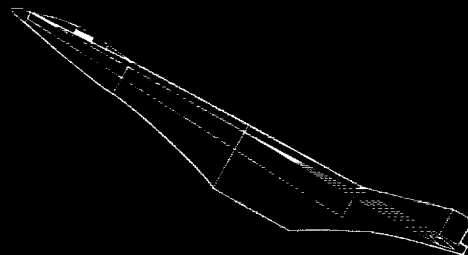
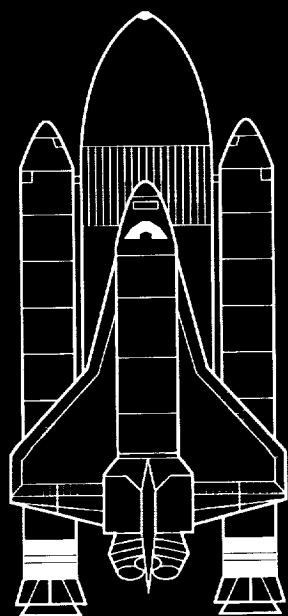


From Earth To Orbit

An Assessment of Transportation Options

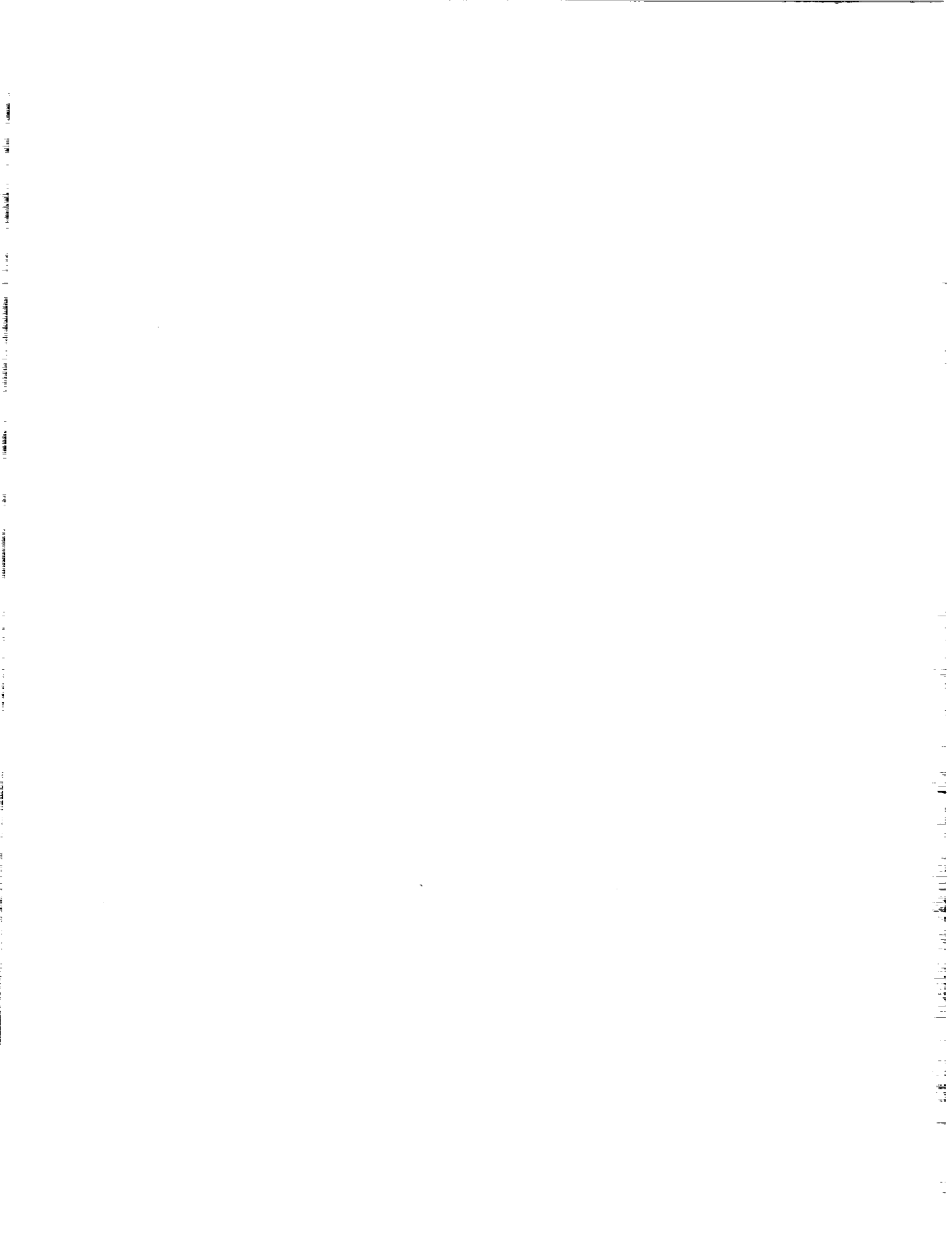


(NASA-CR-192729) FROM EARTH TO
 ORBIT: AN ASSESSMENT OF
 TRANSPORTATION OPTIONS (NAS-NRC)
 103 p

N93-21477

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From Earth to Orbit

An Assessment of Transportation Options

Committee on Earth-to-Orbit Transportation Options
Aeronautics and Space Engineering Board
Commission on Engineering and Technical Systems
National Research Council

National Academy Press
Washington, D.C. 1992

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This study was supported by Contract NASW-4003 between the National Academy of Sciences and the National Aeronautics and Space Administration.

Library of Congress Catalog Card Number 92-60204

International Standard Book Number 0-309-04726-9

Available in limited supply from:

The Aeronautics and Space Engineering Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20008

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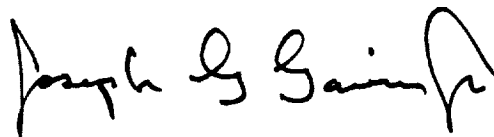
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Preface

The National Research Council (NRC) was asked to make recommendations concerning future Earth-to-orbit transportation options. The following report was prepared during a time in our nation's history when all discretionary spending is undergoing close scrutiny. Thus, a major focus has been on approaches to reduce the costs of access to space while increasing reliability and resiliency. The NRC Committee on Earth-to-Orbit Transportation Options soon found that the most binding constraint to achieving these goals is the way we do business--launch vehicle assembly, payload processing, and launch pad design and availability. These facilities support the highways to space that enable the United States to pursue vital space interests. Like much of the nation's terrestrial infrastructure, they are in a state of obsolescence and disrepair.

A clear imperative also exists to design vehicles and propulsion systems that do not need to be operated at the very limit of their performance. Together, the combination of more robust vehicles and a streamlined infrastructure holds the promise of more routine access to space and the benefits that would accrue in space science, national security, commercial enterprises, and the further exploration of space. This report sets forth the Committee's recommendations regarding the various space transportation options that are available to the United States.



Joseph G. Gavin, Jr., Chairman
Committee on Earth-to-Orbit
Transportation Options

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Summary of Key Findings and Recommendations

The Congressional committees that authorize the activities of the National Aeronautics and Space Administration (NASA) requested that the National Research Council (NRC) assess the requirements, benefits, technological feasibility, and roles of Earth-to-orbit transportation options that could be developed in support of the national space program.

This summary contains the NRC Committee's assessments, principal conclusions, and recommendations that were judged by the Committee to be of highest importance.

LAUNCH VEHICLES AND INFRASTRUCTURE

- **The United States must make a long-term commitment to new infrastructure and launch vehicles.** The United States is now competing with other nations that are able to make long-term commitments to large undertakings in space.¹ In order to meet national needs and be competitive, the United States must find a way to commit to the long term. Multiyear appropriations could be an important step toward this goal.
- **The United States should undertake extensive design of new East and West Coast launch facilities as soon as possible.** Existing facilities are deteriorating and are expensive to operate due to customization for specific vehicles. The construction of the new facilities should be coordinated with the design of a new launch vehicle to achieve the desired improvement in reliability and efficiency while involving fewer people and shorter launch schedules. Preliminary designs and costing are required to demonstrate

¹ See, for example, Sanders, J. November 6, 1991. Memorandum JLS-031-91. United Technologies. Huntsville, Ala.

the feasibility of the various infrastructure proposals. This is an urgent national need and the Committee recognizes that it will take time. A conceptual schedule is suggested in Figure 1, Chapter 4, and Figure 5, Appendix A. The Committee also recognizes there must be a planned transition from the current facilities to the proposed new facilities. During the transition time, it is possible that limited modernization of existing facilities for some of the current vehicles would prove economically useful.

- **The 20,000-pound payload class, National Launch System (NLS-3) vehicle, should be the first of the proposed NLS family to be designed and built in coordination with new launch facilities.** It is the least complex and least expensive member of the NLS family and the one most likely to have possible commercial, as well as national security applications. In addition, based on the projected traffic models presented by the National Aeronautics and Space Administration (NASA), Department of Defense (DoD), and industry, there appear to be requirements for 20 to 30 launches per year, with the greatest potential growth of unmanned launch vehicle traffic suitable for the 20,000-pound class vehicle. Starting the smaller NLS vehicle first will allow more time to refine the requirements for the larger NLS vehicles. Also, the 20,000-pound payload class vehicle would utilize most of the new technologies now contemplated for introduction in the NLS family. Therefore, the Committee believes that developing this vehicle first is of highest priority and will better suit national needs.
- **Investment in improvements for the Space Shuttle Orbiter and its subsystems should be continued.** The Orbiters are complex, sophisticated vehicles and are the heart of the Shuttle system, and as such, critical to human access to space. At present, there are no plans for increasing the size of the four-Orbiter fleet, and the fleet is fully scheduled for many years. Therefore, all Orbiters must be maintained in as effective an operating condition as possible.
- **Reliability should have top priority in the design of new systems, even at the expense of greater up-front costs and lower performance.** The cost of failure in terms of time, money, and national prestige far outweighs the costs of built-in reliability. Improved reliability should be sought for all expendable launch vehicles (ELVs), many of which carry high-value cargo, as well as for manned vehicles.
- **A one-third to one-half reduction in launch and operations costs is required if the United States is to remain competitive in the launch vehicle market.²** This is second

² See also, Carlson, Bob. December 16, 1991. (McDonnell Douglas). "Should-Cost Technologies Required to Make the MELVs World Competitive."

in importance only to reliability. In a market where policy pricing³ is clearly at work, the U.S. government may have to rethink its policies. The United States should look at successful overseas operations to see what can be learned.

PROPULSION

- **Development and qualification of the Space Transportation Main Engine (STME) should proceed immediately and vigorously.** The initial use of the STME is to propel the NLS vehicles, and its development is crucial.
- **Efforts underway to improve the reliability, reduce the cost, and simplify production and refurbishment of the Space Shuttle Main Engine (SSME) should be continued since the nation may need to rely on the Shuttle well into the first decade of the next century.** It is important to pursue both the alternate oxygen and hydrogen pumps under the Alternate Turbopump Program, as well as improve the SSME hot gas ducts and heat exchangers.
- **The growth of a family of vehicles can best be accomplished by using strap-on boosters that, to enhance reliability, would be designed to allow pad hold-down with engine shutdown capability, as well as to be throttleable.** The Committee believes that these capabilities are important characteristics that should be considered in the design of future launch vehicles. Liquid, solid, and hybrid boosters could all be candidates as long as they incorporate these attributes. However, in its discussions, the Committee found a number of considerations that favor liquid as compared to solid propulsion systems. Liquid rocket engines permit a more flexible approach to modular clustering and are amenable to verification before launch. The most compelling characteristic favoring liquids is throttleability and thrust termination capability, which can enable first-stage booster designs to incorporate an engine redundancy capability. Hybrid motors may be able to meet these criteria in the future, but currently the technology is at a very early stage and should be brought to the point where it can be evaluated.
- **A plan is needed to provide an array of engines with a range of thrust levels and propulsion system capabilities for all stages of future launch vehicles.** The proposed STME can be used for first stages of future launch vehicles. In addition, the Rocketdyne F-1A and the current Russian RD-170 engines should be evaluated for liquid booster

³ Policy pricing is based on factors other than standard costs, i.e., policies to achieve larger market share by employing creative financing arrangements or subsidies for various phases of development or production.

applications. Hybrid engine technology should be investigated to determine its suitability for new launch systems. The propulsion system technology for second- and third-stage applications should emphasize low system cost and high reliability as in the initial booster stage. Revival of the Rocketdyne J-2 or upgrading of the Pratt & Whitney RL10 liquid-oxygen/liquid-hydrogen engines could provide upper-stage engines fitting the range of desired propulsion capabilities.

- **In addition to pad hold-down and engine shutdown capability, incorporation of active redundancy for fail-safe capability should be considered in the design of new launch vehicle first stages having multiple engines.** Active redundancy implies the capability of throttling the propulsion system down with all engines operating and throttling up if an engine fails, and may involve the use of an extra engine. The Committee believes that the advantages of this approach are worth the investment for an extra engine and are compelling in view of the costs of vehicle failures, payload loss, and schedule disruption.
- **It is the opinion of the Committee that increased emphasis on propulsion system tests, including the whole propellant feed system, should be a major aspect of any new launch system program.** Increased emphasis is also required in the design phase to include innovative methods to monitor propulsion system health and implement any required shutdowns at appropriate locations.
- **The Committee believes that NASA should rely on the current Redesigned Solid Rocket Motor (RSRM) and that the Advanced Solid Rocket Motor (ASRM) program should be reconsidered.** The current RSRM is capable of meeting all operational requirements of the Space Shuttle. The Committee believes that the balance of costs, technical and programmatic risks, and potential benefits tips in favor of avoiding integration of the ASRM into the Space Shuttle system at this time. Regarding the utility of the ASRM for other future space launch systems, the Committee understands its potential as a strap-on for the heavy payload end of NLS, (i.e., NLS-1); however the Committee has found no compelling rationale for such use other than the fact that it might be introduced in a reasonably short time. The Committee believes that NASA and the nation would be well served if the development of the NLS were directed toward strap-on boosters that have pad hold-down with engine shutdown capability and throttleability as means toward increased reliability.
- **Because of concern over the potential detrimental environmental effects of some launch vehicles, the Committee endorses continuing research to better identify and understand these effects.** Data suggest that pollution due to combustion products from

launch vehicles, at the frequency and scale that is anticipated, is not significant in comparison with other anthropogenic pollution on a global scale. It is, however, a serious local concern in the vicinity of launch test sites and deserves further investigation.

TECHNOLOGY

- **A greater investment in long-term technology must be made to build the technology base for future systems.** Critical, enabling technologies not specifically associated with an ongoing program are chronically underfunded. Underlying research and development provide technical stamina for the future. Today's decisions are hampered by the absence of research and development in the past decade. Specifically, the following areas of technology offer high payoff:

Manufacturing methodology;
Automatic, unmanned docking procedures and methodology;
Modern, miniaturized guidance, navigation, and control;
Propulsion advances;
Propulsion system health monitoring and control; and
Ceramic and intermetallic composite materials.

- **Research and technology development with the goal of developing a new personnel carrier should be continued.** New, enabling technology is needed for Orbiter replacement or a new personnel carrier. The oldest Orbiter will be over 20 years old in the year 2000 and long lead times are necessary for a new, human-rated space vehicle.
- **An investment should be made in demonstrating the technology necessary to validate the engineering practicality of the hybrid rocket motor⁴ for large, high-thrust, strap-on applications.** Hybrid rocket motor development should be advanced to the point that it can be quantitatively evaluated in competition with solid and liquid bipropellant systems designed to directly comparable criteria.
- **The Committee has three specific recommendations in regard to the Delta Clipper (DC-Y) in the Strategic Defense Initiative Organization (SDIO) Single-Stage Rocket Technology Program:** (1) SDIO should continue a vigorous research and development effort directed at adding depth of detail design and analysis; (2) SDIO should examine

⁴ Hybrid motors employ a liquid oxidizer with a solid rocket fuel.

the use of other, already existing engines or engines under development; and (3) SDIO should reconsider the value and timing of the proposed one-third scale model flight tests relative to the more critical need for demonstrating the adequacy of the required low-weight structure and heat protection.

- **The Committee believes that the National Aero-Space Plane (NASP) is a stimulating and productive research and development program and that the materials and air-breathing hypersonic propulsion technologies that have grown out of the NASP program deserve continuing and vigorous support.** The Committee recognizes that the scramjet engines cannot be fully developed on the ground and must be tested in flight. It endorses such flight research as soon as the basic technology development is at a stage to make it worthwhile.

The body of the report covers in some detail the background and reasoning leading to these principal recommendations. Additional recommendations are included in the report. More detailed information is contained in the appendixes.

Terms, Acronyms, and Abbreviations

AFB	Air Force Base
AIAA	American Institute of Aeronautics and Astronautics
ASRM	Advanced Solid Rocket Motor
ATP	Alternate Turbopump Development Program
C ³	command, communications, and control
DC-X	one-third scale model of the DC-Y
DC-Y	McDonnell Douglas Delta Clipper
DoD	Department of Defense
ELV	expendable launch vehicle
ESA	European Space Agency
F-1	U.S. liquid-oxygen/hydrocarbon engine used on the Saturn V launch vehicle during the Apollo program
F-1A	upgraded F-1 engine
GEO	Geosynchronous Earth orbit
GN&C	guidance, navigation, and control
HTPB	hydroxyl-terminated polybutadiene, a solid rocket propellant binder
in	inches
Isp	specific impulse, in seconds
ITL	integration, transfer, and launch
J-2	upper stage U.S. liquid-oxygen/liquid-hydrogen engine used on the Saturn Launch vehicle during the Apollo Program
lb	pound
LEO	Low-Earth orbit
LCC	Launch Control Center
NASA	National Aeronautics and Space Administration
NASP	National Aero-Space Plane
NLS	National Launch System
NLS-1	135,000-pound payload class launch vehicle

NLS-2	50,000-pound payload class launch vehicle
NLS-3	20,000-pound payload class launch vehicle
n. mi.	nautical miles
NRC	National Research Council
P_c	chamber pressure
PBAN	polybutadiene-acrylic acid-acrylonitrile, a solid rocket motor propellant binder
psia	pounds per square inch absolute
RD-170	Soviet liquid-oxygen/hydrocarbon engine
RSRM	Redesigned Solid Rocket Motor
s	seconds
SDIO	Strategic Defense Initiative Office
SEI	Space Exploration Initiative
SL	sea level
SSF	Space Station Freedom
SRM	Solid Rocket Motor
SSME	Space Shuttle Main Engine
SSRT	Single-Stage Rocket Technology Program
SSTO	Single-stage-to-orbit
STME	Space Transportation Main Engine
vac	engine performance in space vacuum
X-30	Experimental NASP vehicle

Introduction

THE TASK

The Committee on Science, Space and Technology of the U.S. House of Representatives and the Committee on Commerce, Science and Transportation of the U.S. Senate requested that the National Research Council (NRC) assess the requirements, benefits, technological feasibility, and roles of Earth-to-orbit transportation systems and options that could be developed in support of future national space programs. The NRC was asked to examine transportation requirements, including those for Mission-to-Planet Earth, Space Station Freedom assembly and operation, human exploration of space, space science missions, and other major civil space missions. These requirements were to be compared with existing, planned, and potential launch capabilities, including expendable launch vehicles (ELVs), the Space Shuttle, the National Launch System (NLS), and new launch options.

In addition, the NRC was asked to examine propulsion systems in the context of various launch vehicles. These included the Advanced Solid Rocket Motor (ASRM), the Redesigned Solid Rocket Motor (RSRM), the Solid Rocket Motor Upgrade (SRMU), the Space Shuttle Main Engine (SSME), the Space Transportation Main Engine (STME), existing expendable launch vehicle engines, and liquid-oxygen/hydrocarbon engines. Consideration was to be given to systems that have been proposed to accomplish the national interests in relatively cost effective ways, with the recognition that safety and reliability contribute to cost-effectiveness. The NRC was also asked to assess, to some degree, related resources, including propulsion test facilities and manufacturing capabilities.

