Chapter 3

Space Shuttle Evolution

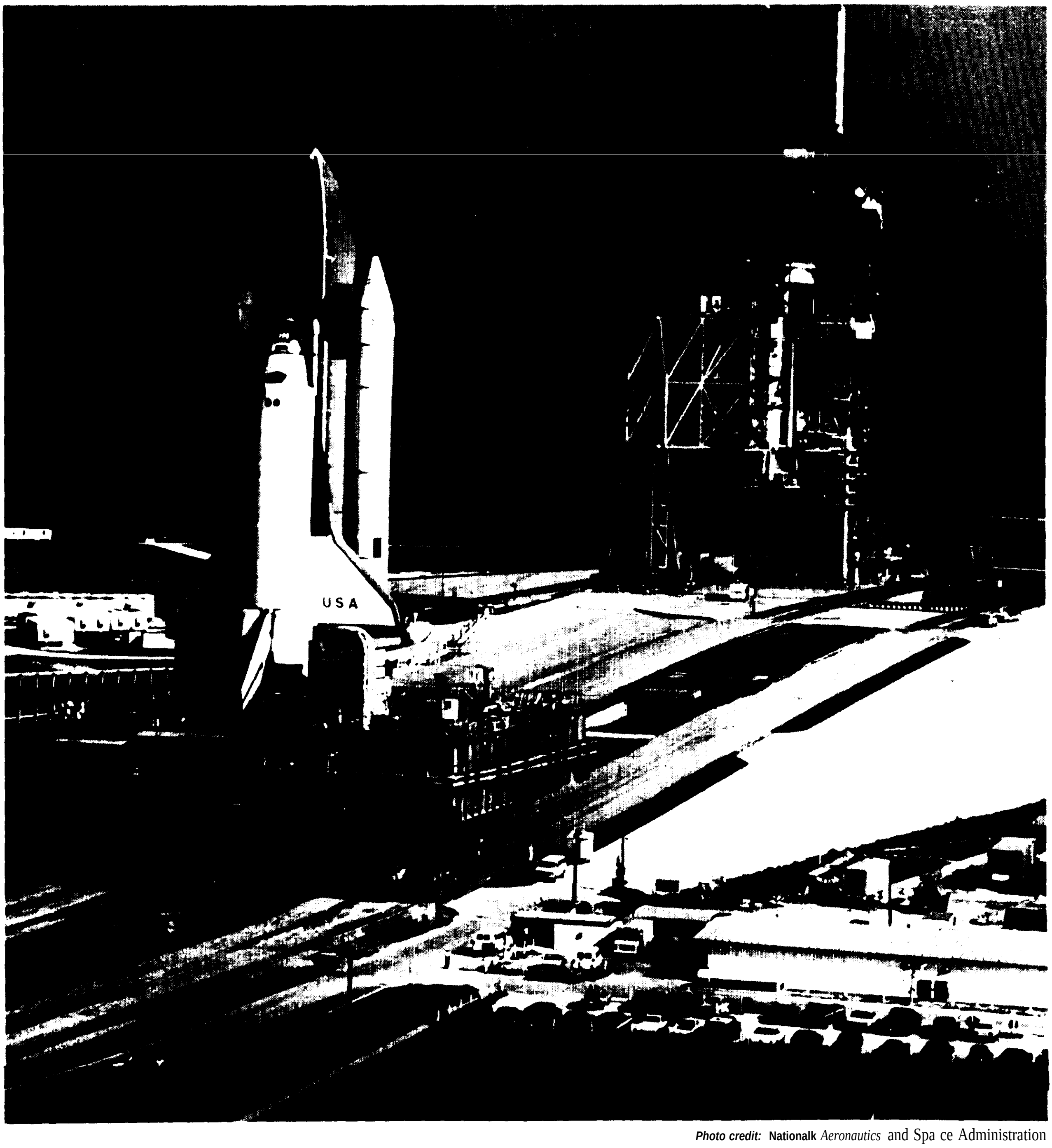

Photo credit: **Nationalk** *Aeronautics* and Space Administration

The Space Shuttle ***Columbia*** begins its roll up the ramp to pad 39A after completing the 3½ mile journey from the Vehicle Assembly Building (September 1982)

