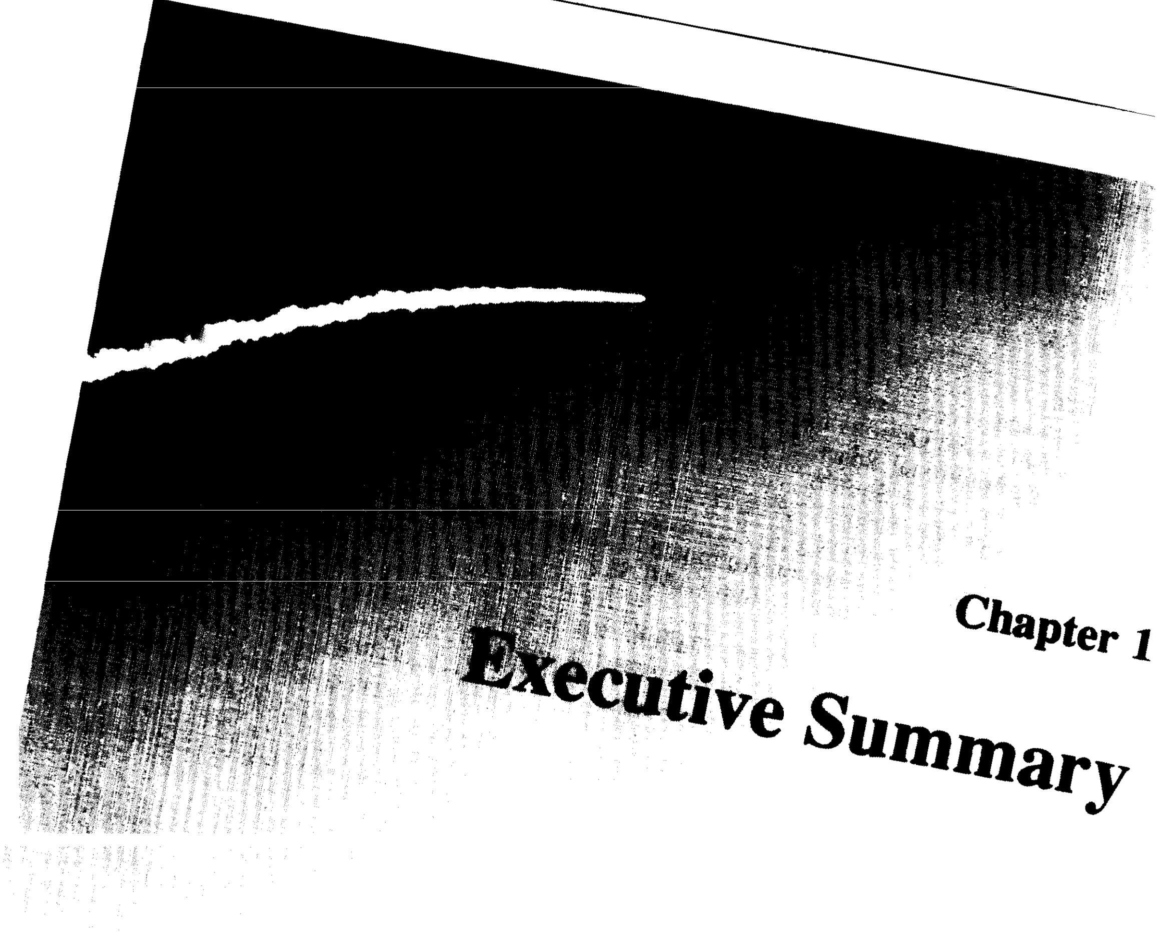

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INTRODUCTION

In the early part of the next century, the National Aeronautics and Space Administration (NASA) and the Department of Defense (DoD) intend to build new, advanced launch systems to carry crews to space. In the interim, NASA hopes to make Space Shuttle launches more routine. Between now and the end of the century NASA expects to employ the Space Shuttle to conduct scientific and engineering research, to launch space probes and satellites, and—in partnership with Canada, the European Space Agency, and Japan—to establish a permanent human presence in space on the planned international Space Station.

This special report examines technologies and systems for transporting astronauts and scientists to and from low-Earth orbit, and explores some of the policy choices that Congress faces in this critical aspect of the U.S. Government's space program. The report analyzes a variety of ways to make the Space Shuttle system safer and more reliable. It also explores several proposed systems to replace the Shuttle early in the next century, and examines proposals for a Space Station crew escape system. Finally, the report discusses the most advanced proposed launch system, the National Aero-Space Plane, and compares it with other potential future launch systems. The report does not examine cargo-only launch vehicles except insofar as their use may affect the need for crew-carrying launchers.

OTA prepared this special report as part of an assessment of advanced space transportation technologies requested by the Senate Committee on Commerce, Science, and Transportation and the House Committee on Science, Space, and Technology. For this assessment, OTA has previously published a special report, *Launch Options for the Future: A Buyer's Guide;*[1] a technical memorandum, *Reducing Launch Operations Costs: New Technologies and Practices,*[2] and a background paper, *Big Dumb Boosters: A Low-Cost, Transportation Option?*[3] A final report will summarize the findings of these interim documents.

PEOPLE IN SPACE

Since 1961, when President Kennedy called for a program to send men to the moon and back, NASA's "manned"[4] space efforts have determined much of the direction and spending of the government's civilian space program. Today, NASA's projects involving humans in space, primarily the existing Space Shuttle and the planned Space Station, consume between 65 and 70 percent of NASA's space budget, or between $6.8 billion and $7.3 billion in fiscal year 1989.[5]

From the early days of the U.S. space program, experts have argued over the appropriate mix of crew and automated civilian space activities. Although employing people in space to conduct most science research and exploration dramatically raises the costs compared to automated approaches, the perceived national and international benefits of having U.S. and foreign citizens live and work in space have nevertheless sustained the human component of the civilian space program.

Assessing the most appropriate mix of spending on automated and crew-dependent activities

[1] U.S. Congress, Office of Technology Assessment, OTA-ISC-383 (Washington, DC: U.S. Government Printing Office, July 1988).

[2] U.S. Congress, Office of Technology Assessment, OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

[3] U.S. Congress, Office of Technology Assessment (Washington, DC: Office of Technology Assessment, February 1989).

[4] The terms piloted or crew-carrying are used in this report in lieu Of 'manned."

[5] These figures exclude $404 million for aeronautics. The fiscal year 1990 civilian space budget request of $12.8 billion (which excludes $463 million for aeronautics) allocates about 71 percent to programs supporting crews in space. Most of President Bush's 20 percent requested budget increase for NASA for fiscal year 1990 derives from scheduled increases in the request for the Space Station.

is beyond the scope of this report. However, **existing U.S. policy calls for expanding "human presence and activity beyond Earth orbit into the solar system."[6] Pursuing this policy earnest would eventually require markedly increased funding of the government's civilian activities involving people in space, and therefore additional space transportation capability.** Major projects requiring crews in space could include the construction of a permanent base on the Moon, or the exploration of Mars. These, or other projects in the early part of the next century, would require the support of substantial in-orbit infrastructure, such as a space station, orbital maneuvering vehicles, and fuel storage depots. The pace and timing of such expansion will depend on the willingness of Congress, on behalf of U.S. taxpayers, to support such activities in competition with other uses of public monies.