APPROACH

The NRC formed the Committee on Earth-to-Orbit Transportation Options, which met on October 23-24, November 13-16, and December 16-18, 1991; January 22-25 and February 3-4, 1992. The Committee heard extensive briefings by representatives from many government

agencies, industry, and other experts in space transportation issues. These included the National Aeronautics and Space Administration (NASA), Department of Defense, National Space Council, Department of Transportation, Office of Technology Assessment, Department of Energy, American Institute of Aeronautics and Astronautics, independent research organizations, and many representatives from launch vehicle and propulsion companies. During this process, the Committee familiarized itself with launch traffic databases; civil, defense, and commercial mission models, requirements, and cost modeling; the capability, availability, and environmental effects of liquid, hybrid, and solid rocket motors; and various launch systems. These systems included the Space Shuttle and the National Launch System, international systems, recently decommissioned ballistic missiles, and other past and proposed systems. The Committee also reviewed the technological status of proposed concepts such as the National Aero-Space Plane (NASP) and other single-stage-to-orbit concepts.

In addressing its task, the Committee decided that it would be useful first to determine the attributes of an effective national space launch system and its accompanying infrastructure. In subsequent chapters, existing, planned, and proposed vehicle and propulsion systems are evaluated, including the potential roles of non-U.S. systems. Recommendations are presented with supporting arguments. The importance of technology development as an investment in the future cannot be overemphasized, and Chapter 6 examines the Committee's views regarding some technology priorities that could lead to more adequate space launch and infrastructure systems. Because of the intense concern expressed during the study regarding the development of adequate infrastructure (i.e., launch pads and processes) to support modern vehicles, the Committee has devoted Appendix A to a discussion of the major considerations and appropriate design elements for a more efficient and reliable launch infrastructure system.

ECONOMIC ENVIRONMENT

Realizing that the current restrictive budgetary environment may continue into the future, the Committee made every effort in its recommendations to delay expenditures of a noncritical nature and, where possible, to phase in the more critical elements as funding permits. Although no cost or future budgetary estimates have been proposed, the approach taken was to establish the necessary space transportation elements for the nation and to let future funding levels define the progress in achieving this goal. The Committee focused on propulsion capabilities and applications to the first stages of potential launch vehicles, recognizing that upper stages, payloads, a cargo transfer vehicle (CTV), a crew return vehicle (CRV), and eventually replacement for the Orbiter will all place demands on future budgets.

Avoiding the historically uneconomical approach of starting and stopping major programs is crucial to the success of any new programs. Funding will vary, but it will be necessary to maintain the long-term objective of improving space infrastructure and vehicle capabilities (with

adequate supportive research) to permit incorporation of more distant goals such as space exploration.

NATIONAL POLICY CONSIDERATIONS

U.S. space activities are conducted by three separate and distinct sectors: civil, national security, and commercial. In considering Earth-to-orbit launch systems and infrastructure, the Committee took into account national policy objectives, which are to: 1) provide safe and reliable access to, transportation in, and return from space, 2) reduce the costs of space transportation and related services, thus encouraging expanded space activities, 3) exploit the unique attributes of manned and unmanned launch and recovery systems, and 4) encourage, to the maximum extent feasible, the development and growth of U.S. private sector space transportation capabilities which can compete internationally.¹ The national policy objectives apply to all three sectors.²

In the past, the United States had a near monopoly on the commercial space launch business. However, in recent years other nations have placed high priority on acquiring this market. They have developed new launch vehicles, streamlined launch processes, and brought to bear pricing policies that are based on factors other than costs, i.e., they have applied policies to achieve larger market share by employing creative financing arrangements or subsidies for various phases of development or production. The major competitor to the U.S. commercial sector is the French firm, Arianespace, which in 1991 launched 11 out of the 16 commercial satellites that were launched in the world.³ Many of the commercial payloads, such as communications satellites, require equatorial orbits, and Arianespace enjoys an advantage in launching from Guiana Space Center in Kourou, French Guiana. In addition to a close proximity to the equator, this site is sparsely populated with a wide opening on the ocean allowing all inclination missions. In the future, the Japanese, the Chinese, and the former Soviet Union are also potential competitors. Thus, in addition to providing more reliable and less costly launch services, the United States may need to reexamine its own policies regarding innovative financing and various forms of subsidies and support for U.S. industry in order to enable it to compete successfully.

¹ National Space Council. July 10, 1991. National Space Policy. Directive 4.

² National Space Council. February 12, 1991. Memorandum.

³ "Market Trends." February 1992. Arianespace. No. 63.

ACKNOWLEDGMENTS

In addition to the many formal briefings mentioned above, the Committee received valuable input from Admiral Richard H. Truly; Dr. Mark J. Albrecht, Executive Director of the National Space Council; Lt. Gen. Thomas P. Stafford, U.S. Air Force (ret.) and chairman of the report America at the Threshold; and several NASA associate administrators (AAs), including Mr. Arnold D. Aldrich, AA for Space Systems Development; Dr. William D. Lenoir, AA for Operations, Office of Space Flight; and Dr. Michael D. Griffin, AA for Exploration. The Committee would like to thank Mr. Edward A. Gabris and Mr. James Taylor for arranging briefings and responding to Committee requests throughout the study. In addition, Dr. Eugene Sevin served as the Committee's liaison with the Department of Defense and was very helpful in obtaining relevant information and briefings. The Committee also benefitted from the work of numerous previous study groups, and a list of key reports appears in Appendix C. In addition to the many helpful briefings, the Committee requested a large number of written responses concerning various issues and wishes to thank all of the contributors from NASA and its contractors; the Departments of Defense, Transportation, and Energy; individual aerospace companies; and independent research organizations for their cooperation in providing existing information and in researching some of the areas that arose.

A Path to a Desirable National Space Launch System

Current U.S. Earth-to-orbit launch vehicles are based on 25- to 40-year-old technology. The infrastructure to support the vehicles is deteriorating, inefficient, highly specialized, and expensive to operate. Even the Shuttle launch complex, which is the most modern, was adapted from facilities built for the Apollo program.

Many U.S. launchers began as military designs. As a consequence, adaptation became the philosophy for U.S. space launchers. Because many vehicles were never intended for their present role, they often are marginal in meeting their mission requirements. This has produced a tendency to treat each vehicle/payload combination as a custom assembly that must be coaxed into orbit by optimizing and adjusting the available margins, even at the expense of schedule, flexibility, and reliability. Customized payloads, in turn, can easily tie up a launch pad for up to one-half a year, blocking any other vehicle from launching at that site.

With the 1970s decision to channel all launch requirements to the Space Shuttle, advances and improvements that might have been expected in expendable launch vehicle systems were deferred until after the decision was reversed in 1986.

These vehicle and infrastructure shortcomings were largely hidden as long as the United States had a near monopoly on space launch capability, but they have now emerged as severe detriments to the health of the U.S. space launch industry from the perspectives of global competitiveness and the ability to meet national needs. This can be seen in the commercial arena where U.S. launch system manufacturers are losing ground to international competitors, such as Arianespace. **The Committee believes that a one-third to one-half reduction in launch and operations costs is required if the United States is to remain competitive in the launch vehicle market.**¹ This is second in importance only to reliability. In a market where policy pricing is clearly at work, the U.S. government may have to rethink its policies. The

¹ See also, Carlson, Bob. December 16, 1991. (McDonnell Douglas). "Should-Cost Technologies Required to Make the MELVs World Competitive."

United States should look at successful overseas operations such as the French Ariane and former Soviet Union (FSU) programs to see what can be learned.

To ensure the future vitality of the U.S. space program, current facilities must remain functional. Therefore, rebuilding of our complete space launch system should be initiated. However, the nation needs a "clean-sheet" approach rather than being handicapped by trying to completely modify the existing infrastructure to accommodate new vehicles as well as current ones. Modification of existing facilities would not allow a completely new way of doing business that the Committee believes is essential for a new launch system.

The most effective way to initiate the "clean-sheet" approach is through the coordinated development of a new class of launch vehicles that are robust and reliable, along with new processing and launch facilities that are flexible and implement a launch philosophy based on integration, transfer, and launch (ITL),² payload encapsulation,³ and multiuse capability. The key to achieving these objectives is a change in the entire launch culture and philosophy.

Details of the desirable characteristics of a new launch vehicle and its supporting infrastructure, along with the launch philosophy are discussed in the following sections. Additional detail is provided in Appendix A.

SUPPORT FACILITIES AND INFRASTRUCTURE ATTRIBUTES

Space launch vehicles have no utility without adequate terrestrial facilities and processes to enable and control a launch. As noted, the close historical tie between the launch vehicle and the infrastructure supporting it resulted in special-purpose, single-use facilities and systems dedicated to specific vehicles and not available to others. Current processes and payload preparation philosophies require a lengthy time on the launch pad, and in the event of damage or other problems on a pad, rapid recovery is not possible. At times, insurmountable difficulties arise if it is necessary to change from one payload to another, and the small number of available pads for each type of launch vehicle on both the East and West Coasts greatly restricts scheduling flexibility. In addition, most launch facilities are in a deteriorated condition, particularly on the East Coast, and pose the potential for safety problems and schedule slips.

Beneficial effects of a modern system should include a material improvement in the throughput capacity of the U.S. launch infrastructure and better utilization of the costly personnel associated with operation of launch sites. Some of these improvements can be made

² Integration, transfer, and launch (ITL): Vehicle and payloads are assembled, checked out, transferred to the launch pad, and launched without further assembly at the launch pad.

³ Encapsulation: Independent checkout of payload that is later integrated in the vehicle with only a minimum number of standard interfaces.

to existing facilities, but the full benefit will not be achieved until these concepts are applied to a vehicle designed from the beginning to be operated in such an environment.

The United States should undertake extensive design of new East and West Coast launch facilities as soon as possible. Given that U.S. investments inevitably will be spread over many years because of budget pressures, it will be necessary to phase in a modern launch system. Preliminary designs and costing are required to demonstrate the feasibility of the various infrastructure proposals. Replacement of facilities can be implemented over time, and with initial capabilities limited to existing and near-term vehicles and flight rates, and with planned growth for future vehicles as requirements dictate. However, the new facilities must be flexible enough to deal with a range of payloads and launch vehicles, and must take full advantage of the dramatic gains in automation and electronics in recent decades.

The Committee does not expect immediate cost savings from the new methodology. It will require large, up-front investments for such items as launch pads, payload facilities, and modern vehicles. Many of the same checkouts will have to be performed, even though automation and better facilities may reduce personnel needs. The new processes will not apply to all systems immediately; the adjustment will be gradual. The Committee does, however, expect a substantial improvement in the potential launch rate, possibly a several-fold gain, as pads are freed up and as integration is simplified. In the Committee's opinion, no other space-related innovation would offer the country as much of a gain in capability as inexpensively and as quickly. The Committee believes that these changes are necessary and will benefit the competitiveness of the U.S. civil launch industry as well as help meet the needs of the National Aeronautics and Space Administration and the Department of Defense.

LAUNCH VEHICLE AND PAYLOAD ATTRIBUTES

A long-term commitment to a new family of vehicles with many common components and a new, flexible support infrastructure is vital to the U.S. civil and military space program. Through improved design concepts and more effective launch operation procedures, it should be possible to obtain lower costs per pound of payload to low-Earth orbit, to provide competitive services to users, and to effectively meet national needs.

The key elements are reliability, flexibility, operability, robustness, and improved launch turnaround rates as discussed below.

Reliability: Reliability can be improved by incorporating active redundancy⁴ and by not operating at the limit of capabilities. Greater automation in manufacturing, ground

⁴ Also referred to as "engine-out" and "fail-safe" capability.

handling, and checkout can reduce the human errors that have contributed to many processing failures in the past. Higher reliability means not only enhanced safety but also lower costs to the user in the long term. In the commercial market, higher reliability can result in lower payload insurance costs.

Flexibility: The vehicle design should be simple, with standard payload interfaces. It should possess growth capability and have multipad launch capability. Presently, the United States cannot react expediently to national emergencies because of inflexible vehicles, processes, and facilities. Important aspects of flexibility are payload and vehicle compatibility, payload encapsulation, and design modularity.

- *Payload and vehicle compatibility.* The ability to switch payloads rapidly is essential. Under existing systems, each payload and vehicle combination is unique. Designs of most vehicles result in requiring dedication of a specific vehicle to a specific payload very early in the manufacturing cycle for the vehicle. This is especially true for the Titan IV. The lack of modularity of U.S. expendable launch vehicles (ELVs), with the exception of the Delta II and Atlas II with small strap-on solids, severely limits matching of payload performance needs with ELV capabilities.
- *Payload encapsulation.* Little attention is currently being paid to the need for the encapsulation of payloads to facilitate processing at the launch facility. This is not only a payload design consideration, but is also a design consideration for the launch vehicle and the infrastructure.
- *Modularity.* Efficient vehicle production is difficult in an environment of continuing vehicle design changes to match payload needs. A modular approach with standardized elements that could be selected to meet payload needs could yield greater production economies. Costs can be reduced through use of basic modules or elements in assembling vehicles with different performance capabilities.

Operability: Payload changeover constraints, a lack of performance margin, a need for considerable and multiple testing, extensive paper checkoff systems, and a lack of continued, automated health monitoring cause poor operability in current U.S. ELVs. These problems are further compounded by an obsolete launch infrastructure, resulting in an extended amount of time to reschedule flights when payload problems arise, which makes it difficult to schedule future launch opportunities. Being unable to guarantee launch opportunities is a serious detriment to commercial users.

Robustness: The early missiles that evolved into current medium and heavy launch vehicles were designed to optimize performance. Saving weight and maximizing performance have resulted in the current relatively fragile U.S. vehicles, which are susceptible to potential ground handling damage, weather-related launch delays, and unanticipated in-flight failures due to conditions that may only slightly exceed design specifications. Robustness can be built into a vehicle by designing for, and maintaining, excess performance margin. Designing for more extreme environments would reduce holds due to weather and also provide extra margin for unknowns or unsuspected design frailties.

Improved Launch Turnaround Rates: The current approach to installing and processing the payload while the ELV is on the launch pad severely constrains launch pad turnaround rates. An example of this problem may be found in the Titan IV launches from Vandenberg Air Force Base. Only two launches per year are normally planned due to the extended time required for on-pad integration and payload processing. Obviously, this is not an efficient method of launching space vehicles. To provide higher launch rates, both the vehicles and the launch complex should be designed for ITL (integration, transfer, and launch) operations, with off-line integration and processing of the ELV and the payload.

Customization of vehicles results in inefficient learning curves and generally higher system costs. A key element to meeting the above objectives is separation of the payload design from the vehicle design. This may cause some loss in performance because the vehicle is not customized for the payload, but the Committee believes that this cost would be relatively small and would be more than made up in the savings in efficiency, flexibility, and pad access.

Efficiencies in production are difficult to achieve when lack of a long-term commitment makes each year's production appear to be the final production run. Multiyear commitment for production has been shown to reduce costs, and other countries such as France, Japan, Germany, and Italy currently have multiyear funding for their space programs.⁵

As noted, it is essential that the new launch vehicle and the supporting infrastructure proceed in a coordinated fashion. The Committee realizes, however, that the new vehicles and associated launch facilities will not be available for several years. Meanwhile, the United States must deal with current vehicles and existing infrastructure. It is essential that the launch system approach described here be incorporated, to the extent practical, into existing launch facilities and the current family of launch vehicles.

⁵ See, for example, Sanders, J. November 6, 1991. Memorandum JLS-031-91. United Technologies. Huntsville, Ala.

ENGINE ATTRIBUTES

The Committee believes that pad hold-down with engine shutdown capability and active redundancy⁶ are important characteristics that should be considered in the design of future launch vehicles. To implement them, the propulsion system must allow controlled shutdown on the pad and be throttleable.

Experience has shown that the initial few seconds after ignition tend to determine whether a rocket engine will or will not fail. For this reason, a rational way to prevent vehicle failure would be to hold the vehicle on the pad until all systems appear to be in order. In the event of a problem, a controlled shutdown on the pad can be executed, and vehicle and payload can possibly be saved. In this way, the vehicle reliability can be enhanced, although the mission will not be accomplished on time. Pad hold-down, generally for five seconds after ignition, makes it possible in the event of engine failure to shut down all engines and abort the mission on the pad.

Active redundancy requires throttleability and may require the use of an extra engine. Through active redundancy, the launch vehicle could complete its mission following failure of any one engine provided, of course, that the engine failure is benign, (i.e., does not destroy the vehicle). Such capability can be realized only if the remaining engines are capable of being throttled up to produce sufficient thrust to compensate for the lost contribution of the failed engine. The probability of a system failure, in this case meaning the failure of more than one engine, can be greatly diminished by the provision of active redundancy.

This increased reliability is at the expense of increased weight and the cost of the extra engine, but the enhanced reliability offers a reduction of the costs associated with launch failures. These include the cost of replacement of the launch vehicle and its payload, plus the lost utilization of the payload during the time required to reschedule the launch. It is difficult to reach general conclusions about the magnitudes of these costs, but it is probable that for many situations they are at least of the same general magnitude as the added engine costs.

The feasibility of active redundancy for liquid-fueled vehicles is strongly supported by a study⁷ which showed that a large fraction of liquid engine-system failures was noncatastrophic in the sense that the engine failure resulted in loss of thrust, but not in immediate destruction of the vehicle. For both ground and flight engines, the benign failure ratio (failures/engine flights) for liquid-oxygen/liquid-hydrogen propulsion systems is two percent, with no catastrophic failures. For other liquid systems (liquid-oxygen/hydrocarbons and hypergolics) the benign failure ratio is six-tenths of a percent and the catastrophic failure ratio is two-tenths of

⁶ Also referred to as "engine-out" and "fail-safe" capability.

⁷ Leonard, B.P. 1991. Projected Launch Vehicle Failure Probabilities With and Without Engine Segment-out Capabilities. L-Systems, Inc. El Segundo, Calif.

a percent. While the number of both large and small solid rocket flight motor failures is small, they have all been catastrophic, rather than benign failures.⁸

Reliability should have top priority in the design of new systems, even at the expense of greater up-front costs and lower performance. The cost of failure in terms of time, money, and national prestige far outweighs the costs of built-in reliability. Improved reliability should be sought for all expendable launch vehicles (ELVs), many of which carry high-value cargo, as well as for manned vehicles.

The Committee believes that the advantages of enhanced reliability are significant and strongly recommends a careful evaluation of the advisability of including pad hold-down with engine shutdown capability and active redundancy in the first stage of the next generation of launch vehicles. Implementation in the upper stage is more problematic, but should be considered for specific systems where the costs and benefits can be quantified.

It should be noted that active redundancy is useful only for multiengine vehicles. For vehicles with a single engine and relatively small, low-cost payloads, other ways of improving reliability should be pursued, such as greater design margins, reduced performance requirements, more extensive system-level testing, and pad hold-down with engine shutdown capability at launch.

⁸ Smith, O. Glenn. 1991. Reliability in Manned Transportation Systems. Johnson Space Center. Houston, Tex.

Projected Launch Requirements

NEAR-TERM REQUIREMENTS

Both civil and military space system developers have relied mainly on the existing U.S. spectrum of expendable launch vehicles and the Space Shuttle. Consequently, space payloads fall into weight classes that generally span the performance bands of these systems. Since there are no firm plans that are not satisfied by the performance of existing launch systems, the prospective launch system and propulsion system developer must rely on speculative projections of potential future users as opposed to firm plans and requirements to define the performance goals of a new system. Thus, a new family of launch vehicles must be capable of satisfying currently identifiable demands as well as potential future demands. This is the only way that transition to a new family of vehicles can be ensured, especially within a framework of international competition.

History has shown that over the past 20 years the average number of U.S. expendable vehicles launched has been relatively constant and in the range of approximately 20 per year. All other nations of the world outside of the former Soviet Union (FSU) have contributed approximately 12 payloads per year. The FSU averaged about 110 launches per year, but launch frequency and payload lift requirements in the future by the new Commonwealth of Independent States are uncertain.

The Committee has reviewed U.S. launch user plans through 1997 and finds that the current firm plans are consistent with historical experience. About 19 expendable launches and 7 Shuttle launches per year are planned for the next five years. In the constrained budget environments of the foreseeable future, it is probable that only a few more than 26 routine U.S. space launches per year might be required well into the next decade as shown in Table 1.