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INTRODUCTION

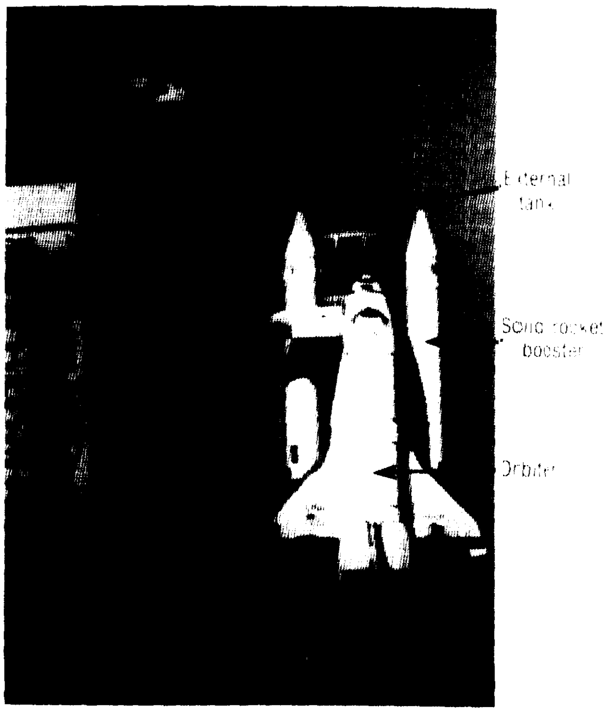
At *some* point early in the next century, Shuttle wearout, attrition, or a combination of advances in technology and the emergence of missions beyond the capacity of the Shuttle fleet will necessitate its replacement. New crew-carrying vehicles would incorporate advances in design, materials, and operations with the goal of attaining safe, reliable, cost-effective transport of humans to space. In the meantime, improvements to the current fleet may be cost-effective.

THE SPACE SHUTTLE SYSTEM TODAY

The Space Shuttle was the world's first partially reusable Earth-to-orbit launch vehicle (figure 3-1). Begun in 1972, the Space Shuttle was first launched in April 1981. It is capable of transporting both humans and heavy, large payloads into low-Earth orbit. Originally designed to carry payloads of 65,000 pounds to a reference orbit 110 nautical miles high, inclined by 28.5 degrees, Shuttles are now capable of carrying payloads of 52,000 pounds to the same orbit. As of May 1989, *the* National Aeronautics and Space Administration had successfully launched the Shuttle 28 times but experienced one tragic failure when one of the *Challenger's* Solid Rocket Boosters (SRBs) failed in January 1986.

At launch, the liquid-fueled Space Shuttle Main Engines (SSMEs) are ignited. If main engine operation appears normal, the SRBs are ignited 7 seconds later; otherwise the main engines can be shut down and the launch aborted. Once ignited, the SRBs cannot be shut down before they bum out, [1] nor can the Shuttle be safely held on the pad until the SRBs bum out should a malfunction occur. Two and one-half minutes into the flight, explosive bolts separate the orbiter from the SRBs, which parachute into the Atlantic Ocean and are recovered. After about 8 minutes of flight, the SSMEs shut down and the external tank separates from the orbiter, breaks up as it reenters the atmosphere, and falls into the Indian Ocean. In space, the Orbiter Maneuvering System (OMS) engines, fueled by hyperbolic propellants,[2] propel the craft into the orbit desired for the mission.

Figure 3-1-Space Shuttle Elements



- the orbiter,[1] with the crew compartment and payload bay, which also contains the three Space Shuttle main engines (SSMEs). About the size of a DC-9, the orbiter weighs about 215,000 Ibs. without its payload and has a 15 by 60 foot cylindrical payload bay.
- the *external tank,* which holds the liquid hydrogen fuel for the SSMEs, and the liquid oxygen used to burn it.
- two segmented solid-fuel *rocket boosters **(SRBs).*** Each is made up of five Redesigned Solid Rocket Motor (RSRM) segments.

[1] There are now three orbiters—*Columbia, Discovery,* and Atlantis. A fourth orbiter, *Endeavor* will join the fleet in 1992.

SOURCE: National Aeronautics and Space Administration.