In contrast to the civilian space program, the DoD has not identified a firm requirement for placing people in space.[7] However, if military needs were eventually to dictate a requirement for the procurement of a fleet of aerospace planes, as is contemplated by supporters of the National Aero-Space Plane program, this development could lead to a major commitment by the DoD to crews in space.

Expanded commitment to placing crews in space for the civilian and/or military space programs would eventually entail developing new launchers and other space vehicles capable of transporting people. It would also require increased yearly outlays for space transportation.

Spaceflight is inherently risky. As America's reaction to the *Challenger* disaster suggested, the loss of another Shuttle orbiter and its crew would likely result in another long standdown of the Space Shuttle, with attendent loss of momentum in the civilian space program. It would most certainly lead to a painful reexamination of the space program's purpose and direction. Yet, as the following section makes clear, the United States should expect the loss of another orbiter (though not necessarily with loss of life) at some time in the next decade. **If the United States wishes to send people into space on a routine basis, the Nation will have to come to grips with the risks of human spaceflight. In particular, it will have to accept the likelihood that loss of life will occur. If such risks are perceived to be too high, the Nation may decide to reduce its emphasis on placing humans in space.**

SPACE TRANSPORTATION OPTIONS FOR THE NEXT DECADE

NASA and the aerospace community have begun to consider how best to maintain or enhance crew-carrying capacity for the next decade, as well as for the beginning of the next century. Decisions concerning systems that would be developed for use in the next decade must be made in the immediate future because of the lead times required for these highly complex systems. Cost and schedule will constrain the decisions on these systems.

Purchasing Additional Space Shuttle Orbiters

To reduce the risk of costly delay in constructing or operating the Space Station, or meeting other NASA and DoD missions, NASA will have to add one or more orbiters to its existing Shuttle fleet by the mid-1990s and restrict the use of Shuttle to essential payloads. Current plans call for reaching 14 Shuttle flights per year by 1993, one year after NASA expects to add orbiter OV-105 *(Endeavor),* now under construction, to the fleet to replace *Challenger.* If the existing three orbiters[8] are still operating at that time, the Shuttle

[6] The White House, "National Space Policy," Fact Sheet, Feb. 11, 1988, p. 1.

[7] Indeed, the Secretary of Defense recently decided to cut spending on the National Aero-Space Plane program dramatically.

[8] The flint now consists of *Columbia, Discovery,* and *Atlantis.*

fleet will then consist of four orbiters. However, continued dependence on only four orbiters could be risky (figure 1-l). Launching each orbiter three or four times every year creates a growing cumulative risk of accidents or "wear out; ' ' supporting the Space Station in addition to other crew-related missions would be difficult if not impossible with fewer than four orbiters. In addition to adding resilience to Space Station operations, building one or more additional orbiters would also help preserve existing expertise and manufacturing ability.

If major structural spares[9] were in the inventory, construction of an additional orbiter would take about 5 years and cost about $2.5 billion, including the cost of replacing the spares. In the absence of structural spares to draw on, construction would take about 6 years. Therefore, should Congress decide that it is important to have another orbiter as soon as possible (1996), it could either:

- fund NASA to build an additional orbiter starting in fiscal year 1990; or
- fund NASA to order structural spares in fiscal year 1990 and defer a final decision on whether to build the orbiter until the fiscal year 1991 budget is decided.

Some structural spares are needed for the existing fleet in any case, so a decision in 1990 to purchase structural spares would not commit Congress to fund construction of an additional orbiter, but could provide necessary backup to the four-orbiter fleet.

Improving the Space Shuttle

NASA is considering ways to extend the useful lifetime of the Shuttle fleet by replacing or enhancing Shuttle subsystems, such as avionics, structural components, and computers, and by improving launch operations procedures (box 1-A). Improvements, some of which have been made or are under way, might keep the Shuttle fleet flying until 2010 or beyond.[10] *Minor improvements* to the existing orbiter, external tank, solid rocket boosters, and facilities could be accomplished during the regularly scheduled structural inspection program (every 3 years). *Major improvements* to orbiters would take a substantial commitment of NASA's energies, and a major funding commitment from Congress. Improvements in the form of weight reduction modifications or performance increases could boost the Shuttles carrying capacity or provide the opportunity to construct an enhanced crew escape capability.

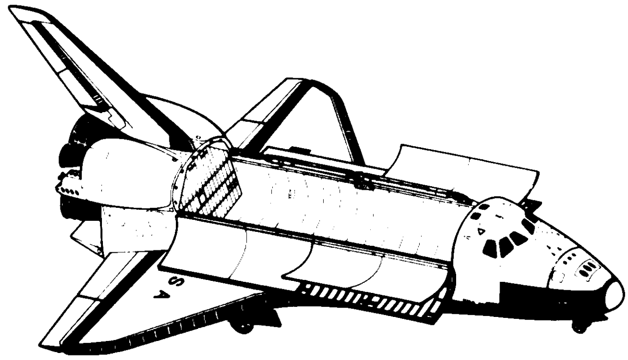


Photo credit: National Aeronautics and Space Administration

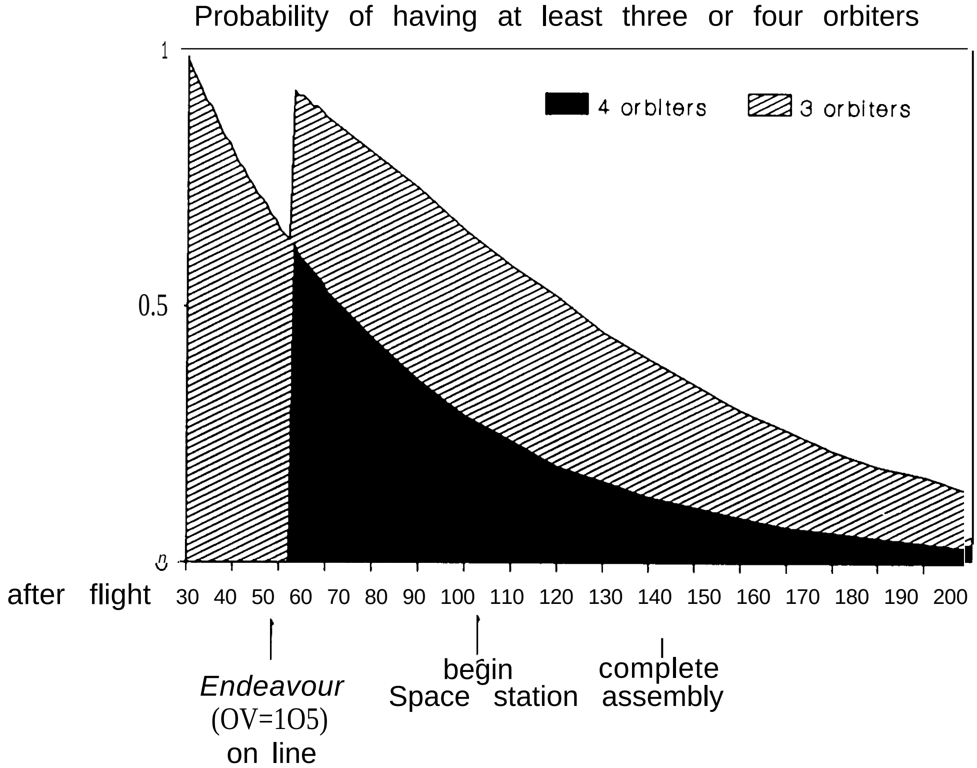
Drawing of Space Shuttle orbiter, showing payload bay doors open.