Table 1 summarizes the Committee's judgement concerning likely launch traffic in the traditional payload classes of launch systems based on data obtained from NASA, DoD, and industry. The Committee examined DoD estimates, NASA estimates, a study by Berner, Lanphier and Associates, and an industry analysis of payload sizes and requirements for the 1990s and the first decades of the next century. For the size payloads applicable to a 20,000-

pound payload class vehicle, the above data indicate an average of 17 launches per year, a number greater than any estimates for heavier lift launch vehicles. In view of the fact that it is not currently possible to be sure that these payloads will all be funded, in light of recent international developments leading to a reduction in the DoD budget, and recognizing that past studies have used mission requirements later shown to be overly optimistic, the Committee discounted the payload traffic to a level more consistent with current experience (Table 1). However, if this estimate proves too conservative, the Committee believes, from examination of the various payload estimates, that the majority of the increased traffic will occur in a weight range compatible with a 20,000-pound payload class vehicle. For example, the recent World Administrative Radio Conference (WARC) meetings resulted in an agreement to allocate additional spectrum for fixed satellite services and communications satellites. This may increase the launch demand for satellites, such as those for mobile telecommunications, high quality radio transmission, and data messaging, which would be of appropriate size for a 20,000-pound payload class vehicle.

INTERMEDIATE-TERM REQUIREMENTS

From 1998 to 2005, the NASA plans three major programs that will require additional launches over and above those routinely needed in the past. These are Space Station Freedom (SSF), Mission to Planet Earth, and the Space Exploration Initiative (SEI). During the construction phase and early man-tended SSF operations, an additional three Space Shuttle flights per year will be required. Likely unmanned precursor missions to the moon and Mars by the SEI program during this eight-year period could require additional expendable launch vehicle (ELV) launches, probably involving medium or heavy (Titan-class) capability. Although these missions are more speculative, there could be as many as one or perhaps two additional launches each year required on average in the intermediate term.

The major SEI thrusts announced by President Bush include a permanently manned outpost on the moon and manned exploration of Mars. These missions will require new heavy lift launch capabilities that do not presently exist. SEI constitutes the only recognized U.S. requirement for lifting large masses to low-Earth orbit (LEO) that exceeds the weight-lifting capabilities of current U.S. launch vehicles. SEI will define the performance baseline for a future heavy lift vehicle. Although rather speculative because of near-term budget constraints, some early transport of large masses to the moon's surface could occur before 2005.

The Committee also observed that a new trend toward less expensive, lightweight satellites operating in LEO, which support civil cellular communications, tactical military communications, and other defense applications, could produce additional traffic in the 2,000-pound-or-less payload class during this intermediate period. Currently, a fledgling, venture-

TABLE 1 Conservative Projection of Traffic Requirements

Payload Class	Flights per year		
	Near Term (1992-1997)	Intermediate Term (1998 - 2005)	Long Term (> 2005)
Light (<4,000 lb to LEO)	3	4	5
Medium (4,000-20,000 lb)	9	10	12
Heavy (20,000-50,000 lb)	7 Shuttle flights and 7 unmanned flights	10 Shuttle flights ^a and 7 unmanned flights	7 Shuttle flights and 2 unmanned flights
Very Heavy (> 50,000 lb)	0	0	2
Total Flights Per Year	26	31	28

^a Includes SSF deployment.

SOURCES:

- (1) Angell, John. October 23, 1991. (Department of Defense). "Space Launch Operations."
- (2) Aldrich, Arnold. January 24, 1992. (NASA Headquarters). "Mission Model of Legislative Strategy."
- (3) Berner, Steven. December 16, 1991. (Berner, Lanphier and Associates). "Assessment of Commercial U.S. and Foreign Space Industries."
- (4) Carlson, Bob. December 16, 1991. (McDonnell Douglas). "Should-Cost Technologies Required to Make the MELVs World Competitive."
- (5) Marcus, Daniel J. March 2-8, 1992. "Slow Progress at WARC." Space News. Vol. 3, No. 8.
- (6) Marcus, Daniel J. March 9-15, 1992. "Delegates Bestow Mobile Market." Space News, Vol. 3, No. 9.

capital-financed commercial space launch industry is growing in response to this potential demand.

LONG-TERM REQUIREMENTS

In the period beyond 2005, projected national launch needs are speculative. Only SEI and perhaps a space element of a strategic missile defense system (an outgrowth of the Strategic Defense Initiative) may specify heavier lift requirements for space launch in the 135,000- to 600,000-pound to LEO range.

In addition, routine support of SSF during its continuously manned operational phase may require as many as six service missions per year, including two or three missions that transfer personnel in a man-rated launch vehicle.

It should be noted that if the United States dramatically improves the reliability and costs of launch services, it may secure a large share of the worldwide commercial launch business. In that event, the Committee's estimates could prove to be very conservative.

Launch Vehicle Options

The Committee examined existing, planned, and potential launch capabilities, including expendable and manned U.S. and international launch vehicles as well a large number of conceptual designs. Only the vehicles that the Committee judged most important are discussed in detail.

CURRENT U.S. EXPENDABLE LAUNCH SYSTEMS

Current U.S. expendable launch vehicles (ELVs) can be categorized as small-, medium-, or heavy-lift vehicles, as shown in Table 2. Although this assortment of expendable vehicles can satisfy most near-term U.S. national and commercial needs, with small modification as necessary, most of the small and all of the medium and heavy launch vehicle systems date back to the 1950s and early 1960s. Their design philosophy dates from an era of maximizing performance capability at the expense of operability. As a consequence, the current vehicles lack flexibility, operability, modularity, and robustness. Further, they do not incorporate payload encapsulation and are not cost-effective. For this reason, the current U.S. space launch program is constrained and limited in today's highly competitive space market. Evidence of the declining U.S. capabilities in commercial space launches is readily apparent by the trend of commercial satellites toward launches on foreign boosters, brought about by increased capability, better scheduling, and lower cost.

PROPOSED U.S. LAUNCH SYSTEMS

In accordance with National Space Policy, the Committee believes that there is both an opportunity and a necessity for the United States to embark on the creation of a new family of

TABLE 2 Current and Proposed U.S. Launch Vehicles

Performance Range	Launch Vehicle	Payload Lift Capability to 100 n. mi. at 28.5° (lb) ¹	Gross Lift-Off (lb)	First Launch Year (actual or planned)
Small (<4,000 lb to LEO)	Scout I	560 at 38°	48,000	1979
	Scout II	1,000 at 38°	110,000	Exact date uncertain
	Pegasus	1,000	42,000	1990
	Taurus	3,200	180,000	1992
	Delta II (7920)	11,100	506,000	1990
Medium (4,000-30,000 lb)	Atlas II	14,100	413,500	1991
	Atlas IIA	14,900	414,000	1991
	Atlas II AS	18,500	516,000	1993
	Titan II SLV (no strap-ons)	4,200 at 90°	340,000	1988
	Titan II SLV (up to 10 strap-ons)	8,200 at 90°	Not available	Exact date uncertain
Heavy (30,000-60,000 lb)	Titan III	32,000	1,500,000	1989 (commercial)
	Titan IV (SRM)	39,000	1,900,000	1989
	Titan IV (SRMU)	48,000	Not available	1993
	Shuttle	51,800	4,500,000	1981

SOURCES: Isakowitz, Steven J. 1991. International Reference Guide to Space Launch Systems. American Institute of Aeronautics and Astronautics (AIAA); and manufacturers data sheets.

¹ In general, the inclination represents the latitude of the launch facilities with the exception of launches out of Vandenberg AFB that are intended for polar orbit. However, if a higher orbital inclination is required, then the payload lift capability is decreased since more propellant is necessary to achieve the desired orbit due to the loss of the velocity component from the Earth's rotation.

launch vehicles together with a fully integrated complex of associated ground facilities. Given the advances in engineering science and technology (especially in avionics) during the last quarter-century, systems having significantly enhanced economy, reliability, efficiency of operation, and performance can be designed and built. Development of the new launch vehicles could help revitalize the private sector and allow it to meet the severe challenge of foreign competition for commercial space launches. Equally important, this program could stimulate the basic and applied space technology research that is crucial for the continued vitality of a U.S. role in space.

National Launch System (NLS)

The National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) have begun work on a new family of launch vehicles, the National Launch System, which is sometimes referred to as the New Launch System. The proposed National Launch System was conceived to implement national space policy,¹ which is discussed in Chapter 1.

The NLS concept consists of a family of vehicles with various payload capabilities. NASA and DoD plan to construct the supporting infrastructure and the vehicles in a coordinated fashion, while incorporating a design philosophy that emphasizes reliability and operational efficiency rather than maximum performance. Common components and subsystems will reduce development and manufacturing costs, and streamlined operating procedures will reduce the launch turnaround time. The Committee supports the new system and encourages this approach while discouraging the nation from continuing the old way of doing business.

The NLS Joint Program estimates development costs of \$11.5 billion for a first launch in 2002. This estimate includes system design and integration, the Space Transportation Main Engine, development of three launch vehicles, a cargo transfer vehicle, an upper stage, and manufacturing and launch facilities.

The current NLS concept consists of three vehicles: (1) the NLS-1, a 135,000-pound payload class vehicle that will utilize a new core design, four STMEs, and strap-on boosters; (2) the NLS-2, a 50,000-pound payload class vehicle that will use six STMEs, but no strap-on boosters; and (3) the NLS-3, a 20,000-pound payload class vehicle that uses the STME, no strap-on boosters, and other equipment such as the guidance and control systems common to the NLS-1 and the NLS-2. While the specific vehicle configurations are still evolving, NASA and DoD currently plan to develop the core vehicle and launch the 135,000-pound payload class NLS-1 in 2002, to launch the 50,000 pound payload class NLS-2 vehicle next, and to bring the

¹ National Space Council. July 10, 1991. National Space Policy Directive 4.

20,000-pound payload class NLS-3 vehicle to initial operation within two years after NLS-2. Redesigned Solid Rocket Motors (RSRMs) or the Advanced Solid Rocket Motors (ASRMs) will be used to augment thrust on the 135,000-pound payload class NLS-1 core vehicle. It is anticipated that the NLS-1 could be used to deliver payload to Space Station Freedom (SSF). However, firm requirements for this largest vehicle were not apparent to the Committee. In addition, it is the most complex and expensive member of the NLS family.

The Committee believes that the 20,000-pound payload class vehicle (NLS-3) should be the first of the proposed NLS family to be designed and built in coordination with new launch facilities. Plans for NLS-2 and NLS-1 should be pursued as funding becomes available. Lessons learned from the NLS-3 system design may influence the final design approach taken on the more ambitious, larger-scale NLS-2 and NLS-1. In addition, the NLS-3 is the least complex and least expensive member of the NLS family, and the one most likely to have potential commercial, as well as national security applications. An analysis of mission requirements presented by NASA, DoD, and the commercial sector (Table 1) shows that there appear to be requirements for 20-30 launches per year, with the greatest potential growth of unmanned launch vehicle traffic suited for the 20,000-pound class vehicle.

Since the Air Force has recently committed to using the Titan IV (40,000-pound payload category) by procurement of 41 new vehicles with a purchase of 10 additional vehicles (with an option for another 22 vehicles planned), there is no immediate need for a new vehicle in the 50,000-pound payload class. Thus, the Committee believes that building the NLS-3 vehicle first is of highest priority and would better suit national needs. The 20,000-pound payload class vehicle (NLS-3) would utilize many of the new technologies now contemplated for introduction to the NLS family. Starting the smaller NLS vehicle first will allow more time to refine the requirements for the larger NLS vehicles.

Figure 1 shows a conceptual National Launch System schedule as compiled by the Committee. The schedule shows the priorities of the Committee and is based on plans and projections from several government agencies that were presented to the Committee during the study. The Committee explored possible sequencing of events to avoid unacceptable major funding aggregation in any one year.

In examining possible timing for the NLS vehicles, a question arises concerning the feasibility of designing the first stage to be partially or wholly recoverable. The Committee did not have the time or means to evaluate the potential for this design direction. There will be time, however, in the NLS program to permit concepts of this nature to be explored prior to committing the configurations of NLS-2 or NLS-1 to detailed design and construction.

The Committee believes that there will be future requirements for heavy lift capability to serve the Space Exploration Initiative, but that it is too early to determine the specific performance criteria that will dictate heavy lift design approaches. Early reconnaissance science programs should be planned with the currently available ELVs augmented by NLS-1 to NLS-3, as they become available.

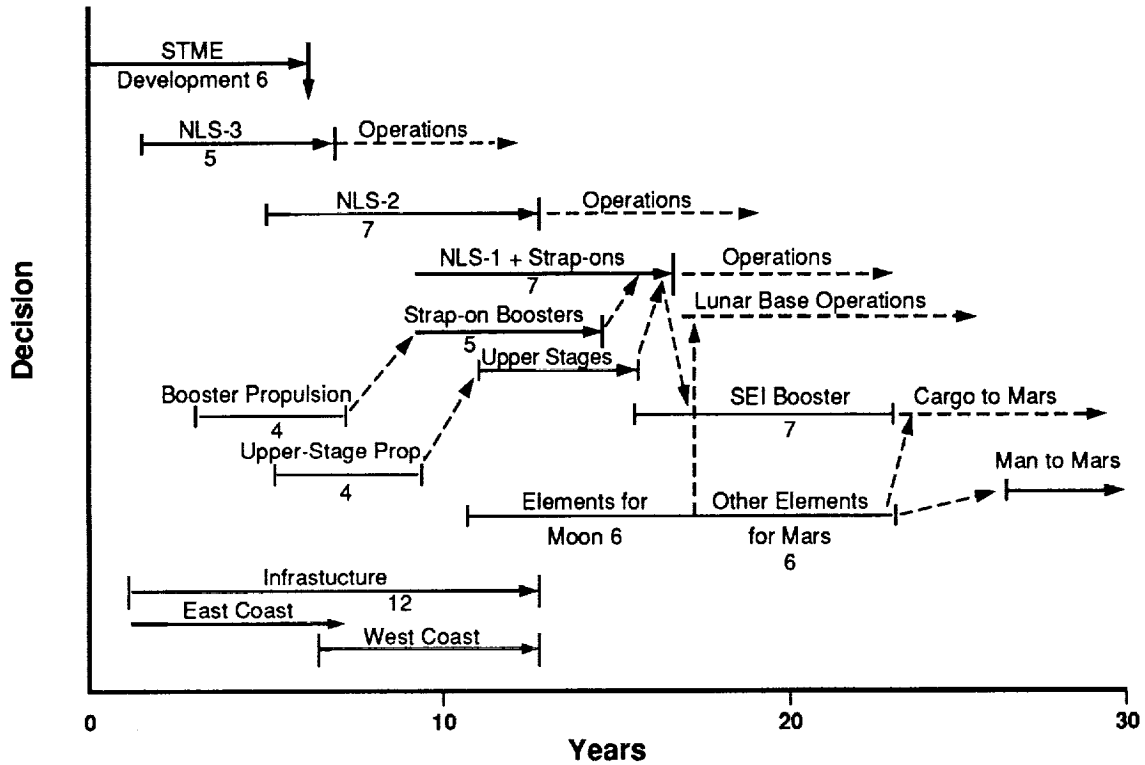


FIGURE 1 Conceptual priority schedule for the National Launch System (NLS).

Although the concept of a family of vehicles with common cores and engines is frequently mentioned, the Committee believes that actual construction and operation are more difficult. **The various vehicles should be designed for optimal operability and reliability, and the family relationship could and should be maintained more at the subsystem and component levels.** The Committee recognizes that such a course of action would represent a departure from the postulated family resemblance of the NLS series and believes that the reality of producing vehicles could be considerably different from the design concepts presented.

Taurus

Taurus is a new expendable launch vehicle under development and with a firm order for 1992 delivery to the Defense Advanced Research Projects Agency (DARPA). It is a derivative of the novel Orbital Sciences Corporation air-launched space vehicle called Pegasus. It incorporates the three Pegasus stages slightly modified for a heavier payload and ground launch. The vehicle is boosted from the Earth by a first stage Peacekeeper booster. The performance goals of this system are shown in Table 2.

Medium Launch Vehicle III (MLV III)

The Committee is aware of a current Air Force competition, the Medium Launch Vehicle III (MLV III), which is aimed primarily at the 12,000- to 15,000-pound payload class for launch of the second block of the Global Positioning Satellite System (GPS). This competition has limited application, and the Committee did not review the specific vehicle proposals, which are proprietary at this stage.

CURRENT U.S. MANNED SYSTEMS

The Space Shuttle

The Space Shuttle is the only U.S. system that provides human access to orbit. It currently consists of the Orbiter, external tank, and two RSRMs.

The Space Shuttle, in spite of its need for continued upgrading, remains a unique capability for round-trip transportation to Earth orbit and is likely to remain so well into the first decade of the next century. Therefore, the viability of our manned space program depends critically on the maintenance, refurbishment, and upgrading of the Shuttle system over the coming years. It is important to recognize that obsolescence or decay of any element of the Shuttle system will lead to safety problems, schedule slips, and unexpected cost increases.

As emphasized elsewhere in this report, the launch infrastructure exerts a controlling influence on overall launch costs, and careful consideration should be given to systematic infrastructure improvements.

The Orbiters are complex and sophisticated vehicles and are the heart of the Shuttle system, and as such, critical to human access to space. At present, there are no plans for increasing the size of the four-Orbiter fleet, and the fleet is fully scheduled for many years, so all Orbiters must be maintained in as effective an operating condition as possible. In addition to maintenance and refurbishment, several upgrades of the Orbiters have been proposed, and

some have been initiated. Among the most critical of these are improved turbopumps for the Space Shuttle Main Engine (SSME). **The Committee endorses these changes and recommends that they be incorporated into the entire fleet of Orbiters, as practical.** As other opportunities for improvements develop, they too should be implemented if they promise significant benefits in operability or reliability. Although the Committee understands that the changes will be expensive, it believes that the cost will be insignificant compared to that of another Shuttle loss. **Investment in improvements for the Space Shuttle Orbiter and its subsystems should be continued.**

New, enabling technology is needed for Orbiter replacement or a new personnel carrier. The oldest Orbiter will be over 20 years old in the year 2000 and long lead times are necessary for a new, human-rated space vehicle. **Therefore, research and technology development with the goal of developing a new personnel carrier should be continued.**

PROPOSED U.S. MANNED SYSTEMS

Currently, the United States has no approved programs for producing new operational manned launch capabilities. However, there are two programs in advanced development to explore the technical feasibility of reusable single-stage-to-orbit (SSTO) vehicles. Each program has the potential to include manned operation. They are the Single-Stage Rocket Technology Program (Delta Clipper, DC-Y) supported by the Strategic Defense Initiative Office (SDIO) and the National Aero-Space Plane Program (NASP), jointly supported by DoD and NASA.

Studies are also underway to explore the vehicle options for assured crew return from Space Station Freedom. Although assessment of the specific crew return vehicle designs is not within the scope of this study, it is of concern to the Committee because of the potential impact on the Earth-to-orbit requirements necessary to place the vehicle at Space Station Freedom.

The Single-Stage Rocket Technology Program Delta Clipper (DC-Y)

The McDonnell Douglas Delta Clipper (DC-Y) was recently selected in the SDIO Single-Stage Rocket Technology Program (SSRT) as the most promising concept of a reusable single-stage-to-orbit vehicle. The proposed vehicle is envisioned to provide 20,000 pounds of payload into a low-Earth orbit with low recurring costs, operational flexibility, and a rapid turnaround time.

Unfortunately, all of these desirable attributes require changes that increase inert and propellant weights--weights that, in single-stage vehicles, directly (i.e., pound for pound) reduce the payload. Therefore, to be useful, a reusable, single-stage vehicle must represent a compromise between the desirable properties and the size of the payload. In the Committee's

opinion, the DC-Y represents a promising and logical approach to the realization of such an objective.

