reserves are controlled by the Centers. The Committee believes that the Centers will need major portions of these reserves in order to have reasonable confidence that their obligations can be fulfilled. Program-wide reserves to insure against serious unexpected problems in one or more of the work packages may, therefore, be insufficient.

e. Funds for some components unique to Space Station are not included in the $16.0 billion estimate. They have been incorporated in the estimates shown in Table 1. These components are the flight telerobotic servicer, an orbital maneuvering vehicle and crew emergency rescue vehicles. Funds for the servicer are covered in NASA's financial plan, but funds for the other two elements are not.(1)(2)(3)

f. The estimates of Space Station costs customarily used, for example the $16.0 billion figure cited elsewhere in this report, cover only the costs of services, hardware and software for Space Station purchased from contractors--that is, such things as development and production of Space Station flight hardware, ground support and test equipment, software, and the integration of Space Station systems. These are the costs of Space Station that would be carried in the Research and Development account of NASA's budget.

---

(1) Development of the orbital maneuvering vehicle is funded in the Space Transportation Program and procurement of one unit is planned for the Shuttle. A second will be needed for Space Station to manage satellites and payloads in close proximity to the Station; the second unit is not in NASA's financial plan.

(2) Crew emergency rescue vehicles are not now part of the Space Station Program. Current plans are to use "safe haven" techniques in Space Station (backed up by rescue with the Shuttle) to deal with emergencies. NASA is now considering whether or not crew emergency rescue vehicles will be needed and is defining the requirements they must satisfy if they are deemed necessary. The Committee believes that such vehicles will be needed to deal with the full range of contingencies that could occur.

(3) The statement that funds for the servicer are covered in NASA's financial plan should be understood to mean that they are covered to the extent that such costs fall in the years encompassed by this plan. This meaning should be attached to similar statements elsewhere in this report.

A number of other costs for services and support required by Space Station are not included in the Space Station Research and Development account. These include costs for such things as launch services, salaries of NASA personnel working on Space Station, spares and other operational costs, and the construction of Space Station facilities.
Table 2 shows a more comprehensive estimate of Space Station costs, including these elements. The additional costs shown in Table 2, except for berthing modifications to the Shuttle, are all provided for in NASA's financial plan and should not be construed as additions to this plan. However, this more comprehensive estimate of Space Station Program costs is useful for understanding the full resource commitment to Space Station and for planning and management purposes.

g. The Committee has not yet addressed the operational costs of Space Station, but it is clear that operating the Station will be a demanding and expensive undertaking. This underlines the importance of making those initial investments necessary to insure that Space Station can be operated economically.

The Committee in its review of Space Station costs has identified three related issues that could substantially affect costs and program success. In addition to completing other tasks remaining in the Space Station study, the Committee intends to inquire further into these matters.

a. <u>Limitations on Shuttle Payload and Demands on Shuttle Launch Capacity</u>. The limitations on Shuttle payload prevent the launch of fully assembled Space Station modules, complicating on-orbit assembly of Space Station. Moreover, weight growth in Space Station components during development—a phenomenon common to most aerospace systems—could exacerbate this situation. Finally, current plans for Space Station crew rotation would require about two thirds of all available Shuttle launches. (The Shuttle could, of course, carry additional payload to and from Space Station on these crew rotation flights.) Heavy lift launch vehicles, improvements to Shuttle to increase its payload, and longer Space Station crew stay times would alleviate the effects of these limitations. NASA is currently investigating these matters intensively and the Committee also plans to include them in its consideration.

b. <u>Backup Flight Hardware</u>. NASA is planning little backup flight hardware for major components of the Space Station. This policy promises to reduce program cost but runs the risk that the loss of key components of hardware could delay the Space Station Program substantially. The Committee intends to study alternatives to NASA's current policy that reduce these program risks in a cost-effective manner.

c. NASA's Organization to Manage Space Station. As pointed out earlier in this report, Space Station is unusually complex and presents unprecedented integration challenges. These are complicated further by the payload limitations of the Shuttle. Accountability and control in such an environment is extremely important, in both the development and operational phases. Moreover, the Space Station Program will be the centerpiece of NASA's program for the next two or three decades, and it will absorb much of NASA's energy and funding.