There is no way to know with certainty when it is wiser to improve existing technology (the evolutionary approach) or to leap to a new generation of technology (the revolutionary approach). Historically, the Nation has followed a revolutionary path of technology development when the perceived important future needs could not be met by improving the existing system, or when breakthroughs in technology made dramatic new systems possible. **Neither of these conditions exist today with respect to the Shuttle system. Evolutionary improve-**

[9]Such as the aft fuselage module, crew compartment module, or wings.

[10]Estimates of the lifetime of the Shuttle fleet vary from about 2005 to 2020, depending on the flight rate, proposed upgrades, and number of orbiters purchased.

Figure I-I-Shuttle Fleet Attrition if Orbiter Recovery Reliability is 98 percent.



Shuttle reliability is uncertain, but has been estimated to range between 97 and 99 percent.[1] If the Shuttle reliability is 98 percent, there would be a 50-50 chance of losing an orbiter within 34 flights. At a rate of 11 flights per year, there would be a 50 percent probability of losing an orbiter in a period of just over three years. The probability of maintaining at least three orbiters in the Shuttle fleet declines to less than 50 percent after flight 113.

Although loss of an orbiter would not necessarily result in loss of life, it would severely impede the progress of the civilian space program, as it would likely lead to a long standdown of the orbiter fleet while the cause of the failure was determined and repaired. Seen in terms of Space Station construction, if the probability of recovering an orbiter were 98 percent, the probability of retaining four operational orbiters would be only 28 percent when Space Station construction begins on flight 92 and only 12 percent when the Phase I Space Station is completed 42 flights later.

[1] L-Systems, i.e., *Shuttle/Shuttle-C Operations, Risks, and Cost Analyses*, LSYS-88-008 (El Segundo, CA: 1988).

SOURCE: Office of Technology Assessment, 1989.

ments would allow NASA to increase human spaceflight capabilities incrementally for lower cost and technical risk than would be the case for a whole new generation of vehicles. However, if the Nation were to decide to pursue major programs for people in space, such as a lunar base or a mission to Mars, revolutionary technological advances would be needed to increase capabilities and reduce operating costs.

Congress is faced with several options for enhancing the capabilities of the Shuttle system or improving its safety and reliability:

Enhance the Performance of the Redesigned Solid Rocket Motors (RSRMs)

Following the *Challenger* disaster, NASA redesigned the Shuttle's solid rocket boosters to increase their safety and reliability. At that time, it did not attempt to enhance booster performance. The payload capacity of the Shuttle could be increased by 6,000 to 8,000 pounds by substituting more energetic propellant, changing the motor's thrust profile, and redesigning

Box l-A—Maintaining and Improving the Current Shuttle System

Buying Additional orbiters

Three basic options are available:

- ***Build a copy of OV-105***
  The ***Challenger*** replacement (C)V-105), already being built, includes several important improvements:
  —addition of an escape hatch and pole;
  —improved heat shielding tiles, strengthened landing gear, wing structure, and engine pod;
  —more than 200 internal changes, including electrical rewiring and improvements in the braking and steering systems.
- ***Implement additional improvements***
  —Safety/Reliability;
  --Cost Reduction; and
  —Performance.
  (Some of' these upgrades may involve structural changes, and therefore could not be made in existing vehicles.)
- ***Reduce airframe*** weight-Orbiter airframe weight reduction of 8,000 to 10,000 pounds could ***be*** achieved through the use of
  -composite materials;
  —alloys;
  —intermetallics; and
  —high temperature metallics.

Incremental Changes

Some alterations to the Space Shuttle system have already been accomplished, or are already under way:

- ***Redesigned Solid Rocket Motors*** *(RSRM's)*
- ***Space*** *Shuttle* ***Main Engine Improvements-*** Specific efforts directed at longer life and higher reliability include improved:
  —welds;
  —manufacturing techniques;
  —nondestructive testing;
  —heat exchangers;
  -controllers;
  -engine health monitoring; and
  —turbopumps.
- ***On-Board Computer Upgrades—Specific*** efforts include:
  —identical computer modules ''mass-produced' for economy
  -connection by optical fibers
  —a high degree of fault-tolerance

Other improvements NASA has considered or is now working on:

- *Extended* ***Duration Orbiter*** (EDO)--NASA is building in the capacity to extend on-orbit stays from the current 7 days to 16-28 days.
- ***Automatic Orbiter*** Kit—An existing Shuttle orbiter could be given the capability to fly an entire mission automatically.
- Operations ***Improvernents—Introducing*** a number of new technologies and management strategies to make Shuttle launch operations more efficient and cheaper, e.g., improved Shuttle tile inspection and repair, and expert systems for control.

Major Changes

Some candidates include:

- ***Advanced Solid Rocket Motors (ASRMs)-These*** would replace the existing RSRMs. Compared to the RSRMs, they offer:
  —up to 12,000 pounds additional lift capacity
  —better manufacturing reproducibility
  —reduced stress on the Space Shuttle Main Engines
  —potentially higher reliability
  —potential for enhancing competition
- ***Improve*** *Redesigned Solid* ***Rocket Motors--The*** existing RSRMs could be improved further by redesigning them to increase their thrust. The Shuttle's payload capacity could be increased by 6,000 to 8,000 pounds by substituting a more energetic solid propellant and by making other requisite changes to the motors.
- *Liquid Rocket Boosters* (LRBs)—They would replace the solid boosters on the Shuttle. Compared to RSRMs, LRBs offer:
  —-safer abort modes
  —up to *20,000* pounds additional lift capacity
  —long history, potentially greater mission reliability
  -capability of changing mission profiles more easily
  —safer Shuttle processing flow
  —potential application as an independent launch system
  —better environmental compatibility
- *Materials improvements-The* emphasis on improved materials has focused particularly on saving weight. For example, using aluminum-lithium (Al-Li) for the external tank instead of the present aluminum alloy could provide a 20 to 30 percent weight savings. Using composite materials in the orbiter wings and other parts could save an additional 10,000 pounds.
- Crew *Escape* Module--This would allow for safe escape over a larger portion of the liftoff regime than now possible. It would replace the escape pole system presently in place, but would be heavier and much more costly.

its nozzle. NASA estimates such changes would require at least two years of development, testing, and qualification. However, adding a more energetic propellant might make the RSRM less reliable than it now is.