After the Shuttle crew completes its mission, the orbiter fires its OMS engines to leave orbit, reenters the atmosphere, glides to a runway, and lands. For safety reasons, especially after the loss of *Challenger,* Shuttle orbiters will normally land at Edwards Air Force Base, California. However, in an emergency, an orbiter could land at Cape Kennedy,

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[1] The SRBs can be destroyed in flight by the Range Safety Officer if, for example, the Shuttle veers out of control toward a populated area. Destroying the SRBs in flight would also destroy the Shuttle orbiter.

[2] A fuel and an oxidizer that ignite spontaneously when they come into contact. The OMS uses monomethyl hydrazine and nitrogen tetroxide.

Photo credit: National *Aeronautics* and Space Administration

The Shuttle orbiter in the Orbiter Processing Facility, Kennedy Space Center. Visible are the orbiter's three Shuttle main engines **and** the two orbital maneuvering system engines to the right and left of the upper main engine.

Florida; White Sands Missile Range, New Mexico; **Zarogosa,** Spain; Casablanca, Morocco; Rota, Spain; or Guam. At the landing site, any remaining fuels are removed from the orbiter, and the orbiter is ferried atop a Boeing 747 aircraft to Kennedy Space Center, where it is refurbished for the next launch.

Many systems and facilities are required to process and launch a Shuttle and to communicate with and advise its crew during a flight. NASA refers to these systems and facilities, together with the fleet of Shuttle orbiters, as the National Space Transportation System (NSTS, or STS).

Figure 3-2 shows the main facilities at Kennedy Space Center (KSC) used for payload preparation and for Shuttle launch preparation, launch, and landing. The figure shows the Shuttle Landing Facility (runway), the Operations and Control Building, the Vehicle Assembly Building (VAB), the Orbiter Processing Facility, the Vertical Processing Facility, the Launch Control Center, and launch pads A and B of Launch Complex 39. Not shown are the SRB Disassembly Facility, the SRB Rotational Processing and Surge Facility, and the Mobile Launch Platform, on which the Shuttle is erected in the VAB. Facilities located elsewhere include the Michoud Assembly Facility near New Orleans, where external tanks are manufactured and shipped to KSC by barge, and the Lyndon B. Johnson Space Center (JSC) in Houston, Texas, where NASA plans the missions, trains crews, develops flight software, and controls missions via the Tracking and Data Relay Satellite System and communications and tracking stations located around the world. NASA also maintains the Shuttle Landing Facility at Edwards Air Force Base, California, where it uses a dry lake bed as a runway, and the emergency landing sites.

Launch operations include all the activities performed to maintain and launch Shuttles, including refurbishment of orbiters and solid rocket boosters after each flight. Figure 3-3 illustrates the operations performed at Kennedy Space Center.[3] The processing concept used at KSC is called integrate——transfa—launch," or ITL. The vehicle is assembled on a Mobile Launch Platform in the Vehicle Assembly Building and carried to the launch pad. This minimizes orbiter time on the launch pad and permits higher launch rates than could be achieved with ''integrate on pad' processing.

As soon as the Shuttle lifts off the launch pad, the mission is controlled from Johnson Space Center. Payloads (experiments) may be controlled from JSC, the Jet Propulsion Laboratory in Pasadena, California, or the Goddard Space Flight Center in **Greenbelt,** Maryland. But mission control is only one part of the operations requirements. Mission operations also include mission planning, training of the flight crew and ground crews, development of flight software, and the tasks performed by the flight