NASA has adopted a management structure similar to that used for the Apollo Program in order to accommodate better the demands of the Space Station Program. However, current organizational arrangements still embody considerable complexity in Space Station interfaces and complicate integration of Space Station subsystems and flight elements. These organizational and management issues will be examined in the second phase of the study.

I want to express my appreciation and that of the other members of the Committee for NASA's excellent cooperation and support in the first phase of our study. The second phase will also require cooperative efforts to address the issues outlined above and others that might be encountered, and we are looking forward to working with NASA during the remainder of our study.

Dr. John McLucas, Vice Chairman of the Committee on Space Station, and I will be available to discuss this report with you on July 2.

Sincerely,

Robert C. Seamans, Jr.

Robert C. Seamans, Jr.
Chairman

TABLE 1 (1)
Space Station Research and Development Cost Estimates (2)
(Billions of 1984 Dollars)

	BLOCK I	BLOCK II	ENHANCED CONFIGURATION	
Phased Approach (3)	$12.2	$3.8	$16.0	
Flight Telerobotic Servicer	.3	0.0	.3	(4)
Orbital Maneuvering Vehicle	0.0	.1	.1	(5)
Crew Emergency Rescue Vehicles	1.5	0.0	1.5	(6)
Total Research and Development	$14.0	$3.9	$17.9	(7)

(1) All estimates in this table are NASA estimates.
(2) The estimates in this table include funds for Space Station that are in (or would be added to) NASA's Research and Development account. This account pays for hardware and services purchased from contractors by NASA, e.g., for the development and production of Space Station flight hardware, ground support and test equipment, software, and the integration of Space Station systems. The Space Station R&D account does not cover other costs such as construction of Space Station facilities, launch services, salaries of NASA personnel working on the Space Station Program, and operational costs.
(3) The phased approach would deploy Space Station in two blocks. Block I, the "Revised Baseline," in NASA terminology, would have 75 kilowatts of photovoltaic power and would exclude dual keels. The addition of Block II would produce the "Enhanced Configuration." This configuration would add dual keels and 50 kilowatts more of solar dynamic power.
(4) These funds are in NASA's financial plan.
(5) Procurement of one unit for Space Station; development funds are in the Space Transportation Program. Funds for the Space Station unit are not in NASA's financial plan.
(6) Development and procurement of two vehicles; funds are not in NASA's financial plan. Source of this estimate is testimony of the Director, Space Station Program Office, before the House Subcommittee on Space Science and Applications, April 8, 1987. He stressed that this estimate is highly uncertain because of the early state of crew emergency rescue vehicle definition.
(7) In addition to these costs, NASA has planned "transition definition" studies—early conceptual studies of Space Station evolutionary possibilities—in the amount of $.2 billion, during the development and deployment of Space Station.

TABLE 2 (1)

Estimated Total Costs to Develop and Deploy Space Station
(Billions of 1984 Dollars)

	BLOCK I	BLOCK II	ENHANCED CONFIGURATION
Total Research and Development (from Table 1)	$14.0	$3.9	$17.9
Elements Essential to Space Station Carried in Other NASA Accounts (2)			
Space Transportation (3)	1.5	.9	2.4
Operations Prior to Full Operational Capability	3.0	1.4	4.4
NASA Personnel (Direct & Indirect)	2.2	.3	2.5
Related Facilities	.2	0.0	.2
Shuttle Mods for Space Station	.1	0.0	.1
Estimated Total Space Station Program Costs	$21.0	$6.5	$27.5

---

(1) All estimates in this table are NASA estimates. No operating costs after full operational capability are included in these estimates.
(2) The elements of cost listed below are covered in other NASA accounts, except for modifications to the Shuttle to permit it to berth at Space Station; Shuttle modification costs will eventually appear in the Space Transportation Program, not in Space Station estimates.
(3) Estimates reflect prices charged to DoD for Shuttle launches. This is the best available approximation of the price of Shuttle launch services, and thus of the opportunity costs associated with Space Station uses of the Shuttle.