The design makes maximum use of existing materials. Only when absolutely necessary, will they be replaced with high-performance, lightweight composites, and advanced metallic or efficient metallic/nonmetallic insulation systems. Some of these materials have been, or are being, developed by the NASP program and promise higher strength and longer life at elevated operating temperatures. However, it should be noted that only limited data are available on the materials properties and that the structures and materials represent a crucial area of uncertainty that may well determine whether a single-stage-to-orbit vehicle with sufficiently low empty weight could be built in the next few years. **Thus, the Committee recommends that, as a first priority, the SDIO concentrate on developing information on properties, joining, and fabrication of new materials to allow a confident (e.g., using aircraft safety factors) design of the DC-Y.**

As originally conceived, the DC-Y was to use a novel modular plug engine² that appeared especially well suited to a single-stage-to-orbit vehicle. Unfortunately, technical immaturity, as well as the high risk associated with the development of such an unconventional device, prompted a change to a still-undeveloped but more conventional modular bell engine.³ Although development of the bell engine is likely to take less time and cost much less than the development of the modular plug engine, it is not as neatly congruent with the DC-Y and may create some drag and heat transfer problems. The Committee also notes that instead of a new modular bell engine, it may be possible to use other engines. **Consequently, the Committee recommends that the SDIO consider reducing the projected engine development costs by seriously examining the possible use of other engines.**

In 1993, the SDIO plans to conduct suborbital test flights of a one-third scale model (DC-X) propelled by modified RL10 engines. The purpose of these suborbital flights is to demonstrate safe return to the launch site and to provide information on the aerodynamic interactions between the engines and the vehicle. The model may also indicate some of the control problems that are likely to be caused by crosswinds during transition from lifting reentry to, and during, thrust braking. In addition, data on time involved in turnaround and maintenance will also be sought. However, because of scaling and lower gross weight, these flights are not likely to simulate the conditions that the full-size DC-Y will experience upon reentry. Thus, because the reentry conditions will not be simulated properly, these tests cannot be expected to yield a good indication of the adequacy of the structure and its heat protection system. In addition, since the RL10 engines are different from the modular bell engine that is still to be developed, even the information on operation and maintenance problems may be distorted. It

² This engine is described more fully in Chapter 6.

³ This engine is described more fully in Chapter 6.

is, thus, doubtful that the suborbital flight program will appreciably reduce the risks and shorten the time of the DC-Y development. **Therefore, the Committee believes that the SDIO should reconsider the value of the DC-X flight tests, relative to the more critical need for demonstration of the adequacy of the proposed low-weight structures and heat protection systems.**

The Committee believes that the use of a lifting body for a reusable single-stage-to-orbit vehicle holds promise and may eventually lead to reduced launch costs, short turnaround time, and operational flexibility. However, the DC-Y has not yet reached the stage at which it can be considered for Earth-to-orbit transportation.

National Aero-Space Plane

The National Aero-Space Plane (NASP) is a research program that focuses on the technologies needed for a manned, experimental vehicle designated the X-30. The NASP is envisioned to be fully reusable, designed for aircraft-like takeoff and landing, and capable of reaching orbital speeds. Its propulsive systems are to be largely air-breathing, consisting of combined ramjet-scrumjet engines fueled by slush hydrogen (a denser form of liquid hydrogen). Should the development proceed on schedule, the decision whether to start building the X-30 experimental vehicle will be made in 1993.

The purpose of the program was defined in a July 1989 National Space Council memorandum⁴: (1) to explore the limits of air-breathing propulsion; (2) to obtain aerodynamic and other data within the hypersonic flight regime; (3) to develop technologies that would enable new hypersonic vehicles; and (4) to demonstrate Earth-to-orbit ascent and rapid turnaround.

To meet its objectives, the NASP program is following a flexible philosophy of design and manufacturing that embodies current engineering materials and their applications while permitting, when necessary, the incremental introduction of new materials and techniques. In particular, the program is proceeding with the development of composites, ceramics, and intermetallic matrices reinforced by ceramic fibers, which should be useful for elevated-temperature applications and may reduce weight. However, the new materials require rigorous testing to determine their physical properties before they can be used in the analysis, design, and fabrication of the X-30 vehicle.

The NASP program has also been developing and making extensive use of new computational techniques as well as experiments to assist in the design analyses. The use of computers as a tool depends on the ability to confirm the validity of the models, which can be done only by extensive experimental testing prior to flight. However, complete engine testing

⁴ National Space Council. July 20, 1989. Memorandum.

is impossible, because the facilities needed for such a task would require impractically high amounts of energy. Consequently, the X-30 will have to begin its flight testing with the scramjet engine not fully proven. This puts very special demands on the X-30 because, during testing of the air-breathing engines, the vehicle will need an additional propulsive system (probably a rocket) to place the engines in proper test conditions and also serve as a backup should the air-breathing engines fail. **The Committee recognizes that the scramjet engines cannot be fully developed on the ground and must be tested in flight. It endorses such flight research as soon as the basic technology development is at a stage to make it most worthwhile.**

It should be apparent from the above discussion that the X-30 will not be easily convertible into an operational NASP vehicle capable of providing low-cost aircraft-like transportation from Earth to orbit. Even if the X-30 were to meet its current schedule and be completely successful, a new, separate development program would be needed for an X-30-derived NASP vehicle that could become a part of our Earth-to-orbit transportation system. In view of the very high risks inherent in this concept and the long time that is likely to be required to overcome them, the Committee decided to exclude the NASP from consideration as a viable option for currently foreseeable Earth-to-orbit transportation. Nevertheless, the Committee considers the NASP a stimulating and productive research and development program. **The development of materials technology and of air-breathing hypersonic propulsion deserves continuing and vigorous support.** In addition, applications of the NASP-derived technology should be considered in cruise vehicles, as well as SSTO vehicles.

Assured Crew Return Capability

Vehicle options for crew return capabilities during the permanently manned phase of the Space Station are currently being investigated. During extended stays on Space Station Freedom, it will be necessary to provide assured crew return capability in case of medical emergencies or other difficulties that require evacuation of the Station. As stated earlier, although the assessment of the crew return vehicle is not within the scope of the current study, it is of concern to the Committee because of the potential impact on the Earth-to-orbit transportation requirements to place the return vehicle at Space Station Freedom.

Currently, studies are underway to examine various crew return options. Three types of vehicles are being considered. One is a reentry-type vehicle, estimated to weigh 12,500 pounds, which can be launched on the Shuttle or by an expendable launch vehicle. Preliminary studies of this concept are underway by two teams, one led by Rockwell, the other by Lockheed. These studies should be completed in one year, at which time a selection will be made. The program is expected to cost between \$1 billion and \$3 billion, and should be completed by the year 2000.

A second concept involves the use of the Russian Soyuz vehicle. Studies are being made by NASA to investigate the possibility and feasibility of this option.

A third, more ambitious concept, is a mini-shuttle or personnel launch system with two-way capability, configured to ensure a runway landing at a selected site. This is now only in the conceptual stages as an in-house NASA study.

In the Committee's view, the requirement for assured crew return from the Space Station poses no launch vehicle requirements that are outside the capabilities of systems planned for other purposes.

EXISTING INTERNATIONAL LAUNCH SYSTEMS

International launch systems are shown in Table 3. Most of the international vehicles possess payload capabilities that are in the small to medium payload class range (up to 40,000 pounds).

Until the 1980s, the United States had negligible international competition for commercial space transportation and considered its commercial capabilities a spin-off of national space requirements. In recent years, foreign space activities have increased to the point where the majority of worldwide commercial traffic has gone overseas. Although the largest segment of commercial traffic has currently gone to the Ariane, a number of additional foreign competitors are now or soon will be entering in this market. From Table 3, which summarizes some of the most important competition, it is apparent that the primary contender for commercial traffic (in the medium 8,000- to 25,000-pound payload range) is the Ariane-4. Japan and China promise to be stronger contenders in the near future.

For the heavy lift market (40,000 pounds and up), Europe and even the newly formed Commonwealth of Independent States are primary contenders. If lunar and Mars exploration missions are planned, then the former Soviet Union's Energia may be capable of supporting such missions. Table 3 provides an indication of how the international competition for commercial space traffic in the medium and possibly heavier payload ranges is growing. **If the United States is to remain a player in the commercial arena, it is clear that it must enhance its space transportation capabilities.**

Energia

The largest Soviet-developed launch vehicle, Energia, was first launched in 1987. It has a core structure with liquid-oxygen/liquid-hydrogen engines and four liquid-oxygen/hydrocarbon strap-ons, resulting in 7.8 million pounds of takeoff thrust, capable of placing 194,000 pounds of cargo payload in low-Earth orbit, or 66,000 pounds when the reusable Buran (similar to the

TABLE 3 International Launch Systems

Origin	Launch Vehicle	Payload Lift Capability		Gross liftoff (lb)	First Launch Year (actual or planned)
		(lb)	n. mi. at inclination		
Europe	Ariane-4 (40)	10,800	100 at 5.2°	529,000	1988
	Ariane-4 (42P)	13,400	100 at 5.2°	747,000	1988
	Ariane-4 (44L)	21,100	100 at 5.2°	1,040,000	1989
	Ariane-5	39,600	300 at 5.2°	1,570,000	1995
	Ariane-5/ Hermes	48,500	50 x 250 at 5.2°	Not available	2002
China	Long March (CZ-2C)	7,040	108 at 28.2°	421,000	1975
	Long March (CZ-2E)	20,300	108 at 28.2°	1,023,000	1990
India	ASLV	330	216 at 43°	86,000	1987
	PSLV	6,600	216 at 43°	606,000	1992
Israel	Shavit	350	100 at 43°	Not available	1988
Japan	H-1	7,000	100 at 30.2°	308,000	1986
	H-2	23,000	100 at 30.2°	582,000	1993
USSR	Zenit-2	30,300	108 at 51.6°	1,012,000	1985
	Proton	44,100	100 at 51.6°	1,550,000	1967
	Energia	194,000	108 at 51.6°	5,300,000	1987

SOURCES: Isakowitz, Steven J. 1991. International Reference Guide to Space Launch Systems. AIAA; and manufacturers data sheets.

U.S. Orbiter) is carried. The strap-on boosters are powered by the RD-170 engines discussed in Chapter 5.

Zenit

The Zenit intermediate-size Soviet launch vehicle was first launched in 1985. It can be used as a two- or three-stage vehicle and is expected to supplant earlier launch vehicles such as Soyuz for both unmanned and manned missions. The first stage is essentially identical to the Energia strap-on boosters; it is powered with the same RD-170 engine. With an approximate capability of 30,000 pounds into low-Earth orbit, it has some potential in the commercial market.

Ariane

The Ariane launch system is a family of vehicles that was designed primarily to launch European satellites. Development work for Ariane-4 began in 1982 and the first launch occurred in 1988. There have been more than 15 launches of the Ariane-4 and it is rapidly taking over the commercial market.

PROPOSED INTERNATIONAL LAUNCH SYSTEMS

Ariane-5/Hermes

The space transportation system incorporating the Ariane-5 launch vehicle and the Hermes space vehicle is a European Space Agency (ESA) project. In addition to launching the Hermes manned spaceplane, the Ariane-5 launch vehicle will be used to place heavy payloads in low-Earth orbit (LEO) or geosynchronous Earth orbit (GEO).

Ariane-5 is a two-stage launch vehicle comprised of a core stage with a single liquid-oxygen/liquid-hydrogen rocket engine and two reusable solid rocket (HTPB propellant) boosters. Thrust at liftoff is 3.5 million pounds and payload to LEO is 48,500 pounds. Flight qualification of the Ariane-5 launch vehicle is targeted for 1995.

The Hermes space vehicle is recoverable and will be deployed by Ariane-5 only when a mission requires a crew. As presently proposed, Hermes is a delta-wing vehicle that can carry a three-member crew, cargo, and an expendable resource module. The primary missions are to service the Columbus Free-Flying Laboratory and to visit Space Station Freedom. On completing its mission, Hermes will return to Earth and land at a predefined terrestrial landing

site. The Hermes program is currently funded, but cost increases due to technical changes and program extensions make its future uncertain.

Hotol

Hotol originated at British Aerospace (UK) in 1983 from studies on fully reusable, low-cost launch vehicles for space operations. Hotol was originally conceived as an air-breathing rocket vehicle, which would have necessitated developing a novel propulsion system in parallel with an advanced airframe. However, the 1989 availability of the Antonov-225 (AN-225) heavy lift aircraft led to consideration of a rocket-propelled concept in which the vehicle is launched from the AN-225 at an altitude of 5 nautical miles before separating and accelerating to orbit using its own liquid-oxygen/liquid-hydrogen rocket engine. Use of a Russian engine from Energia is under consideration. Use of the AN-225 avoids the need for a launch site or a launching trolley for Hotol and improves the vehicle performance.

Since 1990, a joint British/Russian effort has been undertaken, with the British responsible for the aerospace plane and support systems, and the Russians responsible for the rocket engine and problems of vehicle separation. The Hotol design allows for either crew members or a cargo capsule to be carried.

Sänger

In 1988, the Federal Republic of Germany initiated a national program to develop technologies required for Sänger, an advanced space transportation system. Sänger is presently in the concept definition stage, and funding is believed to be at a very low level. It is being designed as a space transportation system consisting of two stages. Sänger's first stage is a hypersonic transport aircraft. Two different second stages are under consideration: (1) the winged reusable version designated HORUS (Hypersonic Orbiting Reusable Upper Stage), capable of carrying two to six crew members and 4,400 to 8,820 pounds of payload into a near-Earth orbit, or (2) the expendable payload rocket CARGUS (Cargo Upper Stage), which can lift up to 33,075 pounds into near-Earth orbit. The Sänger first stage carries either HORUS or CARGUS to an altitude of 20 nautical miles where separation takes place at a Mach number of approximately 7.0.

Propulsion Capabilities for Earth-to-Orbit Vehicles

HISTORY OF LIQUID AND SOLID PROPULSION

The liquid rocket propulsion systems available in the United States stem from three generations of development. First, there are the liquid bipropellant engines developed in the early 1950s and 1960s for the first generation of intermediate-range and intercontinental ballistic missiles. These include the liquid-oxygen/hydrocarbon engines for the Thor and Atlas, and the nitrogen-tetroxide/Aerzine-50 engines for the Titan. Some of these went out of production, but are now available in somewhat improved versions for the Delta II, Atlas II, and Titan II. Titan III, Titan-34D, and Titan IV launch vehicles are major modifications of the Titan II. Titan IVs are still being produced and are expected to continue in production throughout this decade.

In the second generation are the engines developed for the civil space program in the 1960s. These include the very large F-1 liquid-oxygen/hydrocarbon engine for the first stage of the Saturn V, the J-2 liquid-oxygen/liquid-hydrogen engine for the Saturn upper stages, and the relatively small RL10 liquid-oxygen/liquid-hydrogen engine, which is used for the Centaur upper stage. Some other upper-stage engines were also developed in this time period for DoD, such as the nitrogen-tetroxide/Aerzine-50 Transtage engine.

The third generation of liquid engine development produced only the Space Shuttle Main Engine (SSME), a sophisticated, high-pressure, liquid-oxygen/liquid-hydrogen engine tailored specifically to the requirements of the Space Shuttle.

Solid rocket motor developments were initially for jet-assisted takeoff (JATO) and small missiles. The first large high-performance motor design was for the Polaris submarine-launched ballistic missiles, where the requirements for storeability and the logistics of shipboard operations made the solid rocket very attractive. These same characteristics led to their use in the Minuteman silo-deployed intercontinental ballistic missiles (ICBMs). These capabilities provided the base upon which the technology for very large solid rocket boosters, suitable for space launch vehicles, was built. A segmented, 156-inch-diameter solid motor demonstrated the feasibility and practicality of segmented, solid rocket motors, a concept employed as a strap-on booster in the Titan III launch system. When the Space Shuttle program was initiated, solid

rocket boosters similar to the Titan III booster design were selected for the first stage. This, along with the continuing production of both sea-based and land-based missiles through the 1980s, has led to continuous technology development for large solid motors.

The result of this process is that the U.S. rocket engine industry is able to produce modern solid propellant motors in a wide range of sizes. However, large liquid rocket engines are based on technologies from the 1950s and 1960s, with the exception of the SSME. Meanwhile foreign entities, mainly Arianespace, the National Space Development Agency of Japan (NASDA), and the former Soviet Union have proceeded with liquid engine developments established on a more recent technology base.

FLIGHT-PROVEN U.S. AND INTERNATIONAL ENGINES AND MOTORS

In the following sections, flight-proven engines and their international competition are briefly reviewed and assessed. Comprehensive descriptions of them are available from various sources.^{1,2,3} Descriptive data for flight-proven and proposed U.S. and international engines and motors are presented in Tables 4 through 7.

Flight-Proven U.S. Engines and Motors

F-1 and J-2 Engines

The first stage, liquid-oxygen/hydrocarbon F-1 and the upper stage, liquid-oxygen/liquid-hydrogen J-2 engines were central to the success of the Saturn V Apollo launch vehicle. This capability was essentially abandoned at the conclusion of the SkyLab program with the advent of the Space Shuttle development, and the engines have not been in production since then. Sixty-five F-1 engines were launched successfully on 13 Saturn vehicle flights. The F-1 engine is not presently designed for throttleable thrust or for reusability, but these options are available on the proposed F-1 upgrade, the F-1A. To date, two F-1A engines have been ground tested. Both the F-1A and the J-2 engine could become part of a family of propulsion systems for near-

¹ Isakowitz, Steven J. 1991. International Reference Guide to Space Launch Systems. American Institute of Aeronautics and Astronautics. Washington, D.C.

² U.S. Congress, Office of Technology Assessment. 1988. Launch Options for the Future: Buyer's Guide. 07A-ISC-383. U.S. Government Printing Office. Washington, D.C.

³ Wilson, Andrew, ed. 1991. Interavia Space Directory: 1991-92. Jane's Information Group. United Kingdom.

TABLE 4 Characteristics of U.S. and International Liquid-Oxygen/Hydrocarbon Engines

Parameter	US: Delta II	US: Atlas II	US: Apollo	US: F-1A (proposed)	Russia: Energia	Russia: Vostok	Russia: Proton	Japan: H-I
Engine designation	RS 27A	MA-5A	F-1 (out of production)	F-1A (proposed)	RD-170	RD 107	Upper Stage Engine	MB3 BLK III
Thrust (1,000 lb)	200 (SL) 237 (vac)	423 (SL)	1,552 (SL) 1,748 (vac)	1,800 (SL) 2,020 (vac)	1,632 (SL) 1,777 (vac)	185 (SL) 225 (vac)	19.1 (vac)	170 (SL)
Isp (s)	255 (SL) 302 (vac)	264 (SL)	264 (SL) 305 (vac)	271 (SL) 304 (vac)	309 (SL) 337 (vac)	257 (SL) 314 (vac)	352 (vac)	253 (SL)
Chamber pressure (psia)	700	721	982	1,161	3,556	848	1,124	569
Feed system	Gas generator	Gas generator	Gas generator	Gas generator	Staged combustion	Gas generator	Staged combustion	Gas generator
Mixture ratio	2.25	2.25	2.27	2.27	2.43	2.47	2.6	2.15
Throttling capability	100% only	100% only	100% only	Yes (Range unknown)	49-102%	100% only	100% only	100% only
Expansion ratio	12:1	8:1	16:1	16:1	26:1	Not available	189:1	8:1
Restart capability	No	No	No	No	No	No	1-7 starts	No

SOURCES: Isakowitz, Steven J. 1991. International Reference Guide to Space Launch Systems. AIAA; and manufacturers data sheets.

TABLE 5 Characteristics of Flight-Proven U.S. and International Liquid-Oxygen/Liquid-Hydrogen Engines

Parameter	US: Shuttle	US: Apollo	Japan: H-I	US: Atlas	US: Atlas	US: Atlas	Europe: Ariane-4	Russia: Energia - (core stage)
Engine designation	SSME (in production)	J-2 (out of production)	LE-5 (in production)	RL10 A-3-3A (in production)	RL10 A-4 (ground tests only)	RL10 A-4	HM7B (in production)	RD-120 (in production)
Thrust (1,000 lb)	470 (vac)	230 (vac)	28.1 (vac)	16.5 (vac)	20.8 (vac)	20.8 (vac)	14.1 (vac)	441 (vac)
Isp (s)	453 (vac)	425 (vac)	448 (vac)	444 (vac)	449 (vac)	449 (vac)	444 (vac)	354 (SL) 453 (vac)
Chamber pressure (psia)	3,200	763	526	475	575	575	508	3,000
Feed system	Staged combustion	Gas generator	Gas generator	Expander	Expander	Expander	Gas generator	Gas generator
Mixture ratio	6.0	5.5	5.5	5.0	5.5	5.5	4.8	6.35
Throttling capability	65-104%	100% only	100% only	100% only	100% only	100% only	100% only	Yes (Range unknown)
Expansion ratio	77.5:1	28:1	140:1	61:1	84:1	84:1	62:1	85:1
Restart capability	No	One restart	Yes	Yes	Yes	Yes	No	No

SOURCES: Isakowitz, Steven J. 1991. International Reference Guide to Space Launch Systems. AIAA; and manufacturers data sheets.