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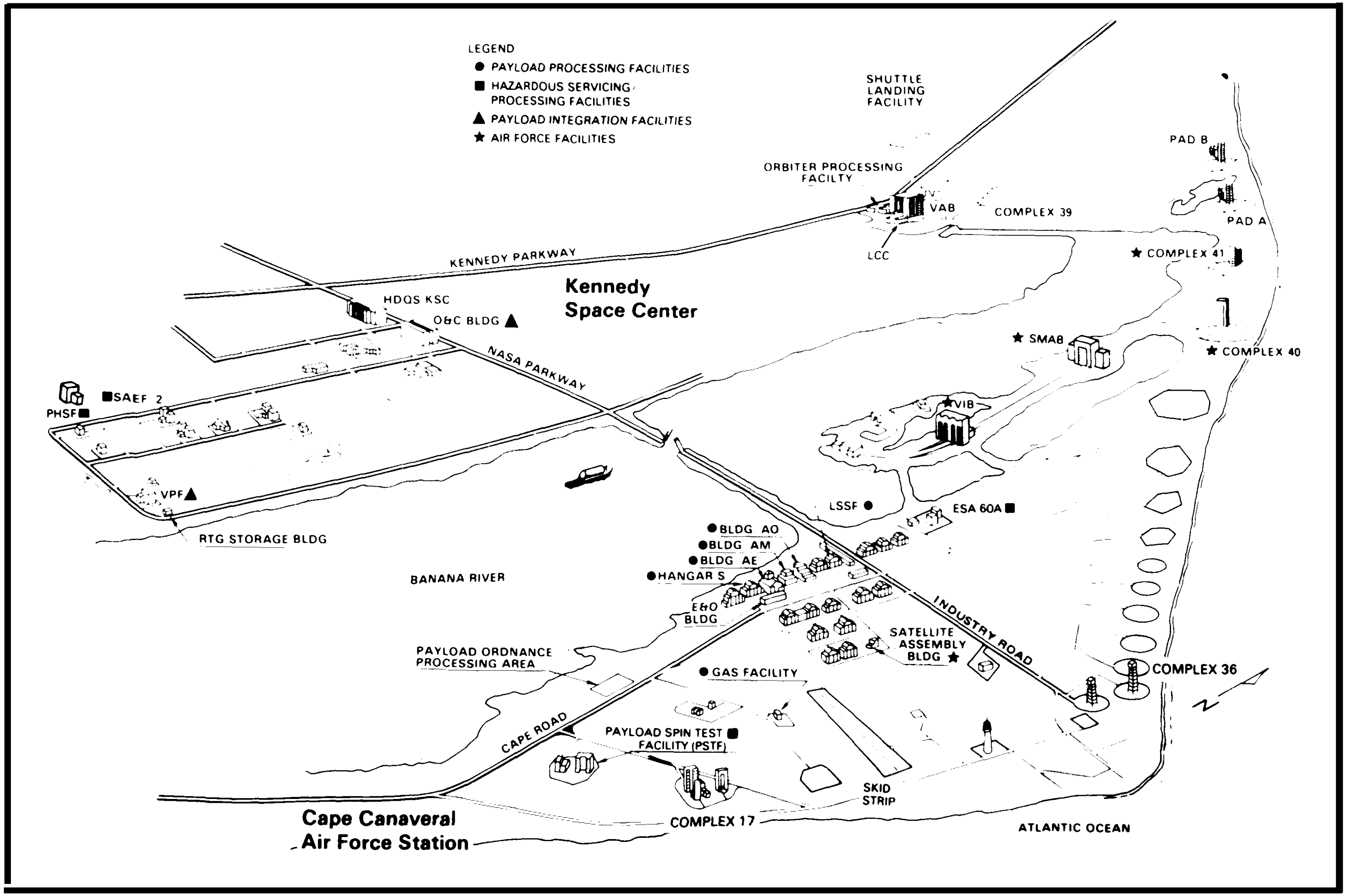
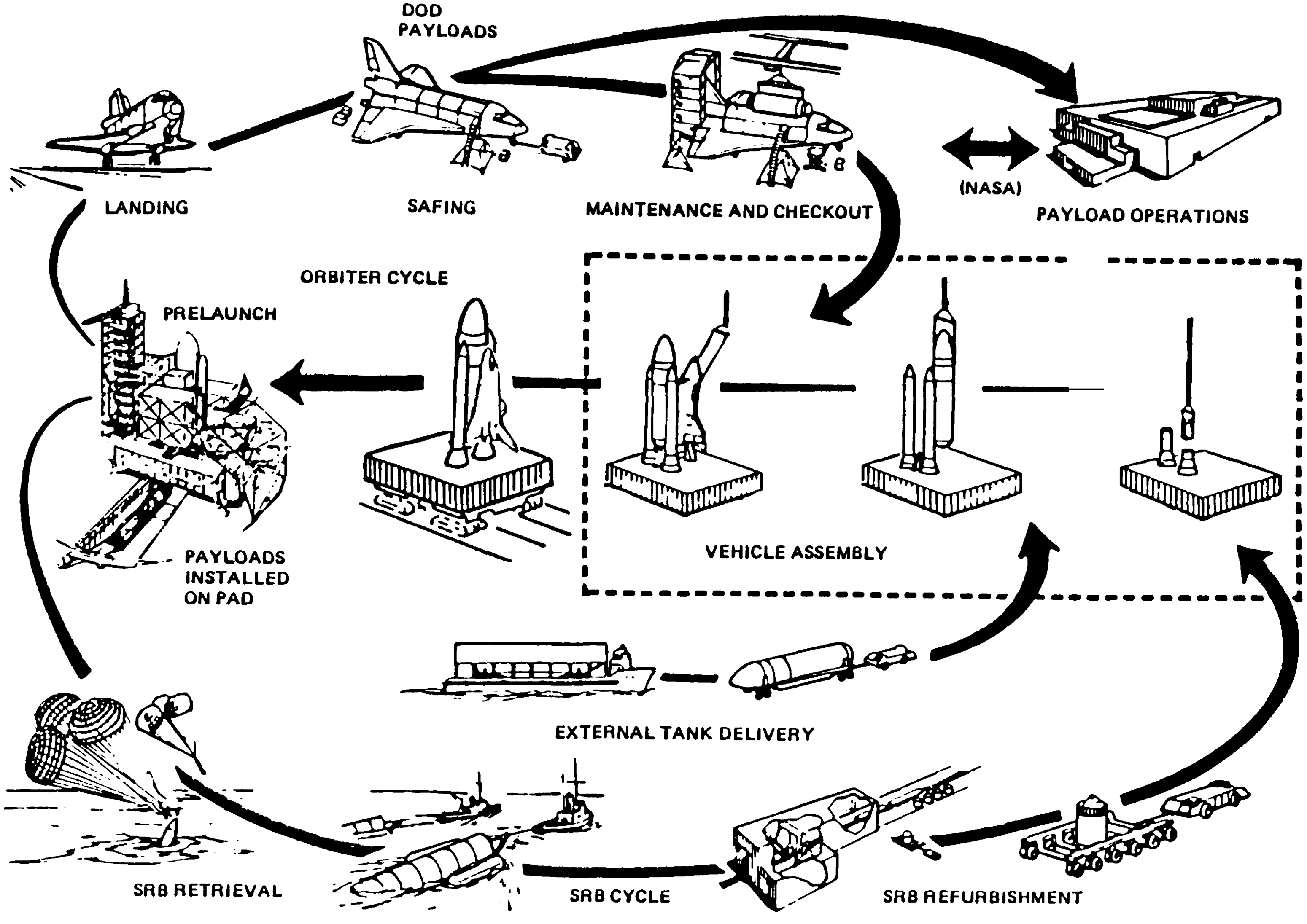
[3] For further details, see ch. 3 of U.S. Congress, Office of Technology Assessment, ***Reducing Launch Operations Costs: New Technologies and Practices,*** OTA-TM-ISC-28 (Washington, DC: U.S. Government Printing Office, September 1988).