APPENDIX 3

CHRONOLOGY OF MEETINGS

The Committee and its various subgroups convened in excess of 25 meetings between inception of the study in May 1987 and its completion at the end of August 1987. Major meetings are listed below:

COMMITTEE/SUBCOMMITTEES

May 4-5: Full Committee Meeting, Washington, D.C.
May 12: Meeting at Goddard Space Flight Center, Greenbelt, Maryland
May 22: Meeting at Johnson Space Center, Houston, Texas
May 26: Meeting at Marshall Space Flight Center, Huntsville, Alabama
May 28: Meeting at Lewis Research Center, Cleveland, Ohio
May 29: Subcommittee on Defense and International Affairs, Washington, D.C.
June 1-2: Full Committee Meeting, Langley Research Center, Hampton, Virginia
June 6: Subcommittee on Program Alternatives, Washington, D.C.
June 6: Subcommittee on Transportation Issues, Washington, D.C.
June 7: Subcommittee on Program Management, Washington, D.C.
June 18: Review Group of Outstanding Issues, Washington, D.C.
June 22-23: Full Committee Meeting, Washington, D.C.
July 8: Subgroup Review of Harwood Configuration, Los Angeles, California
July 10: Subcommittee on Transportation Issues, Washington, D.C.
July 14-15: Full Committee Meeting, Washington, D.C.
July 20-24: Task Force on NASA Cost Model, Huntsville, Alabama
July 23-24: Subcommittee on User Requirements, Los Angeles, California
August 3-4: Full Committee Meeting, Washington, D.C.
August 18: Staff Meeting with Life Sciences Strategic Planning Study Committee, Boston, Massachusetts
August 25-26: Full Committee Meeting, Washington, D.C.

MEETINGS WITH INTERNATIONAL PARTNERS

June 5: Meeting between Dr. Friedman and the Director General of the European Space Agency, Paris, France
August 13: Meeting with the Japanese Science Counselor and Japanese Space Station Negotiating Team, Washington, D.C.
August 13: Meeting with the Canadian Science Counselor, Washington, D.C.
August 14: Meeting with the Canadian Negotiating Team, Washington, D.C.
August 14: Meeting with Washington ESA Representative and ESA Technical Representative, Washington, D.C.

APPENDIX 4

LIST OF PARTICIPANTS

NATIONAL AERONAUTICS and SPACE ADMINISTRATION

John AARON, HQS
George ABBEY, JSC
Max AKRIDGE, MSFC
Judith AMBRUS, HQS
Robert ARMSTRONG, JSC
Sharon BABB, HQS
Stephen BALES, JSC
Russell BARDOS, HQS
Gerald BARNA, LeRC
David BATES, HQS
Everette E. BEAM, MSFC
Marc BENSIMON, HQS
Dan BERNATOWICZ, LeRC
Ronald L. BERRY, JSC
Vince BILARDO, HQS
David BLACK, ARC
Don BLEVINS, JSC
Darrell BRANSCOME, HQS
Ronald BROWNING, GSFC
Raymond BURNS, LeRC
Ernest BUSBOSO, GSFC
Cindy CARPENTER, MSFC
Edward CHEVERS, JSC
Aaron COHEN, JSC
Harold CONWAY, JSC
Clarke COVINGTON, JSC
Jerry CRAIG, JSC
Mark CRAIG, JSC
William CREASEY, JSC
Roger CROUCH, HQS
Philip CULBERTSON, HQS
Carroll DAWSON, JSC
James DePAUW, LeRC
Al DIAZ, HQS
R. H. DIETZ, JSC
Anton DORR, HQS
Larry EARLY, HQS
Andrew EDWARDS, HQS
Dee EDWARDS, HQS
W. ELLIS, JSC
Glenn EUDY, MSFC
Margaret FINARELLI, HQS
Ken FIKES, MSFC
Terrence FINN, HQS
Mark FONTAINE, HQS
Floyd FORD, GSFC

Key for Center Abbreviations

ARC = Ames Research Center
GSFC = Goddard Space Flight Center
HQS = Headquarters (NASA)
JSC = Johnson Space Center
KSC = Kennedy Space Center
LaRC = Langley Research Center
LeRC = Lewis Research Center
MSFC = Marshall Space Flight Center

NATIONAL AERONAUTICS and SPACE ADMINISTRATION (Continued)