TABLE 6 Characteristics of Flight-Proven U.S. and International Nitrogen-Tetroxide/Hydrazine-Based Engines

Parameter	US: Titan III	Europe: Ariane-4	Russia: Proton	Russia: Kosmos	China: Long March
Engine designation	LR87-AJ11	Viking	RD-253	RD 216	YF-20
Thrust (1,000 lb)	548 (vac)	152 (SL) 171 (vac)	331 (SL) 368 (vac)	165 (SL) 194 (vac)	166 (SL)
Isp (s)	302 (vac)	248 (SL) 278 (vac)	285 (SL) 316 (vac)	248 (SL) 291 (vac)	259 (SL) 289 (vac)
Chamber pressure (psia)	829	848	2,130	1,066	Unknown
Feed system	Gas generator	Gas generator	Gas generator	Gas generator	Gas generator
Mixture ratio	1.9	1.7	2.69	Not available	Not available
Throttling capability	100% only	100% only	100% only	100% only	100% only
Expansion ratio	15:1	10.5:1	26.1:1	Not available	Not available
Restart capability	No	No	No	No	No

SOURCES: Isakowitz, Steven J. 1991. International Reference Guide to Space Launch Systems. AIAA; and manufacturers data sheets.

TABLE 7 Characteristics of the Flight-Proven U.S. RSRM and the Proposed ASRM Solid Rocket Motors

Characteristics/Motor	RSRM	ASRM
Diameter/length (in)	146/1,513	150/1,513
Thrust (1,000 lb)	2,590 (vac)	2,636.6 (vac)
Isp (s)	267.9 (vac)	269.18 (vac)
Expansion ratio	7.72	7.54
Motor weight (lb)	1,255,978	1,350,381
Propellant mass fraction	0.882	0.895
Inert weight (lb)	148,809	142,313
Metal case weight/segments	98,740/4	99,442/3
Single nozzle weight (lb)	23,965	18,217
Solid propellant type	PBAN	HTPB
Thrust vector control	Flexible bearing	Flexible bearing
Recovery/reuse	Yes	Yes

SOURCE: Bardos, Russell. November 14, 1991. (National Aeronautics and Space Administration Headquarters). "Advanced Solid Rocket Motor and a Comparison of the RSRM and ASRM."

term application but would require new tooling, updating to modern materials and manufacturing procedures, and requalification to today's standards. **The Committee recommends that the F-1A and J-2 engines be evaluated for future applications.**

MA-5 and RS-27 Engines

The Rocketdyne MA-5 and RS-27 are engines used on the Atlas and Delta launch vehicles. Both engines were originally developed for the Atlas and Thor missiles, respectively. They use liquid oxygen and a hydrocarbon fuel, a relatively low chamber pressure, and a gas generator cycle that results in a relatively low specific impulse (i.e., performance) for this propellant combination. Having been designed originally for missile applications, these engines

do not incorporate the elements of redundancy or the design margins desired for maximum reliability on a new class of vehicles.

LR-87 and LR-91 Engines

The Aerojet LR-87 and LR-91 engines power the core of the Titan launch vehicle family and have had a history of successful flights. They operate on storable propellants, nitrogen tetroxide and Aerozine-50, both now considered toxic materials. The use of these propellants has raised some concern regarding transport safety and environmental impact associated with launch due to their hazardous nature, and the Committee could identify no distinct advantages that are offered by these engines or their fuels.

RL10 Engine

The Pratt & Whitney RL10 is a high-performance liquid-oxygen/liquid-hydrogen upper-stage propulsion system that has been in production for well over 20 years. Its expander cycle leads to performance characteristics that are still attractive for modern upper-stage propulsion application. It is used in the Centaur stages for the Atlas and Titan launch vehicles. The design is amenable to upgrading to meet specific stage needs. A version of the RL10 is currently being modified for the one-third scale model (DC-X) of the SDIO Single-Stage Rocket Technology Program's Delta Clipper (DC-Y) presently scheduled for flight test in 1993.

Space Shuttle Main Engine

The Rocketdyne Space Shuttle Main Engine (SSME) development started more than 20 years ago as a reusable, liquid-oxygen/liquid-hydrogen engine for use on the Shuttle. To maximize the specific impulse and minimize its size and weight, the SSME was designed to develop extremely high chamber pressures and uses a staged combustion cycle that requires even higher turbopump delivery pressures. These characteristics led to severe problems in SSME development and pose continuing problems with the turbopumps. The SSME has been subject to ongoing improvements such as improved oxygen and hydrogen turbopumps under the Advanced Turbopump Program. It is the understanding of the Committee that funding for turbopump development has been partially eliminated in the proposed FY 1993 budget. **However, the Committee considers development of the improved turbopumps necessary and the Advanced Turbopump Program of high priority for the future reliability of the Space Shuttle Main Engine.**

Ballistic Missile Solid Motors

Various types of solid motors are currently used in intercontinental ballistic missile (ICBM) systems. These motors are suitable for use in several space launch vehicles with light payloads to low-Earth orbit (approximately 2,000 pounds). For example, the first stage motor developed for the Peacekeeper is also to be used as the first stage of the Taurus launch vehicle. Some of these solid motors may be available as a result of the recent military deactivation of missiles, but their availability is uncertain. In addition, solid motors are subject to aging, and some have been deployed in the field for as long as 30 years. Their condition and performance are not known with complete surety.

Redesigned Solid Rocket Motor (RSRM)

The Redesigned Solid Rocket Motor (RSRM) is the very large, segmented, solid booster currently used on the Space Shuttle. Two RSRMs provide 80 percent of the total liftoff thrust. The RSRM was derived from and replaced the Solid Rocket Motor (SRM) previously used on the Shuttle, and the main difference is the improved design of the field joint and O-ring seal between the case segments of the RSRM. Since the RSRM rocket case is reusable, it is retrieved, refurbished, refilled with propellant, and returned to Kennedy Space Center for future launches. Table 7 shows the characteristics of the RSRM.

The Shuttle is currently operating satisfactorily with the RSRM. According to present planning, the RSRM is capable of meeting all operating requirements of the Shuttle, including the assembly and operational maintenance of Space Station Freedom. With continued meticulous attention to processing and improvements in nondestructive evaluation, there is every reason to believe that the Shuttle can be operated without failure of the RSRM. It should be noted, however, that even though the costs of inspection and operational precautions are high, they must not be allowed to become routine. The RSRM is now a well-understood propulsion system with established characteristics and, as such, the Committee believes that it is capable of safe operation with careful management.

Flight-Proven International Engines and Motors

The following is an evaluation of some specific foreign rocket engines and motors that the Committee believes to be especially relevant to the considerations in its charge. In overview, the foreign launch vehicles use propulsion systems incorporating modularity to various degrees, which brings a variety of benefits. Based on presentations made to the Committee, the Russians appear to be using noteworthy innovations in materials, manufacturing, and test methods that are worthy of pursuit by technology transfer to the United States.

RD-170 Engine

The Russian RD-170 is the high thrust liquid-oxygen/hydrocarbon modular engine used in the first stage of the heavy lift Energia launch vehicle. It is technologically comparable to the SSME, having very high chamber pressure, and is in the thrust range to compete with the F-1 engine used during Apollo and the F-1A (F-1 upgrade) proposed by Rocketdyne. The RD-170 incorporates the desirable features of throttling and reusability. It is currently in production, and more than 200 engines have been produced to date. The RD-170 is now used in the Zenit and Energia/Buran launch vehicles. At least twenty-five flights have been successfully completed. The qualification and flight status of this engine makes it attractive for direct application in a heavy lift launch vehicle liquid booster stage. Aerojet, Pratt & Whitney, and Rocketdyne are currently engaged in negotiations to test and/or acquire the RD-170 from the engine manufacturer, NPO Energomash. **The Committee recommends that the performance of the RD-170 engine be evaluated thoroughly for application to U.S. systems.** One way to hasten the evaluation could be as part of an international cooperative effort in which the National Aeronautics and Space Administration (NASA) might purchase several RD-170 engines and send personnel to monitor engine testing at Kiminsky, Russia. If the results of the performance evaluation are positive, the engines might be manufactured in Russia or under license in the United States. However, the Committee believes that no critical component, such as an engine, should be solely supplied from abroad.

RD-253 Engine

The Russian RD-253 is the first stage engine for the Proton launch vehicle. It has demonstrated excellent reliability with no known failures in more than 900 flight engines. However, its use of storable liquid propellants (nitrogen tetroxide and unsymmetrical dimethylhydrazine (UDMH)) could raise environmental concerns and pose logistic problems equivalent to those of the Titan launch vehicle.

Viking and Other Engines

The Viking engine (used on the Ariane-4 first and second stages) and the Chinese Long March engines use nitrogen tetroxide and hydrazine propellants. They do not appear to offer enough advantages to the United States in terms of the technology or the basic capability to merit further investigation.

PROPOSED U.S. AND INTERNATIONAL ENGINES AND MOTORS

Proposed U.S. Engines and Motors

Space Transportation Main Engine (STME)

The Space Transportation Main Engine (STME), Figure 2, utilizes liquid-oxygen/liquid-hydrogen propellants and is currently at the technology demonstration stage. Thus, the performance parameters shown in Table 8 are preliminary. The STME is envisioned as a low-cost, highly reliable engine. These goals are to be met through a philosophy of engine development that places reliability at a higher priority than performance. This engine is regarded as the central propulsion capability for the National Launch System (NLS). The STME builds on the technology obtained from development of the SSME, but proposes to use the technology in a less demanding way, emphasizing reliability and low cost rather than ultimate performance, as noted above. Because the STME engine builds on experience gained with the SSME, it is helpful to use the SSME as a basis for comparison.

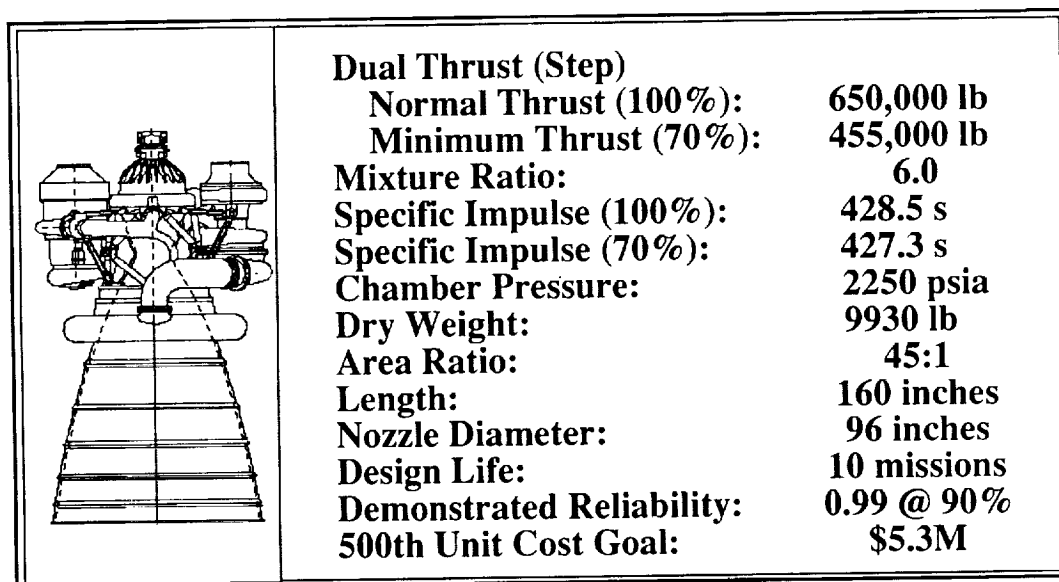


FIGURE 2 Characteristics of the proposed liquid-oxygen/liquid-hydrogen Space Transportation Main Engine (STME).

The physical differences between the STME and the SSME are (1) lower STME chamber pressure, (2) utilization of a gas generator cycle in the STME, and (3) higher STME thrust. As stated previously, the main difference, however, is a dramatic change in design philosophy. The

TABLE 8 Comparison of the STME and SSME

Characteristics/Engine	STME	SSME
Propellants	LOX/LH ₂	LOX/LH ₂
Feed system	Gas generator	Staged combustion
Thrust (1,000 lb)	650 (vac)	470 (vac)
Throttling	70-100%	65-104%
Isp (s)	428.5 (vac)	453 (vac)
Chamber pressure (psia)	2,250	3,200
Mixture ratio	6.0	6.0
Expansion ratio	45:1	77.5:1

SOURCE: NASA/George C. Marshall Space Flight Center; and manufacturers data sheets.

primary drivers of the SSME development were high delivered performance (Isp) and low weight. The stated objective of the STME design is to give priority to reliability, manufacturability, and reduced cost--at the expense of performance. This design philosophy influenced the choice of lower chamber pressure and the use of the gas generator cycle, design factors that result in a lower delivered specific impulse for the STME. Attendant with these choices is a significant reduction in the turbopump outlet pressure that, in turn, is expected to result in a more robust design. Further, the reduced chamber pressure decreases the heat transfer load to the thrust chamber walls, which also contributes to increased design margins.

The stated design philosophy is also geared to producibility of the engine in large numbers at low cost. This has resulted in a closer look at engine materials and manufacturing methods to be employed. The use of low-cost castings in lieu of machined forgings, minimization of weld joints, and relaxed tolerances where possible all are elements of the manufacturing technology aspects of the STME design.

The Committee enthusiastically supports the STME design philosophy. Once the design thrust level has been finalized, the Committee trusts that the urge to relax this philosophy and move toward higher performance will be avoided diligently, even if initial development and tests are highly successful. Escalating the performance requirements during development would negate the positive features of the design.

The Committee believes the STME development should proceed immediately and vigorously and should be tailored to optimum application in a launch vehicle with a payload capacity of approximately 20,000 pounds to low-Earth orbit (LEO). The proposed thrust level of the STME is 650,000 pounds. The Committee endorses this design thrust level, with the assumption that the vehicle will be launched at less than maximum STME thrust level for improved reliability and margin.

The Committee assumes that the initial sizing of the STME not only will accommodate the requirements of a 20,000-pound payload vehicle, but also will allow STME utilization as a core stage engine in our future launch vehicle fleet, along with strap-on booster propulsion modules to augment the payload capabilities of larger vehicles. This approach is consistent with highly successful launch vehicle experience in the international space community, as evidenced by the extensive Russian inventory of strap-on propulsion systems, the Ariane family of launch vehicles, and the Delta launch vehicles.

Advanced Solid Rocket Motor (ASRM)

The Advanced Solid Rocket Motor (ASRM) is a solid rocket booster intended to replace the RSRM for the Space Shuttle vehicle, providing a proposed 12,000-pound Shuttle payload increase. It incorporates a larger diameter case; advanced, lightweight nozzle; different field joint design; and continuous processing of propellant. The ASRM is intended to be produced in a government-owned, contractor-operated facility, currently under construction in Yellow Creek, Mississippi. The characteristics of the ASRM are shown in Table 7.

The projected benefit of the ASRM is an anticipated 12,000-pound payload increase. The significant savings due to reduction in the number of Shuttle missions to support SSF could warrant the use of the ASRM, provided program and technical risks can be fully contained. The Committee is aware of the large investment that has been made in ASRM development and in related facilities; however, there is considerable risk remaining. In particular, the use in the case segments of welded circumferential joints in place of mechanical joints, and a steel alloy that has not previously been used in large rocket cases, introduce significant risk, as pointed out by the 1991 NRC Committee on Advanced Solid Rocket Motor Quality Control and Test Program. Continuous casting of the propellant also is unproven for the large sized motors of the ASRM. These and other new features, such as the lighter-weight nozzle design, could lead to program extensions or failures requiring expensive corrective action. **The current RSRM is capable of meeting all operational requirements of the Space Shuttle. The Committee believes that the balance of costs, technical and programmatic risks, and potential benefits tips in favor of avoiding integration of the ASRM into the Space Shuttle system at this time.**

Regarding the utility of the ASRM for other future space launch systems, the Committee understands its potential as a strap-on for the heavy payload end of NLS, (i.e., NLS-1); however, the Committee has found no compelling rationale for such use other than the fact that

it might be introduced in a reasonably short time. **The Committee believes that NASA should rely on the current RSRMs and that the ASRM program should be reconsidered. It believes that NASA and the nation would be well served if the development of the NLS were directed toward strap-on boosters that have pad hold-down with engine shutdown capability and throttleability as means toward increased reliability.**

In its discussions, the Committee found a number of considerations that favor liquid propulsion systems as compared to solid propulsion systems. Liquid rocket engines permit a more flexible approach to modular clustering and are amenable to verification before launch. However, the most compelling characteristics favoring liquids are throttleability and thrust termination capability, which can enable first-stage booster designs to incorporate an engine redundancy capability.

A recent study⁴ of the causes of liquid propulsion system failures has shown that a large fraction of such failures were noncatastrophic in nature; that is, they resulted in loss of thrust from the engine, but not in a failure that would destroy the vehicle or other engines. This is termed a benign failure. As mentioned earlier, the historical ground and flight data have shown the benign failure ratio (failures/engine flights) for liquid propulsion systems is greater than the catastrophic failure ratio. For solids, there have been no benign failures for flight motors.⁵ When benign failures dominate, reliability enhancement through incorporation of active redundancy becomes feasible and often economically attractive.

Indeed, as far as the propulsion system is concerned, active redundancy is a means of improving reliability. It is a proven approach for aircraft but, in the past, has not been employed on expendable launch vehicles. However, the very high cost of failures, particularly when expensive payloads are involved, makes the use of these techniques worthwhile even for expendable vehicles.

Solid Rocket Motor Upgrade (SRMU)

The Solid Rocket Motor Upgrade (SRMU) is a segmented rocket motor design being developed to provide more lift capability for the Titan IV launch vehicle. It incorporates a composite case, but no other noteworthy technological advantages over the RSRM and the ASRM.

⁴ Leonard, B.P. 1991. Projected Launch Vehicle Failure Probabilities With and Without Engine Segment-out Capabilities. L-Systems, Inc. El Segundo, Calif.

⁵ Smith, O. Glenn. 1991. Reliability in Manned Transportation Systems. Johnson Space Center. Houston, Tex.

Proposed International Engines and Motors

The advanced propulsion systems under development in Europe (Vulcain HM-60) and Japan (LE-7) are similar to existing technologies in the United States and are not discussed in detail in this report. However, the characteristics of some of the international engines are contained in Tables 9 and 10.

TABLE 9 Characteristics of Proposed U.S. and International Liquid-Oxygen/Liquid-Hydrogen Engines

Parameter	US: NLS	Europe: Ariane-5	Japan: H-II	China: CZ2E/HO
Engine designation	STME	Vulcain HM-60	LE-7	YF-75
Thrust (1,000 lb)	650 (vac)	180 (SL) 225 (vac)	190 (SL) 243 (vac)	17.6 (SL)
Isp (s)	428.5 (vac)	430 (vac)	445 (vac)	440 (vac)
Chamber pressure (psia)	2,250	1,450	2,090	Not available
Feed system	Gas generator	Gas generator	Staged combustion	Gas generator
Oxidizer/fuel mixture ratio	6.0	5.1	6.0	Not available
Throttling capability	70-100%	100% only	100% only	Not available
Expansion ratio	45:1	45:1	60:1	Not available
Restart capability	Multiple	No	No	One restart

SOURCES: Isakowitz, Steven J. 1991. International Reference Guide to Space Launch Systems. AIAA; and manufacturers data sheets.

TABLE 10 Characteristics of Proposed International Nitrogen-Tetroxide/Hydrazine-Based Engines

Parameter	Europe: Ariane-5	India: GSLV
Engine designation	L-7	VIKAS
Thrust (1,000 lb)	6.1 (vac)	165 (vac)
Isp (s)	316 (vac)	293 (vac)
Chamber pressure (psia)	218	763
Feed system	Pressure fed	Gas generator
Mixture ratio	2.05	1.7
Throttling capability	50-100%	100% only
Expansion ratio	83:1	Not available
Restart capability	Multiple	No

SOURCES: Isakowitz, Steven J. 1991. International Reference Guide to Space Launch Systems. AIAA; and manufacturers data sheets.