Figure 3-2—Kennedy Space Center Payload Facilities



SOURCE: National Aeronautics and Space Administration.

Figure 3-3—Kennedy Space Center Space Shuttle System Ground Flow



SOURCE: National Aeronautics and Space Administration.

crew in orbit. These activities may span 2 years or more for a specific flight.

SHORTCOMINGS OF THE SPACE SHUTTLE

U.S. dependence on the Space Shuttle for carrying crews to space raises questions concerning the longevity of the Shuttle fleet and the risk that orbiters might be unavailable when needed. These involve:

- the relative inflexibility of the Shuttle System, especially when scheduled to fly at rates close to the maximum sustainable flight rate;
- possible attrition of the Shuttle fleet as a result of unreliability; and
- eventual obsolescence.

NASA's Flight Schedule

NASA has estimated that 14 Shuttles can be launched per year from the Kennedy Space Center with existing facilities,[4] and NASA has scheduled 14 Shuttle flights per year in 1993. However, NASA has never launched more than 9 Shuttle flights per year, and many experts doubt that 14 launches per year can be sustained with a 4-orbiter fleet.[5]

The total number of workdays, or shifts, required to prepare an orbiter for launch is called the ''turnaround time. Keeping it short is essential for reducing the cost per flight and increasing the sustainable flight rate; turnaround time limits the flight rate now. NASA's goal of 20 shifts has never been achieved. Actual turnaround time exceeded 200 three-shift workdays for the qualification (first) flights of each of the first three orbiters, but had been reduced to 55 three-shift days before the 25th flight, on which the *Challenger* was lost (figure *3-4).* After that accident, NASA changed launch preparation procedures; NASA estimates the turnaround time for the first and second *post-Challenger* flights as 322 and 236 days respectively.[6] NASA expects that in 4 years, turnaround time will decrease to 75 days, which would allow 12 to 14 flights per year when a fourth orbiter is added to the fleet. NASA expects that a flight rate higher than 14 per year could not be attained merely by buying more orbiters; with four orbiters and a turnaround time of 75 three-shift days, the flight rate would be limited by current facilities. Additional orbiter processing facilities would be needed to achieve a flight rate higher than 14 per year.

In fact, NASA will have difficulty reaching a rate of 14 flights per year unless it is able to find ways of sharply reducing its current turnaround time. Its goal of 14 flights per year assumes a ''success-oriented processing schedule' and no margin for contingencies. Yet NASA is not achieving the reductions of turnaround time it had anticipated. In addition, some NASA officials have expressed concern that the 90 days planned for structural inspections and orbiter modifications every three years may not be long enough to accomplish all potential necessary work.[7]

Inflexibility

If NASA does eventually prove capable of launching 14 Shuttle flights per year, scheduling launches at the maximum sustainable launch rate estimated by NASA leaves no margin to accommodate a sudden change in launch plans or to fly any missions that may be delayed by a future accident. If a Shuttle mission is changed, payloads and equipment for the original mission may have to be removed before equipment for the new mission can be installed.

If more margin were reserved in Shuttle launch schedules, an orbiter could be on hand to be outfitted quickly for an unplanned mission. This margin could be provided by scheduling fewer missions per year or by buying more orbiters—and more orbiter processing facilities, if they become a bottleneck.

However, even with more margin, it could take as long as a few months to prepare an orbiter for an unscheduled mission, because of the lead time required for mission planning, orbiter processing,