Richard FOX, JSC
Ken FROST, GSFC
Joe GITELMAN, GSFC
Larry GORDON, LeRC
Jesse F. GOREE, JSC
C. GREGG, MSFC
L. GUZINSKY, MSFC
Joseph HAMAKER, MSFC
Leonard HARRIS, HQS
Daniel HERMAN, HQS
Mark HESS, HQS
U. HEUTER, MSFC
Lee HOLCOMB, HQS
Larry HOLLEY, KSC
Alan HOLT, HQS
Caroline HUNTOON, JSC
Ray HOOK, LaRC
Lyle JENKINS, HQS
Charlie JONES, MSFC
William KEATHLEY, GSFC
KELLY, JSC
E. KEMPKE, LeRC
Rick KING, GSFC
John KLINEBERG, LeRC
J. KOBAK, LeRC
Eugene KRAN, JSC
T. LaCROIX, LeRC
Alan LADWIG, HQS
Bill LAND, HQS
Tom LaVIGNA, GSFC
R. LEE, MSFC
Chuck LEWIS, JSC
Jim LEWIS, JSC
Jyles MACHEN, MSFC
Merrill MACKENZIE, JSC
H. MANDELL, JSC
Dan MANGIERI, JSC
R. MARSHALL, MSFC
Frank MARTIN, HQS
Les MEREDITH, GSFC
W.C. MORGAN, HQS
Thomas MOSER, HQS
Dale MYERS, HQS
Joseph NAININGER, HQS
George NEWTON, HQS
Arnauld NICOGOSSIAN, HQS
D. NORED, LeRC
Robert NUNAMAKER, LaRC
Saraj PATEL, MSFC
Granville PAULES, HQS
Don J. PEARSON, JSC
Tom PERRY, HQS
Malcolm PETERSON, HQS
Sam POOL, JSC
Luther E. POWELL, MSFC
P. PRIEST, MSFC
Brian PRITCHARD, LaRC
John QUANN, GSFC
Tony REDDING, JSC
Wayne RICHIE, HQS
Raymond ROBERTS, HQS
James ROMERO, HQS
James ROSE, HQS
Jeffrey ROSENDHAL, HQS
A. ROTH, MSFC
Rudolph SALDANA, HQS
Phillip SHANAHAN, JSC
Carl SHELLEY, JSC
John SHERMAN, HQS
Buck SIMMS, JSC
Jim SMOTHERMAN, JSC
R. E. SNYDER, HQS
Andrew STOFAN, HQS
David SUDDETH, GSFC
O. SULLIVAN, MSFC
Joseph TALBOT, LaRC
F. TEREN, LeRC
R. THOMAS, LeRC
Shelby TILFORD, HQS
Richard TRULY, HQS
Giulio VARSI, HQS
Kim VERIS, HQS
Don WADE, JSC
Dave WALKER, JSC
William WEBB, GSFC
Vern WEYERS, LeRC
Kelli WILLSHIRE, LaRC
Walt WOOD, MSFC
Gwen YOUNG, HQS
Jim ZEREGA, GSFC
Lowell ZOLLER, MSFC

REPRESENTATIVES OF INTERNATIONAL PARTNERS

Canada
William COCKBURN
W. Mac EVANS
Karl DOETSCH
Roy VanKOUGHNETT

Japan
Kaname IKEDA
Massafumi MIYAZAWA
Hideo NAKATSUGAWA
Tetsuhisa SHIRAKAWA

European Space Agency
Dietrich LAMMERS
Reimar LUST
Wubbo OCKELS
Ian PRYKE

CENTRAL INTELLIGENCE AGENCY
Beth BLOOMFIELD

DEPARTMENT OF DEFENSE
Fred IKLE
Milton MARGOLIS

United States Air Force
Lt. Col. Roger COLGROVE
Charles COOK
Gen. Robert T. HERRES
Louis KOUTS
Maj. Richard McKINNEY

GENERAL ACCOUNTING OFFICE
Brad HATHAWAY
Karen KEMPER
Pierre TOUREILLE

NATIONAL SECURITY COUNCIL
Col. Gerald MAY
Col. Roger DeKOK

OFFICE OF MANAGEMENT & BUDGET

Joe HEZIR
Norine NOONAN
Daniel TAFT
Anthony WU

OFFICE OF SCIENCE AND TECHNOLOGY POLICY

Thomas BISHOP
Thomas RONA

OTHER PARTICIPANTS

Edwin ALDRIN
Peter BANKS
Oliver HARWOOD
Don KOCH
John KRIETER

Space Industries Partners

Joseph ALLEN
James CALAWAY
Max FAGET

INVITED GUESTS

Dr. James FLETCHER, NASA Administrator
Dr. William GRAHAM, The President's Science Advisor
Gen. Samuel PHILLIPS, USAF, Retired
Dr. Robert WHITE, National Academy of Engineering

APPENDIX 5

BIBLIOGRAPHY

Aaron, John. "A White Paper on Prime Software Cost Estimates: Cost Commitment Team Recommendations." National Aeronautics and Space Administration. December 1986.