ENGINE AND MOTOR TESTING

System Reliability and Tests

One point that is not always clear in discussions of the reliability of liquid rocket engines versus solid rocket motors is that the solid rocket motor test includes all facets of the propellant delivery system, whereas the liquid rocket engine may not. Specifically, the liquid rocket engine will include the turbopump (if any), which accepts the propellant flow from a facility source that

is not flight weight or flight type in its design and operation. The analysis of propulsion system reliability mentioned previously indicated that significant portions of liquid propulsion system unreliability are associated with the system upstream of the turbopump (tanks, low-pressure feed lines, valves, etc). **It is the opinion of the Committee that increased emphasis on propulsion system tests, including the propellant feed system, should be a major aspect of any new launch system program.** Increased emphasis is also required in the design phase to include innovative methods to monitor propulsion system health and implement any required shutdowns at appropriate locations. The Committee found no evidence that this design approach is currently being addressed in the NLS program.

Propulsion Test Facilities

The nation's capability for testing liquid rocket engines and solid rocket motors is becoming constrained by the pressures of residential and commercial development in the vicinity of rocket manufacturers' facilities and the increasingly stringent environmental standards being imposed. The following is a summary of the most likely test sites for future engine and motor development activities, including a brief assessment of potential restrictions and constraints.

Government-Owned Test Facilities

The major government-owned engine and motor test facilities are:

- Edwards Air Force Base (AFB), California -- The F-1 development test stands (6 in number) are still in place and could be reactivated in approximately 6 months' time. For instance, stand C-1 was converted from a liquid engine test capability to accommodate a Titan 34 solid strap-on test capability (nozzle down, vertical firing) within six months. It is presently being used to test the Solid Rocket Motor Upgrade (SRMU) for the Titan IV. Test stand 2-A is being modified to accommodate the STME combustion device development program.

The area of Edwards AFB is substantial and, to date, the emissions have been able to meet state and local county standards by the time the exhaust cloud reaches the base boundaries. Although the area to the west of Edwards AFB is growing, the prevailing winds are from the southwest. Only the town of Boron is in the area of likely coverage by exhaust clouds, and it is far enough away to ensure that no danger is presented.

- Arnold Engineering Development Center, Tullahoma, Tennessee -- The Air Force has established a number of simulated altitude test facilities that can accommodate both liquid

rocket engines and solid rocket motors of very large size. For example, the Peacekeeper second-stage motor was tested there.

- NASA/Marshall Space Flight Center, Huntsville, Alabama, has a number of large liquid rocket test facilities capable of handling SSME engines as well as larger engines. The buffer zone is quite large, but the issues of noise, air, and groundwater pollution have created questions leading to interaction of NASA/Marshall with various state and local authorities and residents.
- NASA/Stennis Space Center, Mississippi, has 4 very high thrust test stands available for liquid-oxygen/liquid-hydrogen rocket engine testing. Three stands will be in active use until 1994 for SSME testing. NASA is presently evaluating reactivation of the other stand. Currently, a horizontal, solid rocket test stand for the ASRM is being built. Some of the local population is opposed to solid rocket testing in the area. The concern is the combination of high humidity and the presence of hydrogen chloride (HCl) in the solid rocket exhaust. This situation must be monitored closely to see how it develops.

Industrial Test Facilities

The following are the major industrial engine and motor test facilities:

- The Thiokol Corporation in Wasatch, Utah; Hercules, Incorporated in Magna, Utah; and United Technologies in Coyote, California, have test facilities suitable for large solid rocket development efforts. There are presently no known environmental constraints that may affect the ability to continue such testing.
- Rocketdyne, Santa Susanna, California, has extensive liquid rocket test facilities in the Santa Susanna Mountains. Since initial construction, residences have gradually been built closer and closer to the gates of the facility. Strict Los Angeles County air quality and groundwater standards must be met. The impact on the cost of testing and the ability to conduct tests at will is unknown, but believed to be restrictive.
- Aerojet Propulsion Division, Sacramento, California, has extensive liquid and solid rocket test facilities in the Folsom area. There has been substantial commercial development in the area. As a result, Aerojet must restrict test operations to certain atmospheric (wind) conditions to ensure that no effluents pass over occupied buildings outside test facility boundaries.

Each of the above testing sites is unique and must be examined individually with regard to the environmental impact.

ENVIRONMENTAL EFFECTS OF CHEMICAL PROPULSION

Because it has received much discussion and is a source of current controversy, the question of environmental pollution by chemical propulsion commands detailed discussion. The Committee, upon review of the American Institute of Aeronautics and Astronautics (AIAA) Workshop Report on the "Atmospheric Effects of Chemical Rocket Propulsion,"⁶ accepts the conclusions contained therein. Specifically,

- the effects of currently projected launches of the Shuttle and Titan IV annually will result in the depletion of ozone globally on the order of 0.0065 to 0.024 percent;
- ozone depletion in the 60-90 N latitudes will be about 0.2 percent;
- ozone depletion near the exhaust plume is greater than 80 percent during ascent but returns to normal within three hours;
- acid rain is less than 0.01 percent of global anthropogenic sources;
- local launch effects are confined to within 2,500 feet of the launch pad;
- effects on global warming are less than one-millionth of all carbon dioxide (CO₂) produced; and
- for the current projected Shuttle and Titan IV launch rates, local toxicity hazards and air quality are considered manageable.

These facts, which are hardly in dispute, have not allayed concern in the community of environmentalists regarding the effects of space launch vehicle emissions on the atmosphere. These concerns, often expressed in language that suggests dire global consequences of continuing to launch payloads into space, are not supported by the findings of the broadly based group of scientists and engineers encompassing the propulsion and launch vehicle industries. Nevertheless, the protests do pose a possible problem in terms of public reaction to the continued or expanded use of large solid boosters.

Because of concern over the potential detrimental environmental effects of some launchers, the Committee endorses continuing research to better identify and understand these effects. Data suggest that pollution due to combustion products from launch vehicles, at the frequency and scale that is anticipated, is not significant in comparison with other

⁶ American Institute of Aeronautics and Astronautics. Atmospheric Effects of Chemical Rocket Propulsion. October 1, 1991. Washington, D.C.

anthropogenic pollution on a global scale. It is, however, a serious local concern in the vicinity of launch test sites and deserves further investigation.

PRIORITIES FOR INVESTMENT

A plan is needed to provide an array of engines with a range of thrust levels and propulsion system capabilities for all stages of future launch vehicles. The proposed STME can be used for first stages of future launch vehicles. In addition, the Rocketdyne F-1A and the current Russian RD-170 engines should be evaluated for liquid booster applications. Hybrid engine technology should be investigated to determine its suitability with new launch systems. The propulsion system technology for second- and third-stage applications should emphasize low system cost and high reliability as in the initial booster stage. Revival of the Rocketdyne J-2 or upgrading of the Pratt & Whitney RL10 liquid-oxygen/liquid-hydrogen engines could provide upper-stage engines fitting the range of desired propulsion capabilities.

Space Transportation Main Engine

The modern Space Transportation Main Engine (STME) is the beneficiary of a significant investment in the underlying technologies, including fabrication methodologies, advanced materials, and revised design procedures aimed at improving the reliability and cost of a production engine. **Development and qualification of the Space Transportation Main Engine (STME) should proceed immediately and vigorously.** The initial use of the STME is to propel the NLS vehicles, and its development is crucial.

In addition, it is the Committee's recommendation that the STME development team invest in demonstrating a prototype of the 650,000-pound thrust engine concept for the 20,000-pound payload vehicle. The design philosophy should reinforce the robustness aspects of the engine, and should include health monitoring and control technology.

Space Shuttle Propulsion Systems

The Space Shuttle will remain the centerpiece of the U.S. manned presence in space well into the first decade of the next century. **The Committee believes that efforts underway to improve reliability, reduce the cost, and simplify production and refurbishment of the SSME should be continued and that investment should be made in maintaining the operating integrity and effectiveness of all aspects of the propulsion system.**

Because the engine has been plagued with problems, there is no question that Shuttle operations can be enhanced by continuing to upgrade the SSME. As noted earlier, a specific area of concern involves the turbopumps that deliver liquid-hydrogen and liquid-oxygen propellants to the engine main combustion chamber. Pratt & Whitney, under NASA contract, has delivered the first set of 16 improved oxygen turbopumps for the SSME. Budget cuts in NASA's Alternate Turbopump Program (ATP) made by Congress in the hydrogen fuel pump improvement program will delay the flight qualification required to show that the turbopumps are interchangeable with the current Rocketdyne turbopumps and that they have the required mission lifetime. **It is important to pursue both the alternate oxygen and hydrogen pumps under the ATP because Shuttle operations are likely to continue well into the first decade of the next century, and it is believed that both turbopumps can offer greatly increased safety margins and reduced requirements for pump replacement/changeout.**

The Redesigned Solid Rocket Motor also deserves future investment to ensure the continued success of Space Shuttle operations. In particular, the RSRM could benefit from continued investment in improved manufacturing technology to ensure the repeatability of manufacture and nondestructive inspectability of the motor.

PRIORITIES FOR LONGER-TERM PAYOFF

Engines

Major investment priorities have been listed in the foregoing paragraphs. The Committee believes that there are also other promising engines in early stages of development that require investment in experimental development and testing to validate their engineering practicality. These are the modular plug engine, the modular bell engine, dual-fuel engines, and variable mixture ratio liquid-oxygen/liquid-hydrogen engines. The technology for these engines is discussed further in Chapter 6.

Booster Stages

Although not required for the 20,000-pound payload class vehicle lift capability recommended by the Committee as the critical U.S. need, a modular approach to providing booster strap-ons is required for 135,000-pound (and greater) payload class vehicles. Propulsion candidates for booster rockets include liquid, solid, and hybrid rockets. Some characteristics of solids, liquids, and hybrids are shown in Table 11.

Hybrid rocket boosters as shown in Figure 3, use a liquid oxidizer and a solid fuel, and have been studied and tested in a variety of thrust ranges since the 1960s. The Committee

TABLE 11 Characteristics of Solid, Liquid, and Hybrid Boosters

Characteristics	Solid Boosters	Liquid Boosters	Hybrid Boosters
Specific impulse	Relatively low specific impulse	Relatively high specific impulse	Relatively low specific impulse
Cost	Lower up-front development and production costs	Higher up-front development and production costs	Not available
Failure mode	Failures tend to be catastrophic	Failures tend to be noncatastrophic	Failures tend to be noncatastrophic
Shutdown/restart	No shutdown capability in event of malfunction	Shutdown possible in event of malfunction	Shutdown possible in event of malfunction
Active redundancy	No capability	Yes	Yes
Functional test capability after assembly	No functional test of production article	Functional test possible both after assembly and before liftoff	Functional test of production articles possible before liftoff
Environmental	Emission of chlorides and aluminum oxide particulates	Possible environmental effects are currently not well understood	Environmental effects are comparable to those of a liquid/hydrocarbon booster
Handling and storeability	Fire hazard in handling, storage, and vehicle assembly Fully storable, but materials and bond are temperature sensitive and subject to aging	Use of cryogenic liquids requires careful handling, storage, and launch preparations	Use of cryogenic liquids requires careful handling, storage, and launch preparations Fuel grain design is more robust than that of a solid booster
Complexity	Operational simplicity	Turbomachinery results in complexity	Greater operational simplicity
Reusability	Reusability of cases	Tankage probably not reusable	Reusability of cases
Propellant density	High propellant density	Relatively low density leads to larger volume	High propellant density

recognizes that the hybrid rocket has not achieved the flight-proven status of solid and liquid boosters. However, the attractive features of hybrid rockets such as the ability to control liquid oxidizer flow that permits throttling and engine shutdown make them viable candidates for thrust augmentation booster applications on future vehicles.

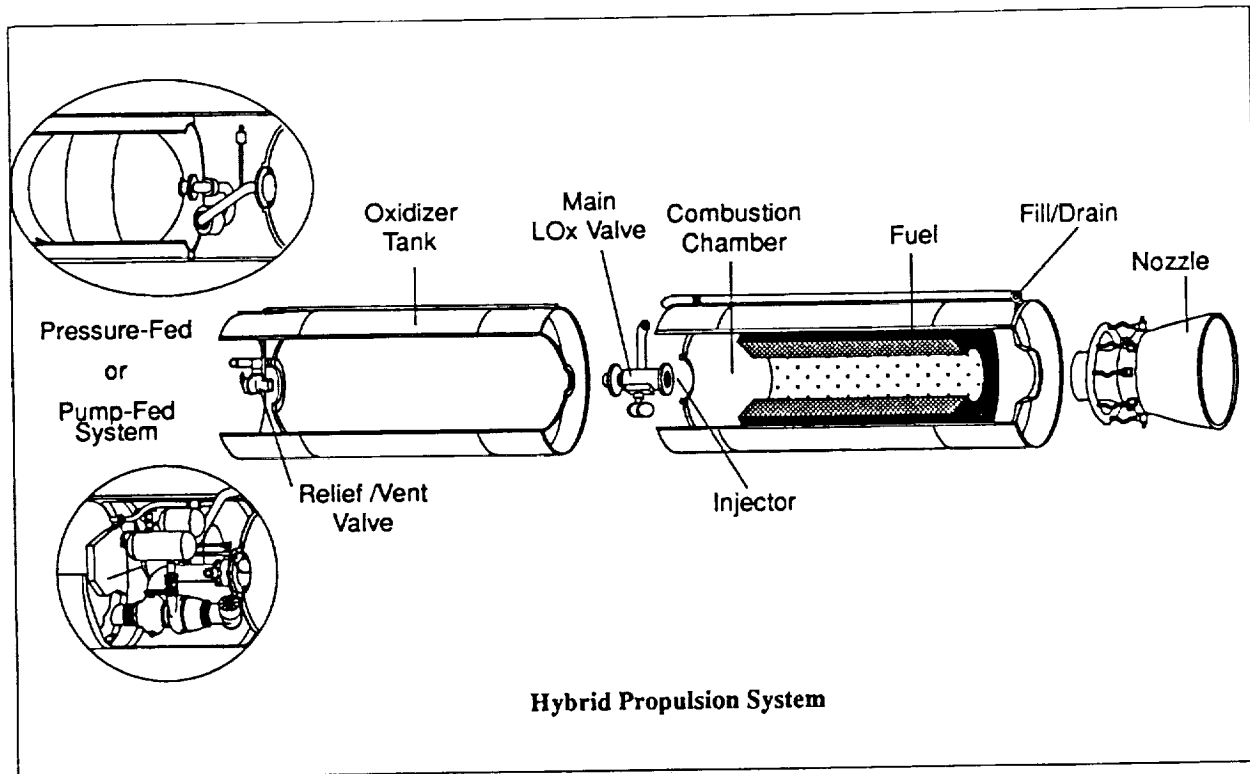


FIGURE 3 Hybrid motor that uses liquid oxygen and a solid fuel. The liquid oxidizer flow can be controlled to permit throttling and engine shutdown. Courtesy of Thiokol Corporation.

The time scale for the development of a 135,000-pound payload class vehicle, would permit investment in hybrid rocket motor development now, so that its status is advanced to the point at which it can be quantitatively evaluated in competition with solid and liquid bipropellant systems designed to directly comparable criteria.

Two liquid rocket engines that the Committee also believes are candidates for booster applications are the F-1A and the RD-170 engines as discussed earlier.

Technology Development

The Committee concluded that inadequate attention and funding are devoted to long-term technology development. Such development is a necessary precursor to a new generation of Earth-to-orbit launch systems. The portion of the National Aeronautics and Space Administration (NASA) Office of Aeronautics and Space Technology fiscal year (FY) 1992 budget dedicated to space technology is only \$293 million. This amount is much smaller than other FY 1992 NASA program budgets, such as the physics and astronomy budget of approximately \$1 billion and the Advanced Solid Rocket Motor Program budget of \$465 million.

The availability of reasonably well-validated new technology is essential to carrying out the design and development of engines, boosters, spacecraft, reentry vehicles, their component parts, and the various features of infrastructure necessary for a healthy and robust space utilization and exploration program. As noted earlier, many launch vehicles and systems are based on very old technology. Development of a new system based primarily on currently available advanced technologies holds the promise of significant improvements to U.S. capabilities. The existing situation with respect to technology for new launch systems has come about, to a large extent, because managers are motivated to minimize the number of technical innovations in a new program because too much innovation affects their credibility, and cost and schedule difficulties can arise after program initiation. The paradox is that those who develop technology must have requirements or "targets" on which to base their program expenditures. Without technology readiness, innovations cannot be included in new programs; at the same time, little technology development is authorized without specific programmatic requirements.

After considering both near- and long-term goals in space utilization and exploration, the Committee has identified several areas in which current programs would now be benefiting if certain technology development had been supported in the past. In addition, the Committee urges that technical records and technology development be kept free of security classification to the maximum extent possible. Current, routine classification procedures unduly impede

communication among engineers and scientists, and hamper progress. Reassessment of the criteria for classification is in order.

The following are technology development areas that the Committee believes deserve long-term continuing support.

PROPULSION TECHNOLOGIES

To achieve U.S. space goals for the next century, new, low-cost launch vehicles are necessary. Advanced technology is the foundation for the next generation of space transportation systems and should focus on propulsion because this technology must be well in hand before being designed into any new vehicle system. However, propulsion system technology development should take place in step with other important aspects of launch vehicle and launch system design to reduce costs and improve operational efficiency. Some propulsion technology advances, in addition to the Space Transportation Main Engines (STME), that the Committee believes merit consideration for a new generation of launch vehicles are discussed below.

Hybrids

The hybrid rocket is a concept in which one of the propellants is a solid and the other a liquid (or gas) (see Figure 3, Chapter 5). Most frequently, this takes the form of a solid fuel and a liquid oxidizer. The higher-energy combinations tend to be of this general configuration. Although this concept is not new, it has generally suffered from a lack of funding in the propulsion industry, possibly because there has been a low priority placed on its technology development despite the recent efforts of the Hybrid Propulsion Industry Action Group (HPIAG)¹.

The Committee examined various means by which to increase system reliability, such as pad hold-down and motor shutdown prior to launch for propulsion system check and active redundancy. Pad hold-down, generally for five seconds after ignition, makes it possible to shut down a faulty engine and/or abort on the pad, while active redundancy implies the capability of throttling the propulsion system up to compensate for a lost engine. These attributes have been conceded to liquid systems historically but may be possible with hybrid rocket systems. Additionally, the fact that the solid grain is composed of only fuel and contains no oxidizer significantly facilitates system manufacturing and addresses handling safety issues. Further, an oxidizer-free fuel grain which has a greater elasticity than a grain containing a large amount of

¹ The HPIAG is an association of 11 aerospace companies interested in hybrid propulsion.

oxidizer, may reduce the risk of catastrophic failures associated with cracks in propellant grains or debonds at the case. The ability to control the flow of liquid oxidizer permits throttling and engine shutdown.

An investment should be made in demonstrating the technology necessary to validate the engineering practicality of the hybrid rocket motor for large, high-thrust, strap-on applications. As envisioned, the fuel grain would be a hydrocarbon type and the oxidizer would be liquid oxygen. Technology efforts need to be directed to demonstrating satisfactory combustion characteristics along the length of the fuel grain and minimizing the residual fuel at the completion of burn. This includes tailoring the internal geometry of the motor to achieve the best combination of these characteristics. The combustion process needs to be free of oscillations that may introduce unacceptable stage vibrations or detrimental internal conditions. These investigations must be accomplished at a scale that is large enough to be representative of a full-scale booster motor, but sufficiently small to keep costs affordable. This development activity might include tests at a variety of thrust levels to permit the establishment and evaluation of scaling criteria. **Hybrid rocket motor development should be advanced to the point that it can be quantitatively evaluated in competition with solid and liquid bipropellant systems designed to directly comparable criteria.** This hybrid motor technology should be targeted initially for thrust-augmentation booster applications such as the 135,000-pound payload class vehicle, NLS-1.