Continue To Develop the Advanced Solid Rocket Motor (ASRM)

NASA expects the ASRM to enhance Shuttle reliability and performance, and plans to use it starting in 1995 to replace the current, redesigned solid rocket motor. A 1987 National Research Council Report recommended development of the ASRM on grounds that it would ''enhance both the performance and reliability of the post-Challenger Shuttle.''[11] According to NASA, the ASRM would improve flight safety margins, system reliability, and payload capability. However, a recent report by NASA's Aerospace Safety Advisory Panel questioned whether the ASRM would provide sufficient additional safety and reliability when compared to the current RSRM.[12]

Using ASRMs might provide up to 12,000 pounds extra lift capacity and possibly reduce the number of Shuttle flights required to assemble the Space Station from about 21 to about 16.[13] NASA estimates that ASRMs would cost $1 billion for development and testing, and $300 million for facilities construction, and could be developed and tested in about 5 years. The report of the Aerospace Safety Advisory Panel suggested that NASA explore using this money instead for added safety improvements to other elements of the Shuttle system and said that "NASA has not thoroughly evaluated other alternative choices to the ASRM such as liquid rocket boosters. ' '[14]

Develop a Liquid Rocket Booster (LRB)

Compared to solid rocket motors, LRBs offer improved performance, simpler launch operations, fewer environmental hazards, and, potentially, improved mission safety. They could provide from 12,000 to 20,000 pounds of extra payload capacity for the Shuttle. The development of the necessary new liquid-fueled engines for LRBs could be assisted by the research and development already underway in the joint Air Force/NASA Advanced Launch System program. However, LRBs offer greater development risk than the ASRMs and would likely cost more to develop. They might also take from 2 to 3 years longer to develop and test than the ASRMs.[15] NASA estimates that development, demonstration, test and evaluation for the liquid booster alone would cost $3 billion. It estimates that orbiter and pad modifications, which would be required to use the LRBs, might cost as much as $500 million. However, if an LRB could be powered by an engine requiring less ambitious development than that envisioned by NASA, the cost of the LRBs might be brought close to that of the ASRMs and might be available about the same time.[16]

Develop the Shuttle-C

Alternatively, NASA could obtain extra space transportation capability by building an expendable, unpiloted heavy-lift booster using Shuttle

[11] National Research Council, *Report of the Committee on the Space Station* (Washington, DC: National Academy Press, September 1987), p. 23.

[12] NASA's Aerospace Safety Advisory Panel questioned the "wisdom of proceeding with the procurement of a new solid rocket motor. . ." at this time. See National Aeronautics and Space Administration, *Aerospace Safety Advisory Panel Annual Report,* March 1989, p. iii, and p.3.

[13] Some propulsion experts, including some within NASA, have expressed concerns to OTA that the ASRM may not meet its performance goal. They base these concerns on experience with other space systems that have suffered unavoidable weight growth. However, NASA officials familiar with the ASRM program counter that even if the ASRMs do not fully achieve their expected performance, their development will eventually lead to more reliable solid rocket motors for the Shuttle.

[14] *Aerospace Safety Advisory Panel Annual Report, op.* cit., footnote 12.

[15] NASA's LRB studies have estimated that development and testing of LRBs would t&e until 1997. However, recent studies by Rocketdyne and by General Dynamics suggest that LRBs could be purchased more cheaply and developed in less time.

[16] Rocketdyne briefing to OTA, May 3, 1989.

technology .17 This ''Shuttle-C' (for cargo) would use the recoverable solid rocket boosters, the same expendable external tank, and two refurbished main engines (SSMEs) from the Shuttle system. A large expendable cargo cannister, capable of transporting some 85,000 to 100,000 pounds of payload to low-Earth orbit would substitute for the Shuttle orbiter.

Although Shuttle-C could not carry people, it would be capable of flying some missions that would otherwise require Shuttle flights and could therefore substitute for purchasing an additional orbiter. For example, if Shuttle-C were used to ship major subassemblies of the space station to orbit, one Shuttle-C flight would replace two to three Shuttle missions. According to NASA, four Shuttle-C flights could reduce the number of Shuttle flights necessary to assemble the Phase I Space Station from about 21 to about 10.

Shuttle-C would have the advantage of using much of the same technology and parts that have already proved successful in 28 Shuttle flights. It would use the same launch pads, vertical integration facilities, and launch support crews now used for the Shuttle. It carries the disadvantage that because so many of the proposed Shuttle-C's components are common to the Shuttle, an interruption of Shuttle operations as a result of an accident or technical problem might well lead to delays of Shuttle-C flights for the same reasons. Conversely, a failure of the Shuttle-C would probably ground the Shuttle fleet.

Choosing among these alternatives is very difficult because the choices are constrained by budget limitations as well as competing technical capabilities. If Congress determines that NASA should maintain a Space Station construction schedule offering full operational capability of its first phase by 1998, then any of these options except perhaps LRBs would assist that effort. Improved RSRMs could provide a modest increase in Shuttle payload capability. ASRMs and LRBs may both achieve greater payload weight enhancements for servicing, but LRBs might not be ready in time to be of help in constructing the Space Station on the existing schedule. However, LRBs may offer safer Shuttle launch processing and improvements in safety for Space Station operation, any additional Space Station construction, and for other Space Shuttle missions. NASA officials estimate that the costs of developing the Shuttle-C or the ASRM are roughly equivalent, and that either system could be available by 1995. Shuttle-C would provide the greatest payload improvement, and would reduce much of the pressure of depending on the Shuttle for building the Space Station. However, NASA has identified few payloads for a Shuttle-C beyond the Space Station components.

If Congress decides that the advantages of having the heavy-lift capacity potentially provided by the Shuttle-C, and/or the extra margin of safety and reliability provided by the LRBs outweigh the advantages of developing the ASRMs by 1995, it might wish to reconsider its decision to proceed with ASRMs.

Making major Shuttle enhancements on a project-by-project basis may not be the most efficient way to improve the Shuttle system. To choose one improvement may mean not pursuing another, worthwhile improvement. However, having a versatile, capable launch fleet that provides reliable human access to space will be important if Congress desires to maintain a policy of supporting a human presence in space. Hence, **Congress may wish to consider a more integrated approach to strengthening the Nation's space transportation capability by funding a Shuttle Improvement Program lasting, for example, 10 years.** Such a program could include development of advanced solid rocket boosters, liquid rocket boosters, and the

[17] U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide, OTA-ISC-383* (Washington, DC: U.S. Government Printing Office, July 1988).

Shuttle-C, as well as additional, more modest, improvements summarized in box l-A. To support this sort of program, which could cost as much as $850 million per year for 10 years, would require finding extra space program funding, scaling down the Space Station program, or deferring other programs.

RESCUE OR ESCAPE VEHICLES

Crews living and working in the planned Space Station could be exposed to substantial risk from major failures of the Station or the Space Shuttle that transports the crew. NASA is attempting to reduce such risk by building safety features into the Space Station and improving the Shuttle's design. Nevertheless, many analysts in NASA and the broader U.S. space community believe that the United States may need some means independent of the Shuttle to rescue crews from the Space Station. Several options have been suggested (box 1-B); these could be based at the Space Station or on Earth. **To decide whether a risk-reducing effort is worth the investment required, Congress must be advised about how much the investment would reduce the risk. Even if an alternate crew return capability were provided and worked as planned, it would not eliminate all risks to station crewmembers.** A risk assessment of the Space Station should take into account all phases of the crews' experience in space. For example, if the greatest risk to Space Station crew members were experienced in the flight to orbit, it may be more cost-effective to improve the safety of the Shuttle or any later crew-carrying space transportation systems than to build a crew escape craft.