Abbott, A.D. "Space Station Transportation Support Requirements." The Aerospace Corporation. May 26, 1987.

The Aerospace Corporation. "Advanced Launch System Baseline Concepts." August 1987.

The Aerospace Corporation, Vehicle and Control Systems Division. "Space Station Study Background." 1987.

Beggs, James M. "Space Station: The Next Logical Step." NASA. 1984.

Bernstein, Harry and Dwight Abbott. "Space Transportation Architecture Resiliency." The Aerospace Corporation. March 1987.

Black, D.C. "Scientific Customer Needs: NASA Users" AIAA-87-2196. Presentation to AIAA/NASA International Symposium on Space Information Systems in the Space Station Era, Washington, D.C. NASA. June 22-23, 1987.

Branscome, Darrell B. "Cargo Launch Vehicles: Presentation to NRC Committee on Space Station Subcommittee on Transportation Issues." NASA, Office of Space Flight, NASA Headquarters. July 10, 1987.

Browning, Ronald K. "GSFC Work Package-3 Presentation to the National Research Council Committee on Space Station." NASA. May 12, 1987.

Craig, Mark. "Space Station Configuration Chronology (1983-1987)." Presentation to National Research Council Committee on Space Station. NASA. July 14, 1987.

Crawley, Edward F. "Validating Space Station Dynamic Behavior." Paper presented at AIAA Aerospace Engineering Conference. February 19, 1987.

Colgrove, Lt. Col. "Space Launch Outlook." Presentation by United States Air Force. Department of Defense. July 10, 1987.

Culbertson, Philip E. "Space Station: A Cooperative Endeavor." Presentation to 25th International Meeting on Space, Rome, Italy. NASA. March 26-28, 1985.

Diaz, A.V. "Space Station Evolution Planning (Transportation Node). Presentation to the National Research Council Committee on Space Station." NASA. July 14, 1987.

Diaz, A.V. "Transition Definition." Presentation to the National Research Council's Committee on Space Station. NASA. July 31, 1987.

Edwards, A. "Extended Duration Orbiter (EDO)." Presentation to Committee on Space Station National Research Council. Orbiter Division, Office of Space Flight, NASA. July 31, 1987.

Egry, I., G. Otto and B. Feuerbacher. "Scientific User Requirements for Microgravity Research, European Aspects" AIAA-87-2195. Presentation to AIAA/NASA International Symposium on Space Information Systems in the Space Station Era, Washington, D.C. German Aerospace Research Establishment (DFVLR), Federal Republic of Germany. June 22-23, 1987.

Faget, Max. "Industrial Space Facility Program Briefing." Presentation to the National Research Council. Space Industries Partnership. 1987.

Fletcher, James C. "Summary of Major Actions Taken or in Work in Response to the Recommendations of the NASA Management Study Group." NASA. January 7, 1987.

General Accounting Office. Space Operations: NASA's Use of Information Technology. April 17, 1987.

General Accounting Office. Space Station: National Aeronautics and Space Administration's 1987 Cost Estimate. GAO/NSIAD-87-180FS. July 1987.

Goddard Space Flight Center. "GFSC Work Package-3 Presentation to the National Research Council Committee on Space Station: Science User Perspective; Prime Program Element Technical Risk Description; Cost Estimates, Prime and Non-Prime." May 12, 1987.

Goddard Space Flight Center, Office of Space Station, NASA. "Preliminary Program Plan for the Space Station Flight Telerobotic Servicer Program." November 1986.

Hall, Clifford N. and Jerome P. Mullin. "Dynamic Power: A Key to the Promise of Space." Presented to Twenty-Second Space Congress, Cocoa Beach Florida. April 23-26, 1985.

Hall, D.L. "NASA Space Information Systems Overview" AIAA-87-2189. Presentation at AIAA/NASA International Symposium on Space Information Systems in the Space Station Era. NASA. June 22-23, 1987.