Modular Plug Engine

The modular plug engine, as conceived by Aerojet General Corporation, consists of 12 identical modules arranged circumferentially to form a central, truncated surface, as shown in Figure 4. In addition, each of the modules contains 16 very small rectangular thrusters that burn the propellants and internally expand the exhaust gas, directing it along the central surface for additional, external expansion to the surrounding environment. One may think of the modular plug engine as having a nozzle that self-adjusts its expansion to the external pressure that exists at the vehicle's flight altitude. Thus, in spite of some loss caused by the truncation of the central surface, the modular plug engine is especially well suited for single-stage-to-orbit (SSTO) vehicles because it promises to operate relatively efficiently at low and high altitudes without mechanical nozzle extensions. Its fully modular design may greatly simplify the logistic and maintenance operations, thus reducing turnaround time. Also, a novel platelet² construction promises practical and cheaper fabrication of small thrusters. Although the actual performance

² Platelet construction permits accurate fabrication of small propellant passages required for cooling and injection.

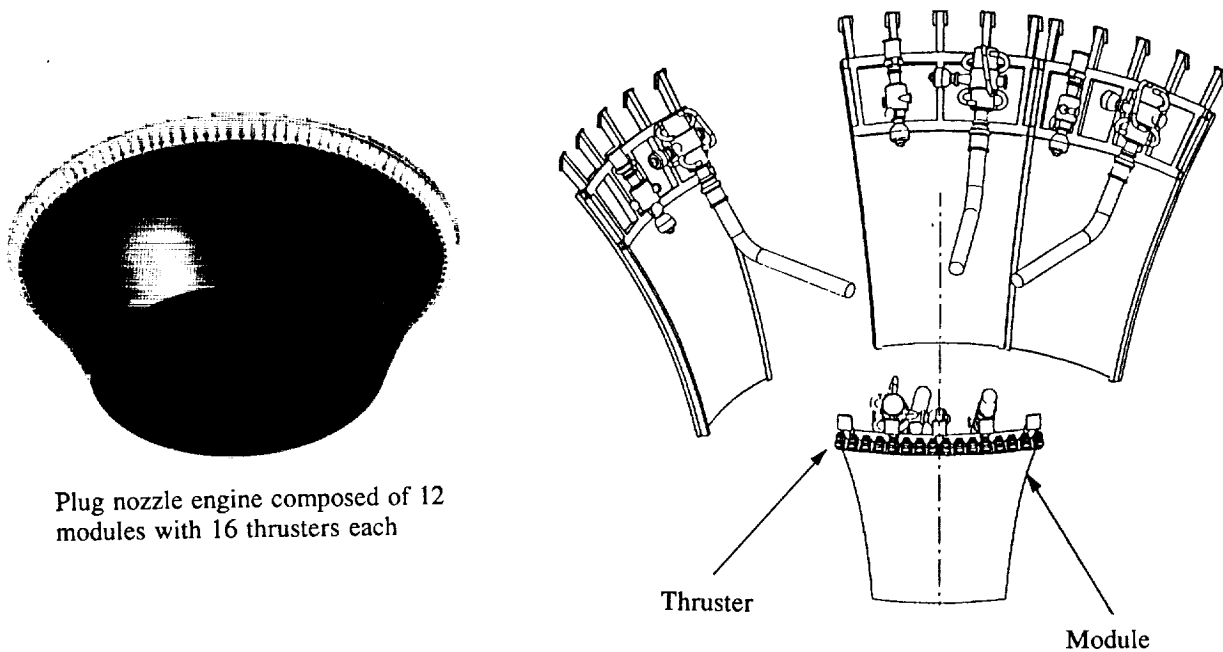


FIGURE 4 Modular plug engine. Courtesy of Aerojet General Corporation.

data for such engines are meager, some analytical studies indicate that the plug engine could do the job of propelling the Delta Clipper (DC-Y) into orbit with a payload of the order of 20,000 pounds. When developed, this engine also could conceivably be used effectively in other launch vehicles. **Therefore, the Committee recommends that research to provide the missing data and the development of components be continued.**

Modular Bell Engine

Recently, the Strategic Defense Initiative Office (SDIO) proposed the development of a new, modular bell engine³ designed for rapid turnaround operations similar to those of an aircraft, including provisions for thorough monitoring to allow regular, scheduled maintenance. The modules of this engine consist of a combustion chamber and either a short nozzle or an extendable two-position nozzle. Since modules are not identical, some advantages of full

³ Multiple thrust chambers with a single turbopump.

modularity would be lost. Nevertheless, the engine is similar in concept to the successful Russian RD-170 engine.⁴ Its development risks and the development time in all likelihood will, therefore, be relatively small. **The Committee recommends that studies of the need and advantages of the proposed engine be made and that research be supported to investigate critical technologies.**

Virtual Staging Engine Concepts

The ability to incorporate the advantages of both denser propellants and higher performance propellants in a single stage or vehicle is known as virtual staging. Such concepts could be enhancing for a SSTO rocket-powered concept. Denser, lower performance propellants result in a more compact propulsion system. For this reason, liquid-oxygen/hydrocarbon engines have been used for first stages and for strap-on boosters. The same reasoning makes solids or hybrids attractive as first stage boosters. Alternatively, a less-dense, liquid-oxygen/liquid-hydrogen fuel combination is used in upper stages to provide higher performance, even at the expense of much bulkier tankage. Current NASP-related research on slush hydrogen, a denser form of liquid hydrogen, may lead to a more compact, higher performance fuel for the future. Combining the attributes of both denser propellants and higher performance propellants through virtual staging could prove beneficial in future systems.

Two concepts of virtual staging are discussed below:

- **Dual-Fuel Engines:** The engine is designed to operate with liquid oxygen and a hydrocarbon fuel at launch and then convert to liquid-oxygen and liquid-hydrogen operation at some point later in the flight. Studies have indicated that the hardware may be compatible for such operation, but issues remain to be fully evaluated in the hot firing environment.
- **Variable Mixture Ratio Liquid-Oxygen/Liquid-Hydrogen Engines:** The concept is to run the engine on an oxidizer-rich mixture ratio (12:1) for boost operations, then shift to a fuel-rich mixture ratio (6:1) for the high-performance, sustained operation to orbit. The problem is that to make such a shift, the engine must transition through the stoichiometric mixture ratio which yields the highest temperatures of engine operation. Engine control and the means to affect the mixture ratio transition are critical technologies.

⁴ The RD-170 engine cluster consists of four identical thrust chambers and nozzles and, therefore, is fully modular.

Nuclear Propulsion and Power

The Committee reviewed nuclear thermal and nuclear electric technology for space applications. At this time, it appears that the most likely potential applications of nuclear propulsion involve transportation beyond Earth's orbit. For example, many studies have shown that a nuclear thermal rocket, with a specific impulse roughly double that attainable with hydrogen-oxygen propellants, could cut in half the initial mass required in low-Earth orbit (LEO) for a human Mars mission. Similarly, nuclear-electric propulsion could greatly reduce the mass required in LEO for unmanned precursor missions or for cargo transport for human missions.

There are at least three possible technological approaches to the nuclear-thermal rocket that hold promise for future space exploration missions: (1) reactors based on the 1970s Nuclear Engine Rocket for Vehicle Applications (NERVA) program, (2) pebble-bed and particle-bed reactors, and (3) the tungsten-cermet fueled fast reactor. All offer considerably higher specific impulse than chemical propulsion. Only the NERVA program has been carried to the stage of engineering demonstration; the feasibility of the others has yet to be demonstrated. In addition, the SP-100 nuclear electric power system has been underway for many years and could enable economical unmanned exploration as well as provide a source for high levels of power in remote locations such as the moon or Mars.

In the context of this study, nuclear power and propulsion systems are of concern to the Committee primarily because of their potential impact on the Earth-to-orbit launch requirements as future payloads and are factored into the projected needs for space exploration. The Committee recognizes that carrying such nuclear payloads to Earth orbit requires a thorough understanding of safety under all conceivable emergencies. **At this time, the Committee does not consider nuclear propulsion suitable for use in Earth-to-orbit launch vehicles, even in upper stages. Nevertheless, the potential benefits in other applications could be great, and continuing investment in research and development could have high future payoffs, presuming the inherent safety issues are adequately addressed.**

COMPONENT AND GENERAL TECHNOLOGIES

Materials Technologies

The next generation of launch vehicles should be guided as much as possible by a flexible philosophy of design and manufacturing that embodies the concurrent engineering of materials and their applications. Materials engineering should be considered throughout planning and development of any new launch system and should play a central, integrated role in the design

process. In addition, a vigorous program of generic research in structural materials for space propulsion should be maintained independently of the development of particular vehicle systems.

Composites made up of ceramic or intermetallic matrices reinforced by ceramic fibers are promising for elevated-temperature engine applications and may contribute to significant improvements in engine thrust/weight ratios. Similarly, conventional polymer-matrix composites and new aluminum alloys, as well as ceramic-fiber-reinforced metal-matrix composites, may permit substantial weight reductions in vehicle structures and tanks. Improved structural mass fractions may also result from the introduction of advanced monolithic metals and alloys.

In all cases, rigorous test programs are essential to determine the extensive array of physical properties that are required for the characterization of new materials before they can be used in the design and fabrication of launch vehicle components. Research on methods of quantitative nondestructive evaluation of materials and structures, and the exploitation of such techniques, is strongly encouraged. **The Committee recommends renewed emphasis on materials research and development for the engine environment and for modern airframes, as well as nondestructive evaluation techniques.**

Health Monitoring of Rocket Systems

Pad hold-down with engine shutdown and throttleability are considered highly desirable attributes of a new family of vehicles. **Hence, innovative methods are needed to monitor the propulsion system and implement any required shutdowns at appropriate locations.** There was no evidence presented that this design approach is being addressed in the National Launch System (NLS) program as it currently exists.

Connectors and Interfaces for Fuel and Electrical Systems

The technology incorporated in current launch vehicle liquid propulsion systems is rooted in the 1960s. A reliability analysis⁵ indicated that 50 to 70 percent of propulsion system failures occur outside the engine itself. There needs to be an investment directed to upgrading propellant feed system technology, with an emphasis on improving system reliability and simplifying launch operations and serviceability of these components. The design process should include analyses to trade off the reliability and serviceability of fixed connections as opposed to other types.

⁵ Leonard, B.P. 1991. Projected Launch Vehicle Failure Probabilities With and Without Engine Segment-out Capabilities. L-Systems, Inc. El Segundo, Calif.

The Committee believes that reusability of launch systems will come with time and encourages the development of technologies toward that end. The design of interfaces to facilitate quick disconnect and reconnect of propulsion system components is essential to achieving that goal. Research on such concepts must be supported to facilitate on-pad checkout of system operability.

Guidance, Navigation, Control, and Autodocking

In reviewing the proposed missions, vehicles, and potential schedules, the Committee identified guidance, navigation, and control (GN&C) as an area in which technology development carried out in the near future would enable superior vehicle and mission capability. Two specific items that could have definite application are (1) a modern, miniaturized GN&C system and (2) an automatic, unmanned docking capability within this GN&C system.

The current progress in solid-state guidance components and fiber-optic gyroscopes suggests that flightworthy systems could be available in time for early missions of the proposed new vehicles. The advantages to be gained include lighter weight (redundancy), ruggedness, less sensitivity to the environment, and reduced manufacturing cost. There is also the attractive potential for updating systems based on the Global Positioning Satellite System.

Unmanned docking capability has not previously been required by NASA. However, such a requirement seems likely for Space Station Freedom and space exploration. It appears that a suitable system could be derived from former Soviet Union (FSU) systems or could be assembled from more modern components. Even if new U.S. technology were employed, there would be some benefit from international cooperation with the FSU in this area.

Launch Operation Technology Needs

Launch operation concerns are wide ranging. They encompass closed aft compartments, fluid system leakage, conditioning of the cryogenic systems, bleeds and purges, and the need for external gas supplies for turbopump spin-up for start operations. Many of these issues can be resolved in the design of a modern launch system, but some will require new technology. For example, the issue of leaks dictates research on eliminating devices that may have the potential for leaks as well as on methods of detection that can survey a large area, determine that leakage is occurring, and isolate the location of the leakage to permit repair without extensive invasions into the vehicle system.

The vehicle and engine health monitoring system is an essential ingredient for the automated checkout of the system(s) on the pad. Technology needs to be advanced that permits both launch system readiness and in-flight status evaluation.

For example, a single-stage-to-orbit vehicle promises significant reduction in the number of interfaces that must be dealt with on the launch pad and, hence, the time required in launch preparations. The technology to enable such a vehicle will also serve to simplify launch operations.

Similarly, the modular engine approach permits a significant reduction in the total number of components over a conventional propulsion system.⁶ This, in turn, reduces the complexity of launch servicing and checkout operations on the launch pad. Technology development is needed in the algorithms for the control system that permit selective shutdown of components and rerouting of propellant flows to ensure successful propulsion system operation.

Manufacturing Technologies

A number of overall manufacturing considerations must be included to take full advantage of cost reduction opportunities for any future launch vehicle. These require designing from the outset for producibility, which involves determination of those components, subassemblies, and parts that require close tolerances and those that do not, so that appropriate manufacturing processes can be selected.

Technology advancement must be pursued in forming, joining, and machining to ensure that processes that reduce fabrication time, enhance the quality of the resultant parts, and minimize loss and wastage are brought to fruition to support the next generation launch vehicle program.

Special attention should be devoted to those technologies that enhance inspection techniques to ensure the quality of manufactured parts and joined assemblies. This should include technology to facilitate in-place inspection of welds in low-pressure feed lines and other, critical, installed propulsion subsystems. The Committee assumes that any new undertaking will incorporate the discipline of total quality management (TQM).

CONCLUSION

Research and technology development in areas of high potential payoff such as those identified above are critical to the future of the U.S. launch industry. **A greater long-term investment must be made to build the technology base for future systems.** Critical, enabling technologies not associated with an ongoing program are chronically underfunded, and today's

⁶ Wong, George. April 24, 1990. Operationally Efficient Propulsion Systems (OEPSS) Data Book. RI/RD90-149-5. Rocketdyne.

decisions are hampered by the absence of research and development in the past decades. Underlying research and development provides technical stamina for the future.

Biographical Sketches Of Committee Members

JOSEPH G. GAVIN, JR., served as a Senior Management Consultant for Grumman Corporation until 1991 after retirement as President of Grumman in 1985. During the Apollo years, Mr. Gavin was Director of the Lunar Module Program. In 1971, the National Aeronautics and Space Administration (NASA) awarded him its Distinguished Public Service Medal for his contributions "as the leader and representative of the Lunar Module team at Grumman." Mr. Gavin received a B.S. and M.S. in aeronautical engineering from the Massachusetts Institute of Technology. He is a Fellow of the American Institute of Aeronautics and Astronautics and the American Astronautical Society, a member of the International Academy of Astronautics and the National Academy of Engineering (NAE). Mr. Gavin has participated in many committee activities within the Department of Defense (DoD), the Department of Energy (DoE), and the National Research Council (NRC). He recently served as Chairman on the DoE Research Advisory Board's Panel on Magnetic Fusion, as a board member of the American Association for the Advancement of Science, and as a member of the Massachusetts Institute of Technology's governing board. He is currently a member of the Corporation and was a Director of the Charles Stark Draper Laboratory, Inc.

EDMUND BLOND is retired from the Aerospace Corporation where he spent the last 30 years of his professional career, leaving in 1991. His assignments at The Aerospace Corporation were split between technology, as Manager of Special Studies in the Fluid Mechanics Department, and systems analyses, as Senior Project Engineer and Director of Systems Analysis in the Launch Vehicle Division specializing in the area of costing/trade-offs of launch vehicles for future space missions. His report on space launch vehicle costs (1984), prepared for the Office of Commercial Space Transportation, served as a primary reference for U.S. launch vehicle costs for the U.S. Department of Transportation (DoT). He received a B.S. in mechanical engineering from the University of California (UCLA), an M.S. in mechanical engineering from the University of Southern California, and an M.B.A. from California State University at Dominguez Hills.

YVONNE C. BRILL is currently a consultant for Telespace, Ltd. In 1991 she retired from the International Maritime Satellite Organization, where she was a staff engineer in Space Segment Engineering. She began her career as a mathematician with Douglas Aircraft Company and subsequently served as a research analyst with the RAND Corporation, then as project engineer and consultant at several aerospace firms throughout the 1950s, 1960s, and 1970s. In 1978, she became Manager of NOVA Propulsion Systems for RCA Astro-Electronics Division and later served as Manager of the Solid Rocket Motor program in NASA's Office of Space Flight. Ms. Brill received her B.Sc. in mathematics from the University of Manitoba, Canada, and her M.S. in chemistry from the University of Southern California. She is a member of the International Academy of Astronautics and the NAE, and a Fellow of both the American Institute of Aeronautics and Astronautics (AIAA) and the Society of Women Engineers. She is also a member of the NAE Advisory Committee on International Affairs.

BERNARD BUDIANSKY is currently Gordon McKay Professor of Structural Mechanics, and Abbott and James Lawrence Professor of Engineering at Harvard University. Dr. Budiansky began his career in 1944 with the National Advisory Committee on Aeronautics (NACA) at Langley Field, serving as Head of the Structural Mechanics Branch from 1952 to 1955. In 1955, he joined the faculty of Harvard University. Dr. Budiansky obtained his B.C.E. from the City College of New York and his Sc.M. and Ph.D. from Brown University. He is a member of the National Academy of Sciences (NAS) and the NAE. He has served on a number of boards and committees for NASA, the Defense Advanced Research Projects Agency (DARPA), and the NRC, and is a fellow of the AIAA and the American Society of Mechanical Engineers. He also has received numerous awards from universities and professional organizations.

ROBERT S. COOPER is President, Chief Executive Officer, and Chairman of the Board of Directors of Atlantic Aerospace Electronics Corporation. Throughout more than 30 years of involvement in military and space technology, he has held positions that include Director of DARPA; Assistant Secretary of Defense for Research and Technology; Engineering Vice President of Satellite Business Systems; and Division Director at MIT's Lincoln Laboratory. Dr. Cooper was Director of NASA Goddard Space Flight Center from 1975 to 1979 and was responsible for determining the direction for major NASA research programs and operation of the Thor-Delta launch vehicle. He holds a D.Sc. degree in electrical engineering and mathematics from the Massachusetts Institute of Technology. Dr. Cooper's background also extends to research in plasma physics and electromagnetic scattering from plasmas, and laser, radar, and infrared systems engineering.

WOLFGANG H. DEMISCH is Managing Director at UBS Securities in New York City, where he is responsible for equity investment strategy and aerospace equity research. After

graduating from the Harvard Business School in 1972, Mr. Demisch worked at Smith Barney Harris Upham & Co. Inc.; at Morgan Stanley, Inc.; and at the First Boston Corporation, where he was responsible for equity research regarding the aerospace industry. Mr. Demisch is a member of the AIAA, the American Association for the Advancement of Science (AAAS), the Financial Analysis Federation, and the NRC's Aeronautics and Space Engineering Board.

CLARK W. HAWK is currently Director of the Propulsion Research Center and Professor of Mechanical Engineering at the University of Alabama at Huntsville. From 1958-1991, Dr. Hawk worked for the U.S. Air Force (USAF) as an Air Force civilian. During this time, he served at the Astronautics Laboratory and its precursor organizations in numerous capacities. He was Chief of the Liquid Rocket Division, created and served as the Chief of the Nozzle Technology Section, and most recently, was the Director of the Propulsion Division. Under his management, this division was responsible for providing all solid rocket motor and liquid rocket engine technology for the USAF. He received a B.S. in mechanical engineering from Pennsylvania State University and his M.S. and Ph.D. degrees from Purdue University. Dr. Hawk is an Associate Fellow of the AIAA where he has been active on a number of its committees related to rocket propulsion and was an associate editor of the Journal of Propulsion and Power. Dr. Hawk is a member of the National Society of Professional Engineers and received numerous performance awards for outstanding service during his Air Force career.

JACK L. KERREBROCK is currently R.C. Maclaurin Professor of Aeronautics and Astronautics at Massachusetts Institute of Technology (MIT). His career began in 1951 at NACA Lewis Flight Propulsion Laboratory, and he later held senior positions at California Institute of Technology, Oak Ridge National Laboratory, MIT, and NASA Headquarters, where he was Associate Administrator for Aeronautics and Space Technology from 1981 to 1983. His research and teaching emphases have included nuclear rockets, space propulsion and power, magnetohydrodynamic generators, and aircraft engines. Dr. Kerrebrock received his doctoral degree from the California Institute of Technology in 1956. He was elected to the NAE in 1978. He has served on the Presidential National Commission on Space, several Air Force and NASA advisory boards, and on the NRC's Aeronautics and Space Engineering Board, Air Force Studies Board, and Engineering Research Board. Dr. Kerrebrock served as Chairman of the NRC's Committee on Hypersonic Technology for Military Applications. He is a Fellow of the AIAA, the AAAS, the Explorer's Club, the American Academy of Arts and Sciences, and a senior member of the American Astronautical Society.