A rescue system, if built, would be needed for the life of the Space Station. Therefore, its total operating costs could easily exceed its development costs. **Before committing to a specific rescue strategy, system designers will have to address the costs of developing the necessary support infrastructure, which might include ground operations hardware and personnel at the mission control site, landing site crews, and the necessary subsystems and logistics support to resupply, replenish, and repair a rescue vehicle on orbit.** Each of these factors can seriously influence the operational characteristics and costs of the system.

Box I-B—Escape Vehicles

Several contingencies could require emergency escape of personnel in space. These include medical emergencies of Space Station crew members, major equipment failures, damage from orbital debris, etc. Escape could also be necessary if the Shuttle failed to meet its scheduled launch date by so long a time that the Station risked running out of critical supplies.

Crew Emergency Return Vehicles (CERV)

NASA is considering two types of vehicles for emergency return from space to Earth:

- *Capsule—This* simple vehicle would have an ablative heat shield reminiscent of reentry capsules from the early days of spaceflight, and still used routinely by the Soviet Union. A capsule, which could closely resemble the Apollo capsule, would descend by parachute and land in the ocean. Its advantages include simplicity, relatively low cost, and proven technology. In addition, capsules need little or no piloting, which could be a major consideration if pilots are unavailable because they are unable to function as a result of injury or a long stay in orbit. Depending on its capability, a capsule could cost $0.75 billion to $1.0 billion to develop,
- Small *Glider—A* small, aerodynamically stable vehicle whose shape would provide lift, and could land by parachute or at low speed on a runway. A glider would provide a wider range of landing sites and more frequent opportunities for reentry and recovery (particularly for a version with landing gear), and a softer ride than capsules (important if an injured crew member is returning). However, a glider would cost 20 to 50 percent more than the simplest parachute version of a capsule.

NASA is also studying the possibility of building a specialized glider that could be launched into space atop an expendable launch vehicle as well as return from the Space Station. Such a glider could be used to provide 1) crew emergency rescue, 2) assured access to space by crews, 3) small logistics transport, and 4) on-orbit maneuver. Whether capsules or gliders, emergency rescue vehicles could be launched by Titan III and Titan IV by 1995. Alternatively, a Shuttle could launch two at a time, to be docked at the Space Station.

Photo credit: National Aeronautics and Space Administration

Artist's conception of an Apollo-type emergency rescue vehicle entering the Earth's atmosphere after leaving the Space Station.

OPTIONS FOR THE NEXT CENTURY

Sometime in the early years of the next century our existing launch systems will wear out or become operationally obsolete. At that point the United States will want to replace them with more advanced systems. NASA and the DoD are considering a variety of options for advanced, crew-carrying launch systems.

Personnel Carrier Launched on Automated Launch Vehicles

NASA is beginning to explore the possibility of developing a personnel launch system (PLS) that would use a small glider launched atop an expendable launch vehicle, rated to carry people.[18] Candidate launchers could include a Titan III or Titan IV, or perhaps a new, as-yet undeveloped launcher such as the Advanced Launch System (ALS).

The ALS Joint Program Office has recognized the potential benefit of having a flexible launch vehicle rated for launching crews. It has therefore required that contractor proposals for an ALS provide for a launch vehicle capable of meeting both the design and quality assurance criteria for crew-rating. Designing an ALS launch vehicle at the outset to provide the additional structural strength for crew-rating would be much less expensive than redesigning, rebuilding, and retesting it after it is developed.

Having a crew-rated automated launcher in addition to a Shuttle has three strong advantages: 1) the crew-rated vehicle could launch new orbiters designed for launch with other boosters; 2) it could enhance crew safety (if the crew-rated launch vehicle carried an Apollo-like capsule, crew escape could be easier than with the Shuttle, and escape would be possible during more of the trajectory than with the Shuttle); and 3) there maybe cases where it will be necessary only to deliver personnel and cargo to the Space Station, but not return cargo on the same trip. In that case, there is no need to risk a Shuttle orbiter. **In view of the concerns over Shuttle fleet attrition, it maybe important for NASA to investigate the potential for using a crew-**

18A NASA or Air Force launch vehicle is said to be crew, or ''man-rated, ' if it has been certified as meeting certain safety criteria. These include design criteria as well as quality assurance criteria.

rated ALS or other expendable launcher to reduce the risk of losing crew-carrying capacity early in the next century.

Advanced Manned Launch System (AMLS)

NASA is studying several advanced concepts for vehicles to replace the Shuttle. The Advanced Manned Launch System (AMLS—previously called Shuttle II) program is studying new designs with the goal of achieving an improved U.S. piloted spaceflight capability early in the next century. A vehicle significantly different from the existing Shuttle would result (box l-C). If activities involving crews in space increase markedly in the next decade, and the Shuttle proves unable to perform its missions, an AMLS using advanced technology[19] might be needed. It could offer significant improvements in operational flexibility and reduced operations costs over the existing Shuttle. However, development, thorough testing, and procurement of an AMLS fleet could cost $20 billion to $30 billion (1989 dollars).

The timing of the development phase for an AMLS would depend on NASA'S need to replace the Shuttle fleet. It will also depend in part on progress reached with technologies being explored in the Advanced Launch System and National Aero-Space Plane (NASP) programs. In any event, a decision on AMLS will not have to be made for several more years. For example, if Congress decided that an operational AMLS was needed by 2010, the decision to start the early phases of development would have to be made by about 1995. By that time, Congress should have had adequate opportunity to assess the progress made in the NASP program (see below), which could be competitive with an AMLS.

Box 1-C—Advanced Manned Launch System (AMLS)

The goal of the NASA AMLS program is to define advanced manned launch system concepts, including their development, system and operational characteristics, and technology requirements. A vehicle significantly different from the existing Shuttle would result. NASA is presently evaluating five concepts:

- an expendable in-line two-stage booster with a reusable piloted glider;
- a partially reusable vehicle with a glider atop a core stage;
- a partially reusable drop-tank vehicle similar to the fully reusable concept below but with expendable side-mounted drop tanks;
- a fully reusable rocket with a piloted orbiter parallel-mounted (side-by-side) to an unpiloted glideback booster;
- a two-stage horizontal takeoff and landing air-breather/rocket, which would be fully reusable.