Halpern, R.E. "Space Station Coordinated Users Payload Accommodation Assessment." NASA, Office of Space Station. July 23, 1987.

Harwood, Oliver P. "Evolutionary Space Station." February 1984.

Harwood, Oliver P. "An Evolutionary Space Station Architecture," Journal of the British Interplanetary Society, Vol. 38, pp. 305-314. 1985.

Harwood, Oliver P. 1987 Testimony Regarding an Approach to Station Design. Committee on Appropriations, Subcommittee on HUD and Independent Agencies, United States Senate. May 20, 1987.

Higuchi, K., I. Iizuka, and Y. Fujiwara. "Japanese Customer Needs for Space Station" AIAA-87-2193. Presentation to AIAA/NASA International Symposium on Space Information Systems in the Space Station Era, Washington, D.C. National Space Development Agency of Japan, Tokyo, Japan. June 22-23, 1987.

The JASON Group. The Soviet Manned Space Program. Unclassified Version. The MITRE Corporation. May 1987.

Krebs, Thomas H., James P. Stucker, and Albin D. Kazanowski. "Usage of the PRC Cost Model for Space Station Phase C/D Costing." Report to the Committee on Space Station, National Research Council. August 1987.

Langley Research Center, NASA. "Langley Space Station Activities." June 1, 1987.

LaVigna, Thomas A. and Helmut P. Cline. "Satellite Servicing in the Space Station Era." Paper presented to the 24th Space Congress, Canaveral Council of Technical Societies, Cocoa Beach, Florida. Goddard Space Flight Center, NASA. April 21-24, 1987.

Lewis Research Center, NASA. "Presentation to the National Research Council Committee on Space Station, WP-04." May 28, 1987.

Lyndon B. Johnson Space Center, NASA. "Briefing to the National Research Council: Space Station WP-2 Elements; Data Management System; Communications and Tracking; Thermal, EVA, ECLSS, Propulsion and Fluids; Test and Verification; Cost." May 22, 1987.

Lyndon B. Johnson Space Center, NASA. Life Sciences Research Laboratory (LSRL): Human Research Facility (HRF) for Space Station: Initial Operating Configuration (IOC). October 1985.

Lyndon B. Johnson Space Center, Space Station Projects Office, NASA. "Space Station Crew Emergency Return Vehicle: Status Presentation to National Research Council Committee on Space Station." July 10, 1987.

Marker, W., V. Whitelaw, J. Muratore, and J. Bigham, Jr. "Space Station Information System Requirements for Integrated Communications" AIAA-87-2229. Presentation at AIAA/NASA International Symposium on Space Information Systems in the Space Station Era. Johnson Space Center, NASA. June 22-23, 1987.

Marshall Space Flight Center, NASA. "Briefing to the National Research Council: WPOI Contents; Resource Nodes and Airlock Systems; Logistics Elements; Non-Prime Review; Cost Estimate Review." May 26, 1987.

Marshall Space Flight Center, NASA. "Shuttle-C Report to National Research Council." August 25, 1987.

Martin, Franklin D. "Space Station: Accommodating User Requirements." Office of Space Station, NASA. June 23, 1987.

McKenna, R., R. Niggemann, and P. Thollot. "Solar Dynamic Power for Space Station" (SAE Technical Paper Series). Presented at Aerospace Congress & Exposition, Long Beach, California. October 15-18, 1984.

Moser, Thomas. L. "Evolution of the Space Station Configurations as Driven by User Requirements: A Presentation to the National Research Council Committee on Space Station." NASA, Office of Space Station. June 23, 1987.

Moser, Thomas L. "Space Station Program Management." Presentation to the National Research Council Committee on Space Station. NASA. July 14, 1987.

Muratore, J., J. Bigham, V. Whitelaw, and W. Marker. "Space Station Information System Integrated Communications Concept" AIAA-87-2228. Presentation at AIAA/NASA International Symposium on Space Information Systems in the Space Station Era. Johnson Space Center, NASA. June 22-23, 1987.

NASA. "Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy: Executive Overview, Volume I." March 1985.

NASA. "Advancing Automation and Robotics Technology for the Space Station and for the U.S. Economy: A Technical Report, Volume II." March 1985.

NASA. "An Agreement Between the Government of the United States and Governments' Members of the European Space Agency on Cooperation in the Detailed Design, Development, Operation, and Utilization of the Permanently Manned Space Station." April 17, 1987.