BYRON K. LICHTENBERG is currently the President and Chief Executive Officer of Omega Aerospace, Inc. In 1983, Dr. Lichtenberg became the first non-NASA Payload Specialist astronaut to fly aboard the Space Shuttle on the flight of *Spacelab 1*. This multinational, multidiscipline, space science mission lasted for 10 days and included the first

flight of a non-US. astronaut as well. During the 168 orbits of the Earth, Dr. Lichtenberg conducted more than 70 experiments in five different scientific disciplines including Earth observation, plasma physics, materials science, and life science. He received his B.S. from Brown University, cum laude, in aerospace engineering and entered the U.S. Air Force Pilot Training Program. After a combat tour in Vietnam, where he received 10 Air Medals and two Distinguished Flying Crosses, he returned to graduate school at MIT. Dr. Lichtenberg was awarded an M.S. in mechanical engineering and a D.Sc. in biomedical engineering from MIT. In 1984, he founded Payload Systems, Inc., a space flight engineering and support services company that assists commercial, academics, government, and foreign users in preparing for space experiments. Payload Systems, Inc., is probably best known for being the first U.S. company to negotiate a launch agreement with the Soviet Union. Dr. Lichtenberg recently completed his second spaceflight mission in April, 1992.

ARTUR MAGER is currently an aerospace consultant. He is a former Group Vice President of the Engineering Group and member of the Executive Council of The Aerospace Corporation. In that position he had responsibility for all aspects of the engineering support of the company's work on the U.S. Air Force's launch vehicle and space programs. He has authored many publications in the areas of three-dimensional boundary layers, swirling flows, supersonic burning, heat transfer, thrust vectoring, space vehicle design, propulsion, and reliability. Upon his retirement, he was honored by the establishment of the Artur Mager Prize at the California Institute of Technology, where he received his Ph.D. in aeronautics and physics in 1953. As a consultant, he has served on numerous DoD, NASA, NRC, Los Alamos, and aerospace company advisory boards and committees. He is a member of the NAE and a Fellow and former President of the AIAA. Dr. Mager is a Trustee of the West Coast University, a Fellow of the American Association for the Advancement of Science and the Institute for the Advancement of Engineering, and has been honored by several organizations for his work aimed at helping individuals with developmental disabilities.

FRANK E. MARBLE is currently the Richard L. and Dorothy M. Hayman Professor Emeritus at the California Institute of Technology. He is a member of the NAS and NAE. His career began with the NACA at Lewis Flight Propulsion Laboratory in 1942, where he also served as an instructor at the Case School of Applied Science. In 1948, Dr. Marble joined the faculty of the California Institute of Technology, where he has served in numerous capacities. Throughout his career he has been a consultant to a number of aeronautics and other engineering companies and has served as a visiting professor at many U.S. and foreign universities. Dr. Marble received his Ph.D. in aeronautics and mathematics from the California Institute of Technology. He has served on numerous committees and advisory groups for NACA, NASA, the Air Force, the North Atlantic Treaty Organization (NATO), and the NRC's Aeronautics and

Space Engineering Board. Dr. Marble is a Fellow of the AIAA and was the recipient of its Annual Propellants and Combustion Award for 1991.

ALTON D. SLAY retired from the U.S. Air Force in 1981 after more than 38 years of military service, rising from the rank of private to four-star general. General Slay's last assignment on active duty was as Commander, Air Force Systems Command. Prior to that, he held a series of distinguished assignments including Deputy Chief of Staff, Research and Development and Acquisition, Headquarters, USAF. General Slay has accumulated more than 9000 hours of flying time, mostly in fighter aircraft. He flew every USAF fighter and attack aircraft from the P-40 through the F-16 and was current in the F-15C at the time of his retirement. General Slay accumulated 181 combat missions in fighters in Southeast Asia. He holds a degree in mathematics from George Washington University and is a graduate of the Harvard Advanced Management Program. He was the Chairman of the NAS Committee on Shuttle Criticality Review and Hazard Analysis Audit subsequent to the loss of *Challenger*. General Slay is currently President of Slay Enterprises, Inc., which has performed more than 450 "Red Team" reviews for its clients in the last 10 years.

JASPER A. WELCH is currently a private consultant in the aerospace field. General Welch retired from the U.S. Air Force after more than 30 years experience in conducting and directing advanced technology programs in the aerospace industry. He held a number of posts within the government, including Defense Policy Coordinator for the National Security Council, USAF delegate to NATO's Council of National Armaments Directors, and technical lead for the Air Force Research, Development and Acquisitions Program. General Welch received his doctorate in physics from the University of California, Berkeley in 1958. He is a member of the NAE and the Council on Foreign Relations. He currently chairs a special advisory panel for the Director of the Central Intelligence Agency and has led the NASA Task Force on Space Transportation. General Welch also serves on a number of corporate boards and senior advisory boards for Lawrence Livermore National Laboratories, Los Alamos National Laboratory, and Lincoln Laboratories of MIT.

Appendix A

AN APPROACH TO SPACE INFRASTRUCTURE

The National Aeronautics and Space Administration (NASA) currently operates launch facilities on the East Coast at Kennedy Space Center (KSC) for the Space Shuttle and at Wallops Island for smaller ELVs and sounding rockets. The Department of Defense (DoD) operates facilities on both the East Coast (Cape Canaveral Air Force Station, CCAFS) and the West Coast (Vandenberg Air Force Base, VAFB) for expendable launch vehicles.

Deficiencies of Current Space Launch System and Infrastructure

The entire U.S. space launch system lacks flexibility and resilience. Although the shuttle facilities are reasonably modern and adequate to support the current Shuttle manifest, they cannot support other launch vehicles. In addition, expendable launch vehicle (ELV) facilities are generally old, and many have deteriorated badly. The launch pads are dedicated to specific vehicles and, with current methods of processing vehicles and payloads, are inefficient and greatly constrain operations. The command, communications, and control (C³) infrastructure supporting the ELV program is more flexible and resilient than the launch pad portion of the infrastructure, but it is also old and inefficient. Attention must be paid to these problems and corrective measures planned, budgeted for, and implemented to provide a serviceable and efficient launch capability for the future. National needs are not well served by the current infrastructure, and the situation will continue to deteriorate unless action is taken. Specific problems are discussed below in detail.

Lack of Flexibility of the Launch System

- Each pad is dedicated to a single type of ELV. This greatly constrains flexibility and engenders delays and other schedule problems. It is highly inefficient in terms of both the cost and the manpower required to support total launch requirements.
- There is no capability for changing payloads once a payload and ELV are matched on the schedule. This occurs many months before the launch and is a particularly constraining factor.
- The current process and payload preparation techniques require lengthy time on the launch pad. Most payloads are completely integrated on the launch pad. None of the current ELV launch facilities has complete payload encapsulation and off-pad integration capabilities.
- The small number of launch pads for each type of ELV on both the East and the West Coast greatly restricts scheduling flexibility. For instance, although NASA could beneficially use Titan III-type launch vehicles, there are no launch pads generally available to support such launches because the launch pads are usually reserved for Titan IV launches. Furthermore, Titan IV launch pads are generally reserved for DoD payloads, thus greatly constraining the use of Titan IV by NASA.

Lack of Resilience of the Launch System

In the event of damage or other significant problems on a pad, there is extremely limited capability to effect recovery and return to schedule in an expeditious manner.

- In many cases, only one launch pad is available to support a launch requirement. A disaster on any of these launch pads would result in lengthy downtimes and concomitant slips in schedules.
- There are no satisfactory alternate launch pads available. The situation that currently exists provides no backup to accommodate high-priority DoD and national payload launches. If a launch pad is badly damaged, such high-priority payloads must await complete repair prior to launch.

Scheduling Difficulties in the Launch System

- It is difficult to schedule commercial launches. Even if commercial users could be enticed to employ the current U.S. ELVs, there would be a large problem of pad availability. There is little capability currently available to guarantee a commercial launch on a specific schedule; thus, commercial payloads often go to foreign competitors for more suitable arrangements.

Shortage of Land for Construction of Launch Facilities

- *East Coast:* Although there is more land available at CCAFS and KSC, the proximity of built-up areas south of the reservation makes much of the area unusable due to quantity and distance criteria. Also, much of the terrain is taken up by old, obsolete facilities that are in a state of decay and are incapable of supporting today's ELVs. Heavy infiltration of the launch complex with industrial buildings and facilities is also a constraining factor.
- *West Coast:* Only a very narrow strip of land at VAFB is suitable for launches into polar orbit without overflight of populated areas. Only the southern tip of the government reservation can be used for space launches. However, some of the facilities there (e.g., SLC-6) are unusable in their current state. Use of northern areas of the reservation would require launches which are highly inefficient in propulsion power and cause penalties in terms of payload capability in order to stay within certain restricted areas.

Description of Recommended Infrastructure Improvements

General

In light of the severe shortcomings of the existing ELV infrastructure, at both the East and West Coast launch sites, the Committee recommends the construction of new universal launch complexes at each site. These complexes would then incorporate the necessary improvements to eliminate the shortcomings that now exist and would be sized to accommodate existing ELVs as well as all foreseeable new developments. Preliminary designs and costing are required to demonstrate the feasibility of the various infrastructure proposals. As previously described, the available land on both coasts no longer permits the luxury of tying launch complexes to specific ELVs. The existing ELV launch complexes should be maintained to support the current launch vehicle fleet until the new complexes come into operation. The timing of new launch complex construction should be phased to coincide with the operation of

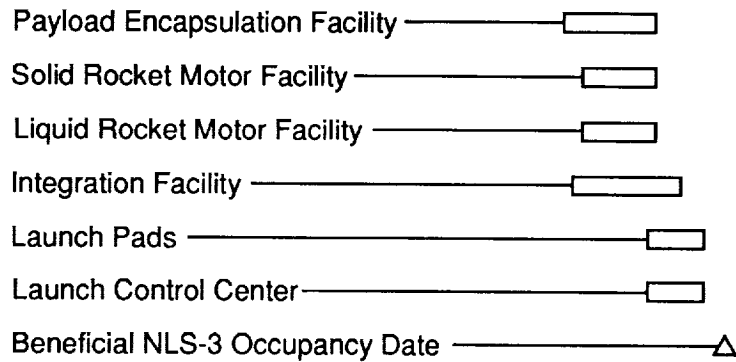
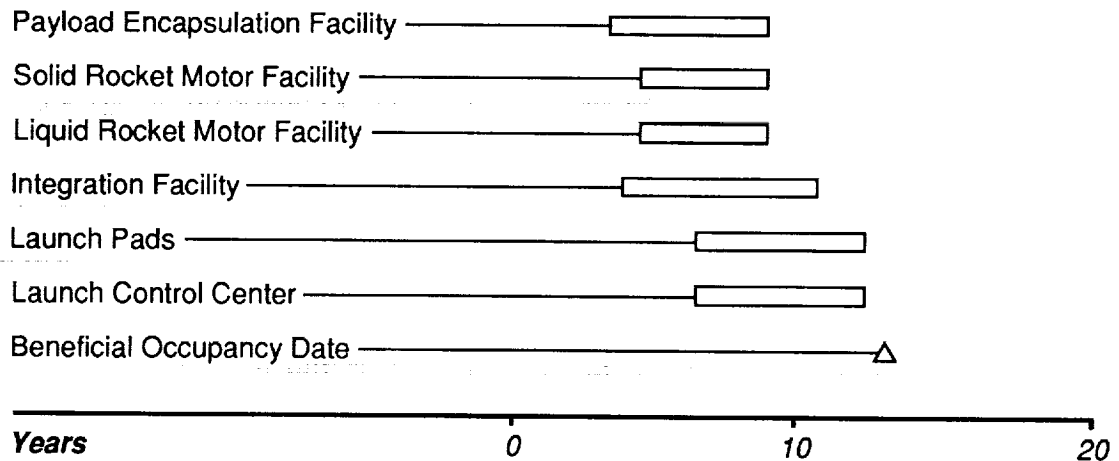
East Coast**West Coast**

FIGURE 5 Proposed schedule for the development and construction of a new launch infrastructure.

the National Launch System (NLS) also recommended by the committee. The various launch complex elements can be appropriately phased to avoid funding constraints and to meet the needs of the NLS elements as they come on-line. This would indicate an initial operational capability in the early 2000 time frame, with planned growth to meet future needs as requirements or funding permits. A conceptual time schedule for facilities is shown in Figure 5.

Launch Complex Philosophy

Enabling new launch complexes to achieve the desired goals of multivehicle use, high flight rates, reduced operational costs, improved flexibility, robustness, and resilience requires several changes in the current general operational philosophy:

- *Integration, Transfer, and Launch (ITL):* The integration, transfer, and launch (ITL) philosophy requires that all launch vehicle/payload assembly, integration, and testing be accomplished away from the launch pad. In this scenario, the assembled vehicle is delivered to the launch pad for final interface verification, main propellant loading, countdown, and launch. Thus, the time spent on the launch pad itself is minimal. If a vehicle or payload problem is discovered, the entire assembled vehicle is returned to the off-line integration facility for correction.
- *Payload Encapsulation:* Payloads must be encapsulated and integrated onto the launch vehicle off-line by using standardized fittings (attachment, power, etc.) with no payload-induced launch pad delays. Ariane successfully uses this approach to maximize launch rate capability.
- *Multiuse Capability:* To enable use by all current and future launch vehicles, the facility elements must be designed with the ability to handle the range of potential vehicle sizes that can reasonably be envisioned or to provide room to add the additional capabilities necessary as a preplanned improvement.

Launch Complex Elements

Though the Committee has not attempted to describe all possible elements of the new launch complexes, some of the more important elements are briefly described below:

- *Payload Encapsulation Facility:* A separate facility to permit payload encapsulation, with a minimum of two bays will be necessary. This will also provide an on-site facility for final integration as well as checkout before encapsulation for the payload contractors.
- *Integration Facility (Vehicle Integration Building, VIB):* The integration facility should have a number of separate cells, which may be modular to cover a reasonable range of vehicle sizes. Allowance should be made for additional future cells. The intent is to have a sufficient number of cells of appropriate size to ensure that this is not a restricting element in achieving more rapid turnaround.

- *Mobile Launch Platform (MLP):* The assembled launch vehicle will be transported from the integration facility to the launch pad and launched off the mobile launch platform (MLP). To minimize the number of different MLPs necessary for the variation in potential launch vehicle sizes to be handled, a modular platform that can be adjusted over a reasonable range to match vehicle configurations and with flame openings to handle the largest vehicle considered would be essential.
- *Launch Pads:* The launch pads are basically simple, with no fixed or mobile service towers (all repairs are done off line). They contain simplified interfaces and are sized for multivehicle configurations. A minimum of two launch pads for any complex is essential to ensure alternative launch capabilities in the event of launch pad damage.
- *Supporting Facilities:* A separate liquid rocket motor facility, with a minimum of two bays, will be necessary for assembling the variety of boosters, upper-stage liquid engines, and associated propulsion elements, prior to delivery to the integration facility. A similar facility is needed for handling solid and hybrid rocket elements. A Launch Control Center (LCC) is essential for any launch complex.

Conceptual Launch Complex

The Committee has sketched a tentative design for a conceptual launch complex at the eastern test range (ETR) and western test range (WTR) to represent the potential interaction of the elements described above.

- *East Coast Launch Facilities:* The Committee conservatively split the integration/pad elements into two size groupings, considering the large potential range of vehicle sizes and the pad separation distances dictated by the launch vehicle quantity/distance criteria (explosive hazard). Whether this split is necessary or not is unknown at this time. The launch facility groupings (Figure 6) were then assumed as follows to handle the anticipated traffic scenarios:
 - One multi-ELV four-pad facility capable of launching vehicles with low-Earth orbit (LEO) delivery capabilities up to 20,000 pounds.
 - One multi-ELV two-pad facility capable of launching vehicles with greater than 20,000 pounds LEO delivery capability.
- *West Coast Facilities:* A similar arrangement is shown in Figure 7, based on anticipated less-demanding traffic scenarios.

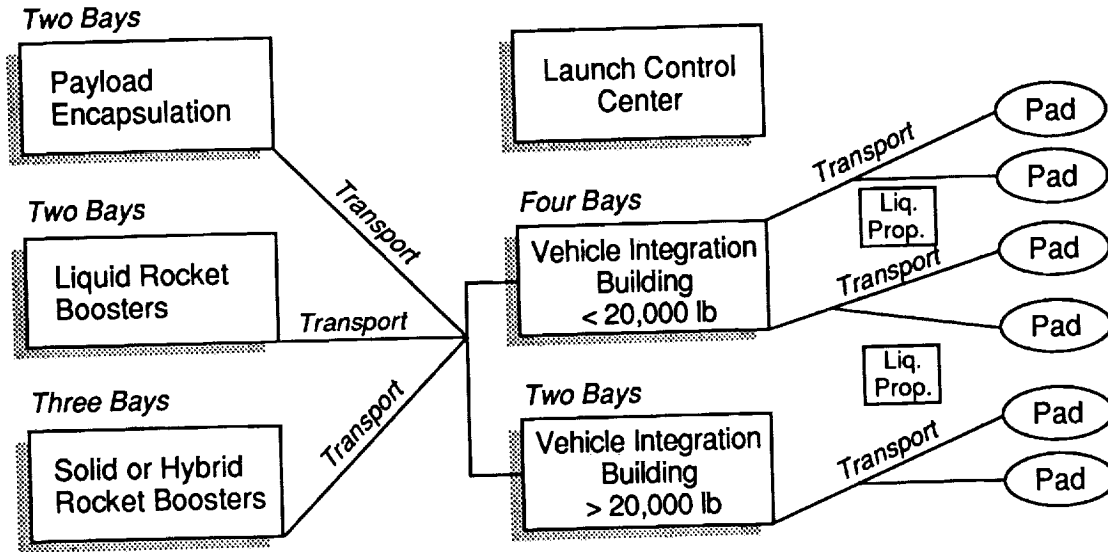


FIGURE 6 Proposed schematic for East Coast launch facilities.

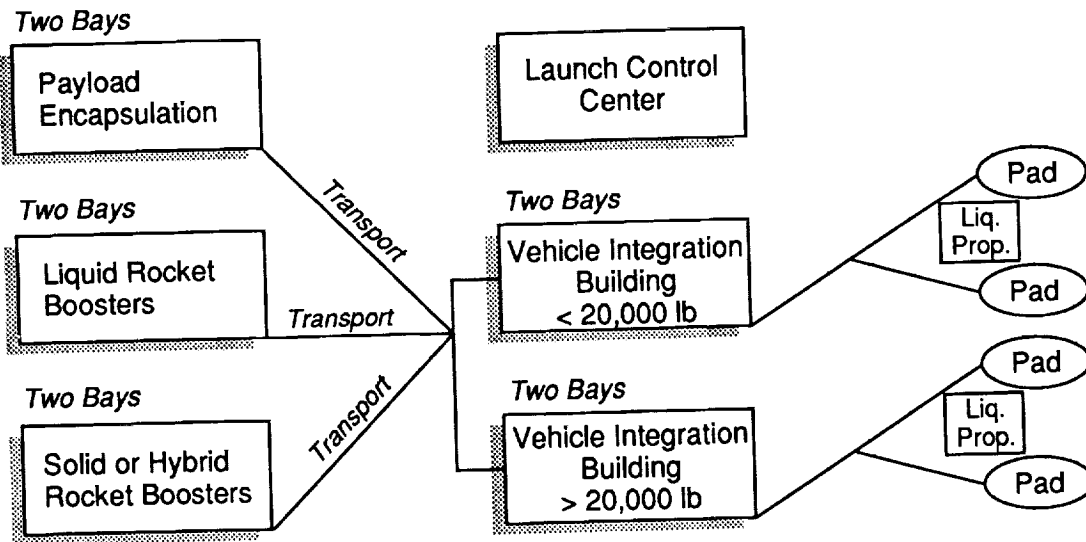


FIGURE 7 Proposed schematic for West Coast launch facilities.

Appendix B

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Appendix C

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