Critical technology needs for all AMLS concepts include:

- light-weight primary structures
- reusable cryogenic propellant tanks
- low-maintenance thermal protection systems
- reusable, low-cost hydrogen propulsion
- electromechanical actuators
- fault tolerant/self-test subsystems
- autonomous flight operations

Building an Aerospace Plane

Developing a reusable vehicle that could be operated like an airplane from conventional runways, but fly to Earth orbit powered by a single propulsion stage would provide a radically different approach to space launch and a major step in U.S. launch capability. However, building such a vehicle poses a much larger technical challenge than building a two-stage, rocket-based AMLS. An aerospace plane could spur the development of

[19] The character of technology used in an AMLS would depend on NASA's goats for this launch system and the epoch in which its design was selected. For example, if technologies used for the AMLS were frozen at 1992 levels, they would be considered "near term. " However, if a decision to build an AMLS were not reached until the middle of the 1990s, the technologies designers would usc to create an AMLS could be far more advanced.

two new classes of military aircraft--one that would combine quick response, global ranges, and hypersonic[20] speed with take-off or landing in any part of the world, and another that would combine access to space with quick response from conventional runways.

The Department of Defense and NASA are jointly funding the NASP program to build the X-30 (box 1-D),[21] a research vehicle intended to demonstrate both single-stage access to space and endo-atmospheric hypersonic cruise capabilities. **NASP is a high-risk technology development program. Building the X-30 and achieving orbit with a single stage would require major technological advances in materials and structures, propulsion systems, and computer simulation of aerodynamic and aerothermal effects from Mach 1 to Mach 25.[22] The** uncertainties in meeting design goals are compounded because the successful operation of the X-30 would require all of the key enabling technologies to work in concert with one another. In addition, ground test facilities cannot replicate all of the conditions that would be encountered in ascent to orbit. Therefore, it is impossible to predict precisely how the X-30 would perform when pilots make the first attempts to push it far into the hypersonic realm.

As the NASP program is presently structured, it is organized to meet a series of technical and programmatic milestones, rather than a given schedule. However, there is some danger that in the current fiscally constrained environment, the program office might relax some of its own technical criteria in order to meet a schedule. The next major milestone will occur when the NASP program reports on its progress in meeting the Phase H technology development goals. If the NASP program were funded at the level requested in the 1990 budget submission ($427 million), NASP officials estimate they would be ready to decide on development of an X-30 at the end of fiscal year 1990. Program officials estimate that if the program experiences no delays as a result of unanticipated technical problems or of budgetary cuts, an X-30 begun in fiscal year 1991 could achieve orbital spaceflight by October 1996.

The X-30 would be a research vehicle, not a prototype of an operational vehicle. To develop an operational vehicle would require an additional, costly program beyond NASP. A development cycle that took full advantage of lessons learned in the X-30'S planned test program could not commence until the late 1990s at the earliest. An operational vehicle derived from the

Box l-D-What Is the National Aero-Space Plane Program?

NASP is a program to build the X-30, an experimental, hydrogen-fueled, piloted aerospace plane capable of taking off and landing horizontally and reaching Earth orbit with a single propulsion stage. The design of the X-30 would incorporate advanced propulsion, materials, avionics, and control systems, and make unprecedented use of supercomputers as a design aid and complement to ground test facilities. NASP is a technically risky program that could spur the development of a revolutionary class of reusable, rapid turn-around hypersonic flight vehicles, that would be propelled primarily by air-breathing "scramjet" engines,

Operational follow-ons to the X-30: An aerospace plane derived from NASP technology offers the promise of dramatically reduced launch costs if the vehicle can **truly be** operated like an airplane using standard runways, with minimum refurbishing and maintenance between flights.

[20] Mach 1 is the speed of sound. *Hypersonic* usually refers to flight at speeds of at least Mach 5—five times the speed of sound, or about 4,000 miles per hour.

[21] However, a recent decision to cut the proposed DoD contribution to NASP funding by two-thirds for fiscal year 1990 and to terminate funding for it in subsequent years puts the program in doubt, See later discussion in this section.

[22] Mach 25 (25 times Mach 1), is the speed necessary to reach Earth orbit.

Photo credit: McDonnell Douglas

Artist's conception of an X-30 aerospace plane.

proposed X-30 would therefore be unlikely until approximately 2005 or even later unless it were closely modeled on the X-30.

If the X-30 proved successful, the first operational vehicles that employ NASP technologies are likely to be built for military use, possibly followed by civilian space vehicles. Commercial hypersonic transports (the "Orient Express' are a more distant possibility. Recent studies have shown that from an economic standpoint, commercial hypersonic transports compare unfavorably with proposals for slower Mach 3 supersonic transports based on less exotic technology and conventional fuels. Therefore, **the most economic route to commercial high-speed air transport is unlikely to be through the X-30 development program. However, the X-30 program could provide technical spin-offs to aerospace and other high-technology industries through its development of advanced materials and structures and through advances in computation and numerical simulation techniques.** It is too early to judge the economic importance of such spinoffs.

Operational hypersonic aircraft and spaceplanes may raise concerns about their effect on Earth's atmosphere. Designers are hopeful that vehicles that cruise well above the stratospheric ozone layer, and whose combustion products are mostly water vapor, will not affect the environment significantly. The NASP program office is sponsoring research on the potential atmospheric effects of a fleet of follow-on vehicles to give a preliminary assessment of the major environmental questions.

Even assuming a rapid resolution of the myriad of technical issues facing the creation of an X-30 capable of reaching orbit with a single propulsion stage, translating this technology into an operational spaceplane might come late in the period when an AMLS could be ready, and perhaps after the time when replacements for the Shuttle will be necessary. With their less exotic technologies, rocket-propelled AMLS vehicles could probably be funded in the mid to late 1990s and still be developed in time to replace aging Shuttles. An AMLS program begun in this period would also benefit from the technical base being developed in the NASP program. **However, the technical uncertainties of both programs suggest that Congress would benefit from monitoring their progress and comparing the probability of success of each before committing development funds for operational vehicles in the mid-1990s. The costs of each program, as well as other competing budget priorities, will play a major role in such a decision.**

The revised DoD budget of April 1989 would cut DoD fiscal year 1990 funding for NASP from $300 million to $100 million. DoD would contribute no funds in subsequent years. DoD has also proposed transferring responsibility for managing NASP from DoD to NASA and allowing NASA to obligate the $100 million of fiscal year 1990 DoD funds.

The proposed cuts and change of management have raised the concerns of NASP proponents and accelerated a review of the NASP program. Many of the ongoing research efforts on materials, structures, and propulsion design, which would be needed to support an informed decision on the technical feasibility of building an X-30, are scheduled for completion in fiscal year 1990, the last year of Phase II. Furthermore, critical applications and cost studies are not yet complete.

Congress has three broad options on NASP funding:

- **Continue to fund the program at or near the original requested rate ($427 million).** Funding of this level would allow the NASP program to continue its Phase II research program and to complete its application and cost studies by the end of fiscal year 1990. At that point, the Administration and Congress could then decide whether or not to build two X-30 test vehicles, as planned.