NASA. "Heavy Lift Vehicle Requirements/Benefits Presentation to Associate Administrator for Space Station." April 28, 1987.

NASA. "Lunar Base Mission Accommodation at Space Station: Status Report." Presented at CSLI STAS Meeting. May 7, 1987.

NASA. "Manned Mars Mission Accommodation at Space Station: Executive Summary." 1987.

NASA. "Manned Mars Mission Accommodation at Space Station." Presented at CSLI STAS Meeting. May 7, 1987.

NASA. "Memorandum of Understanding Between the United States National Aeronautics and Space Administration and the European Space Agency on Cooperation in the Detailed Design, Development, Operation and Utilization of the Permanently Manned Space Station" (Draft #6). April 22, 1987.

NASA. NASA Earth Science and Applications Division: The Program and Plans for FY 1987-1988-1989. May 1987.

NASA. "NASA Study Leading Towards a Reduction in the Dependency of the Space Station on the Shuttle Transportation System." June 15, 1987.

NASA. "NSTS/SS Transportation Study Planning/Status." Presentation to National Research Council Committee on Space Station. July 14, 1987.

NASA. "Planned Space Shuttle Engine Design Changes. Presentation to National Research Council Space Station Cost Group." August 25, 1987.

NASA. "Protoflight versus Prototype Hardware. Presentation to National Research Council for Space Station Program." August 25, 1987.

NASA. "Report of the Critical Evaluation Task Force." 1986.

NASA. "Requests for Proposals." Space Station Work Packages One - Four. 1987.

NASA. "Space Platforms and Their Relationship to the Space Station Program." Presentation to the NRC Committee on Space Station. May 1987.

NASA. "Space Station Materials Science and Life Science Requirements." Presentation to the National Research Council Committee on Space Station. July 14, 1987.

NASA. "Space Station Program Description Document." March 1984.

NASA. "Space Station Program Support Contract (PSC)" RFP 10-W-0001-7. 1987.

NASA. "Space Station Cost Assessment." February 5, 1987.

NASA. "Status, Space Operations Task Force." July 15, 1987.

NASA, Joint Task Team, National Space Transportation Strategy. "National Space Transportation and Support Study: 1995-2010" (Study Overview). May 1986.

NASA, Life Sciences Division, Office of Space Science and Applications, "Space Station Life Science Research Facility." 1987.

NASA, Office of Aeronautics and Space Technology. "Executive Summary Planning Guide for In-Space Technology Experiments Using the National Space Station Complex." First Edition. 1986.

NASA, Office of Space Flight. "Space Station Support Posture." June 16, 1987.

NASA, Office of Space Flight, Office of Space Station. "Report to the National Research Council on the NASA Space Station Transportation Study." August 3, 1987.

NASA, Office of Space Science and Applications. "Earth System Science: A Program for Global Change." 1986.

NASA, Office of Space Station. "A Space Station Program Plan for Selected Design Parameters: Submitted to the Committees on Appropriations, U.S. House of Representatives, U.S. Senate in Response to Committee Report Language in House Report #99-731." April 1987.

NASA, Office of Space Station. "FY 1988 OMB Budget." September 11, 1986.

NASA, Office of Space Station. "Proceedings of the Space Station Evolution Workshop, Williamsburg, Virginia." September 10-13, 1985.

NASA, Office of Space Station. "Proceedings of the Space Station Evolution Workshop, Williamsburg,Virginia." July 9 - August 1, 1986.

NASA, Office of Space Station. "Space Station: A Man-Tended Approach." Submitted to the Committee on Appropriations House of Representatives and the Committee on Appropriations U.S. Senate. April 1986.

NASA, Office of Space Station. "Space Station Management Plan and Procurement Strategy." December 14, 1984.

NASA, Office of Space Station. The Space Station: A Description of the Configuration Established at the Systems Requirements Review (SRR). June 1986.

NASA, Space Station Program Office. "Ground Test and Verification Program." Briefing to the National Research Council Committee on Space Station. July 31, 1987.

NASA, Office of Space Transportation. "Transportation Alternatives." Presentation to National Research Council Committee on Space Station. August 25, 1987.

NASA, Space Station Program Office. "Space Station Program Integration and Verification." June 1, 1987.

National Commission on Space. Pioneering the Space Frontier: The Report of the National Commission on Space. Bantam Books. May 1986.

National Research Council (NRC), Aeronautics and Space Engineering Board (ASEB). Space Station Engineering and Technology Development. National Academy Press. 1985.

NRC, ASEB. Space Station Engineering and Technology Development, Proceedings of the Panel on In-Space Research and Technology Development, May 21-22, 1985. National Academy Press. 1985.

NRC, ASEB. Space Station Engineering and Technology Development, Proceedings of the Panel on Maintainability. National Academy Press. 1985.

NRC, ASEB. Space Station Engineering & Technology Development, Proceedings of the Panel on Program Performance and Onboard Mission Control, August 6-7, 1985. National Academy Press. 1985.

NRC, ASEB. Space Station Engineering and Technology Development Proceedings of the Panel on Solar Thermodynamics Research and Technology Development, July 31, 1985. National Academy Press. 1985.

NRC, Committee on NASA Scientific and Technological Program Reviews. Assessment of Constraints on Space Shuttle Launch Rates. National Academy Press. April 1983.

NRC, Committee on NASA Science & Technology Program Reviews. Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization. National Academy Press. October 1986.

NRC, Space Applications Board. Remote Sensing of the Earth from Space: A Program in Crisis. National Academy Press. 1985.

NRC, Space Science Board, Committee on Space Biology and Medicine. A Strategy for Space Biology and Medical Science for the 1980s and the 1990s. National Academy Press. 1987.

Nunamaker, Robert R. "Advanced Technology Advisory Committee (ATAC) Progress Report 4." NASA. July 31, 1987.

Ockels, Wubbo J. "The Crew Man's Point of View," Earth-orient. applic. Space Technol., Vol. 6, No. 1, pp. 141-142. Pergamon Journals Ltd. 1986.

Office of Technology Assessment, Congress of the United States. Civilian Space Station and the U.S. Future in Space. November 1984.

Paules, Granville, Peter Lyman, and Carl Shelley. "Briefing to the National Research Council: Summary Results of the Space Station Operations Task Force." NASA. July 15, 1987.

Phillips, General Samuel. "Management Review of Space Station Program." NASA. June 26, 1986.

Piotrowski, William L. and Alan L. Friedlander. "The Role of the Space Station in Solar System Exploration." Presentation at The 37th Congress of the International Astronautical Federation, Innsbruck, Austria. October 4-11, 1986.

Presidential Commission on the Space Shuttle Challenger Accident. Report of the Presidential Commission on the Space Shuttle Challenger Accident. Report to the President. June 6, 1986.

Rau, T.R. "Technical and Management Information System (TMIS)" AIAA-87-2217. Presentation at AIAA/NASA International Symposium on Space Information Systems in the Space Station Era. NASA. June 22-23, 1987.

Ride, Dr. Sally K. Leadership and America's Future in Space: A Report to the Administrator. NASA. August 1987

Romero, James. "In-Space R&T Experiments Program." Presentation to National Research Council Committee on Space Station. NASA, Office of Aeronautics and Space Technology. 1987.

Rose, James. "Space Flight/Space Station Transportation Study (Reducing Dedicated Shuttle Support Flights)." NASA, Space Flight/Space Station Integration Office, NASA, Office of Space Flight. June 18, 1987.

Rose, James. "Space Station Heavy Lift Launch Vehicle Utilization." NASA. July 10, 1987.

Ross, L.J. (Chairman). "Space Station SE&I Task Force Report to Mr. Andrew J. Stofan, Associate Administrator." NASA. October 14, 1986.

Schmoll, Kathryn S. "Microgravity Science and Applications." NASA. 1987.

Stofan, Andrew J. Space Station: The Next Logical Step. Office of Space Station, NASA. 1987.

Stofan, Andrew J. "Space Station Material for AIAA/NASA International Symposium on Space Information Systems in the Space Station Era." Office of Space Station, NASA. June 22, 1987.

Williams, Pete and Dana Hall. "Space Station Information System: Presentation to National Research Council." Space Station Program Office, NASA. June 1, 1987.

Zoller, L.K. "Advanced Solid Rocket Motor (ASRM)." Presentation to the National Research Council Committee on the Space Station. Marshall Space Flight Center. August 25, 1987.