  If the NASP program receives a budget cut, and the joint management arrangement is maintained, the Phase III decision would likely slip by a year or more, depending on the size of the cut. Although the program would then risk losing momentum and industry support, stretching Phase II out but retaining total funding of roughly $427 million would still allow the program to reduce many of the current uncertainties in the technology.
- **Accept the current DoD proposal for program cuts and transfer the-program to NASA.** Under this option, the NASP program would still be able to pursue useful technology studies. However, the focus of the program would change to emphasize the maturation of critical technologies in lieu of building a flight vehicle. In addition, a decision whether or not to construct a flight vehicle might be delayed two or more years. If managed by NASA, the program would compete with funding for alternative launch systems such as the AMLS and also with the Space Station program, which, along with Space Shuttle, will command most of NASAs resources for the next decade and more.[23]

  Moreover, a decision to transfer the program to NASA with only limited funding would delay a decision on whether to build a flight vehicle by several years. In the interim, the Nation might risk losing the substantial technology base that the NASP program has built for hypersonic flight. Recreating this technological base would be both costly and time consuming.
- Close **out the NASP program.** If Congress feels that the long-term goals of the NASP Program are less important than other pressing priorities in the Federal budget, it could terminate funding entirely. However, much of the progress made in the program would be lost because contractors would not be able to continue their research to a logical conclusion.

SPACE TRANSPORTATION AND THE SPACE STATION

NASA's planned Space Station will make permanent demands on space transportation—for construction, servicing, supply, and possibly emergency crew return. **Uncertainty about the adequacy of the current Shuttle fleet for constructing and servicing the Space Station makes station planning itself both uncertain and risky. Deployment, servicing, and resupply of the Space Station face both the risks of delayed launch schedules and loss of one or more orbiters. In addition, losing a critical element of the Space Station in transit to orbit as a result of a Shuttle failure could lead**

[23] U.S. Congress, Congressional Budget Office, *The NASA Program in the 1990s and Beyond* (Washington, DC: Congressional Budget Office, May 1988).

to severe delays in Space Station construction or even loss of the Space Station.[24]

A previous section outlined options for reducing the space transportation risk to Space Station construction and operation. However, most of these options would require additional funding beyond NASA's projected budget for Space Station or for space transportation. **Congress may wish to postpone Space Station construction and operation and focus on improving the Nation's ability to place crews in orbit safely and reliably. Alternatively, Congress could direct NASA to fly fewer non-Space Station-related Shuttle missions in order to reduce the risk that a Shuttle would be lost before Space Station construction is completed.** NASA might, for example, plan to use Titan IVs to carry some Space Station elements into orbit rather than risking the Shuttle to do so. Furthermore, if appropriately designed, many science payloads now tentatively manifested for the Shuttle could be flown on ELVs purchased competitively from the private sector.[25]

THE TECHNOLOGY BASE FOR PILOTED SPACEFLIGHT

Building a new, advanced launch system, or even making substantial modifications to existing launchers, requires a capable aerospace industry, well-supported government research programs, a cadre of well-trained engineers, and an institutional structure capable of putting a vast variety of technologies to innovative use. Yet, according to several recent studies, our existing space technology base has become inadequate in recent years.[26]

Government Programs

Several of these studies have recommended improving the Nation's space transportation technology base. Though specific proposals differ in detail, they cite propulsion, space power, materials, structures, and information systems as areas in need of special attention.

In response to these and other concerns, NASA and the Air Force have initiated four major programs to improve the Nation's launch system technology base (box l-E). As currently organized, these programs are directed primarily toward developing new, advanced capabilities. **In the existing budget climate, it may be more realistic to redirect some funding toward technologies that could be used to improve existing launch systems and make them cheaper to operate.** Several launch vehicle manufacturers have already instituted programs to improve their launch vehicles, based on technologies developed for the Advanced Launch System program.

As noted in *Reducing Launch Operations Costs: New Technologies and Practices,* launch operations and logistics, especially for systems that carry people, are labor-intensive and comprise a significant percentage of the cost of a launch. Yet launch system designers have invested relatively little in technologies that would reduce these costs. NASA's technology programs are addressing issues in automation and robotics, two technology areas that could significantly reduce launch operations costs. However, NASA could do much more to apply these technologies to launch operations for the Shuttle. **Funding basic and focused research for space transportation technologies would help**

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24 If a Space Station element for which there was no spare were lost, replacing that element would take many months.

25 Current space policy requires NASA, "to the maximum extent feasible, to purchase expendable launch vehicle services competitively from private launch companies—The White House, Office of the Press Secretary, "Presidential Directive on National Space Policy," Fact Sheet, February 11, 1988, p. 9.

26 See, for example, National Research Council, Aeronautics and Space Engineering Board, *Space Technology to Meet Future Needs* (Washington, DC: National Academy Press, December 1987); National Commission on Space, *Pioneering the Space Frontier* (New York: Bantam Books, May 1986); National Aeronautics and Space Administration, *Leadership and America's Future in Space* (Washington, DC: NASA, August 1987).

Box I-E-Government Space Technology Programs

- *Advanced Launch System (ALS) Focused Technology Program*—a joint program between NASA and the Air Force, carried out as an integral part of the ALS Demonstration/Validation Program. Its aim is to pursue research on specific technologies of interest to the development of an ALS. The program's contribution to crew-carrying capabilities will be limited, but important. As much as possible, ALS program managers have deliberately targeted their research at generic space transportation issues, in order to develop a broad technology base for designing an ALS. The ALS program plans to spend $81.4 million on focused technology R&D in fiscal year *'89,* out of a total budget of $153 million.
- *Civil Space Technology Initiative*—a NASA program designed to revitalize 'the Nation's civil space technology capabilities and enable more efficient, reliable, and less costly space transportation and Earth orbit operations."[1] Funding for fiscal year '89 is $121.8 million ('90 request—$144.5 million).
- *National Aero-Space Plane*—a DoD/NASA program to develop an aerospace plane capable of reaching orbit with a single propulsion stage. Although this program does not have the specific focus of improving the Nation technology base, some of the technology under development necessary for building the NASP, particularly new materials and structures, new propulsion techniques, new computational techniques, and methods of handling liquid and slush hydrogen, will find application elsewhere. The NASP Joint Program Office is spending $150 million over a 30-month period on materials development alone.
- *Pathfinder-a* NASA program especially directed at technologies for future human space exploration. Funding for fiscal year '89 is $40 million (fiscal year '90 request $47.3 million). Very few of this program's technologies will be useful for Earth-to-orbit transportation, as it is directed primarily toward on-orbit and interplanetary transportation and life-support issues.

[1]National Aeronautics and Space Administration, Office of Aeronautics and Space Technology, "CSTI Overview, ' April 1988.

the United States prepare to meet future space transportation needs.

The Private Sector Role

In providing space transportation for people, private firms now serve primarily as contractors for government-defined needs. Reaching orbit and working in space requires so large an investment compared to the expected return that private firms are unlikely to take the initiative in developing crew-related space systems unless Congress and the Administration set a high priority on involving them more directly in such development.[27] Because the government controls both access to space and most of the technology, it will continue to determine launch specifications and provide most of the funding. This is especially true for systems involving crews in space, in large part because such systems are still in the early stages of development, but also because they represent a major national commitment and are funded solely by public money.

By promoting private sector innovation toward improving the design, manufacture, and operations of launch systems, the government could reduce the cost of government launches. Yet relatively few incentives to involve private firms exist today.

If technology for crew-related systems eventually becomes an important arena for private investment, commercial pressures will themselves provide the incentives for launch system innovation. For the near term, however, such incentives must come from the government because projected future demand for crew-

[27]The NASP program, for example, has set a high priority on directly involving private firms and universities in materials research and other advanced research on the X-30,

carrying space transportation is small and depends entirely on government specifications.[28]

Incentives provided by the government could include:

- direct grants to develop new technology for launch systems specifically directed toward saving costs rather than increasing performance;
- cash incentives to firms for reducing the manufacturing costs of specific items procured by the government;[29]
- encouragement of industrial **teaming arrangements** such as the NASP Materials Consortium.

INTERNATIONAL COMPETITION AND COOPERATION

Competition

This decade has seen the rise of international competition in space transportation. The development of space transportation systems is the major achievement that signals a nation's or region's status as a space power, able to develop and control the use of advanced technology. In addition to the Soviet Union, Europe, Japan, and China now operate systems capable of launching sizable payloads.

At present, only the United States and the Soviet Union are able to send humans to and from space. However, the European Space Agency (ESA), the Federal Republic of Germany, Japan, and the United Kingdom are all developing their own reusable or partially reusable launch systems, which, if successful, would be capable of transporting human crews. **The progress other countries are making in space transportation for human crews is likely to present technological and political challenges to the United States by the end of the century.**

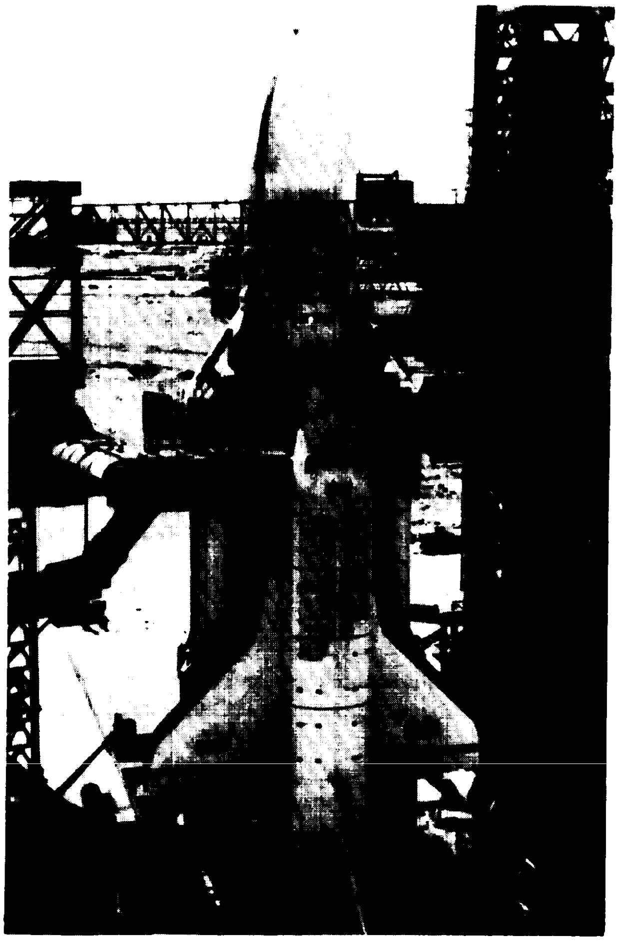

Photo credit: Novosti

Soviet Shuttle *Buran on* the launchpad at the Soviet launch complex.

Cooperation

The United States has always maintained a vigorous program of international cooperation in space science and applications in order to support U.S. political and economic goals. However, it has cooperated very little with other countries in space transportation, in part because most launch technology has direct military applications and is therefore tightly controlled. **Nevertheless, because other countries have**

[28] Richard Brackeen, *Space challenge '88: Fourth Annual Space Symposium Proceedings Report* (Colorado Springs, CO: U.S. Space Foundation, 1988), pp. 76-79.

[29] For example, Rockwell International earns 20 percent of every dollar it saves NASA on building Shuttle orbiter OV-105.

developed their own launch capability, reducing much of the technological lead the United States once held, and because progress in space will continue to be expensive, cooperating on new space transportation systems could benefit the United States.

For example, the United States has a strong need to reduce the number of Shuttle flights needed to construct and resupply the Space Station. It could benefit by sharing responsibility for resupply of the Space Station with its Space Station partners. ESA and NASA have now established a working committee to discuss appropriate standards for packaging, docking, and safety. If such cooperation proves successful, it could be extended to include more sensitive aspects of space transportation. In particular, because ESA and Japan have developed and now operate their own launch systems, they may have specific technologies or methods to share with the United States in return for access to some U.S. technology.

The United States could even be more innovative in cooperating with other countries. For instance, the United States may decide to provide an emergency crew escape or return vehicle for the Space Station. NASA estimates that the development of such a vehicle would cost between $0.75 billion and $1.50 billion, depending on its level of sophistication. **If properly redesigned and outfitted, the European spaceplane,** *Hermes,* **might be used as an emergency return vehicle.** *Hermes* could even complement the Shuttle in Space Station crew rotation. However, this option would require radical change in U.S. thinking about Space Station crew rescue and a similiar change in *Hermes* planning as well. Specifically, it would require partial redesign of *Hermes* to carry more than the three crew members now planned for

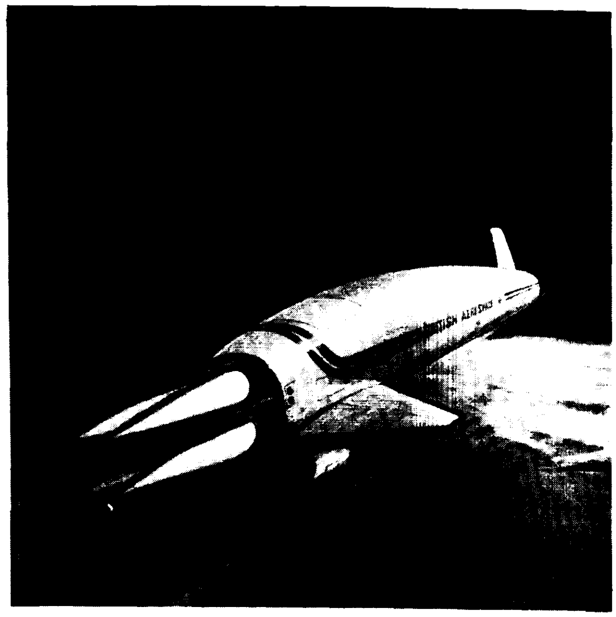

Photo credit: British Aerospace

Artist's conception of British Aerospace's Hotol aerospace plane taking off. If successful, this space plane would reach Earth orbit with a single propulsion stage.

this space plane. It would also require a degree of international cooperation for which the United States has little precedent.

Because of the proprietary and military nature of space transportation technology, cooperation in this area can be expected to be more difficult than cooperation in space science. Yet the United States engages in a variety of cooperative projects for the development of military systems. A deeper commitment to international cooperation would assist the United States in achieving much more in space than it can afford to attempt on its own. To do this will require that NASA and the U.S. aerospace industry do much more to tap the technologies and expertise available in other industrialized countries.