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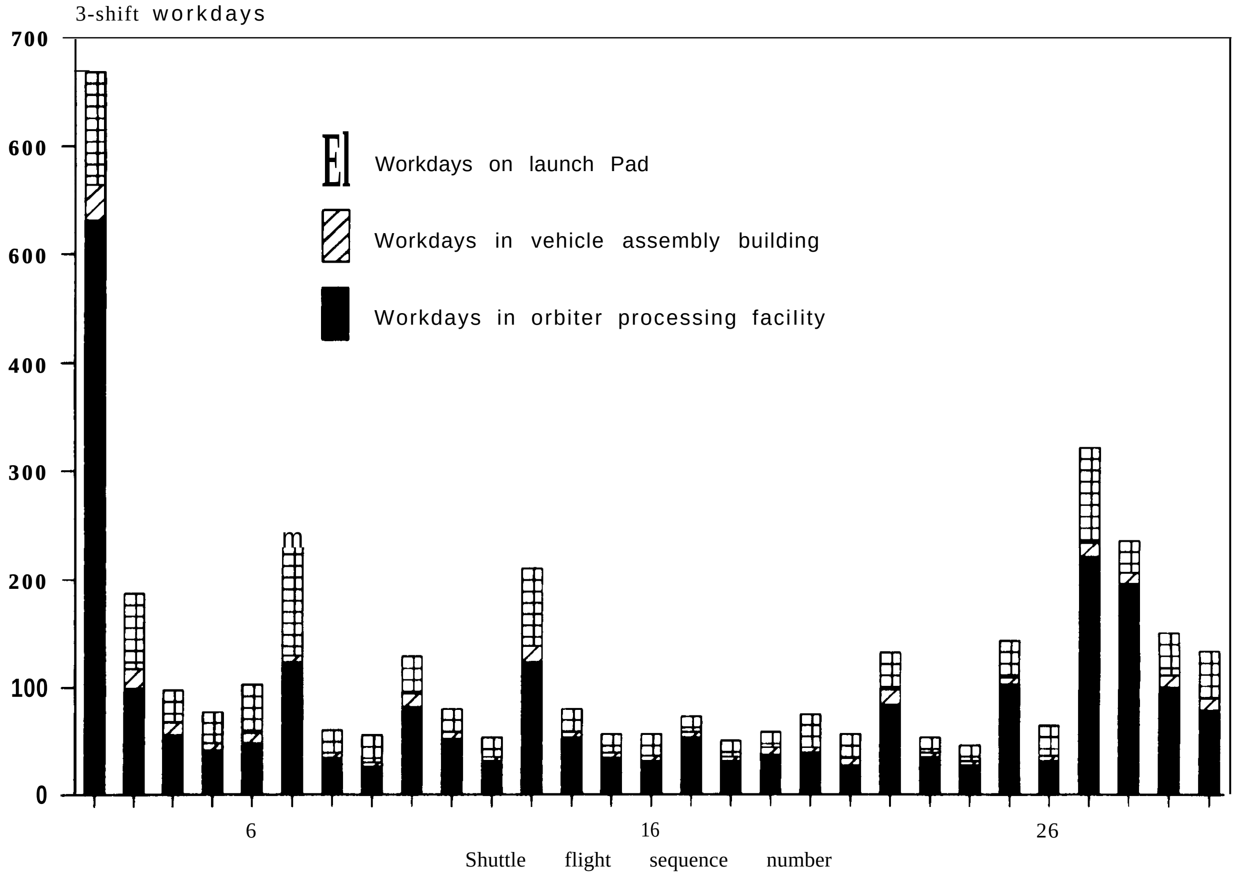
[4] Enclosure to letter from Darrell R. Branscome, NASA HQ, to Richard DalBello, OTA, Mar. 31.1988.

[5] National Research Council, Committee on NASA Scientific and Technological program Reviews, *Post-Challenger Assessment of Space Shuttle Flight Rates and Utilization* (Washington, DC: Nationat Academy press, October 1986), p. 15; Aerospace Safety Advisory Panel, *Annual Report* (Washington, DC: NASA Headquarters, Code Q-1, March 1989), p. iv.

[6] These estimates exclude the time spent improving the orbiters after the *Challenger* accident.

[7] NASA Kennedy Space Center briefing, Apr. 26, 1989.

Figure 34-Orbiter Ground Turnaround Experience



SOURCE: Office of Technology Assessment, 1989.

and crew training.[8] There would still be insufficient flexibility to, say, rescue a Space Station crewmember who has a critical illness or injury. For this, specially designed escape or rescue vehicles (discussed in ch. 6) might be needed.

Eventually, flexibility to schedule unplanned Shuttle missions may decrease because of Shuttle fleet attrition. Scheduling fewer missions per year would compensate for this erosion of flexibility by slowing the attrition of orbiters—but also at the cost of foregoing opportunities for transporting people to space. **If the Nation wishes to improve the safety of its crew-carrying space flight program while increasing its flexibility, NASA and the Defense Department will have to allow more margin in Shuttle launch vehicle schedules.**

Risk of Attrition

NASA intended each orbiter to last 100 flights with a probability of at least 97 percent.[9] If average Shuttle "life" were limited primarily by attrition, this design specification would require a 99.97 percent probability of recovering the orbiter in refurbishable condition after each launch;[10] if fa-

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[8] Normally, Shuttle crews, payloads, and specific orbiter are chosen up to 2 years prior to a flight, in order to provide enough time for payload integration and crew training.

[9] Space Shuttle Phase C/D work statement design specifications.

[10] A failure to recover the orbiter in refurbishable condition after a launch could be caused by a failure of the orbiter, a failure of some other system, human error, or unexpected conditions (e.g., lightning at launch).

tigue or wearout were significant, the probability would have to be even higher. Orbiter recovery reliability was probably lower during the first 25 flights; if it had been 99.97 percent, the odds against losing an orbiter in the first 25 flights would have been greater than 130 to 1. The reliability that would have made the observed success rate most likely is 96 percent; the actual reliability is uncertain. ’l

NASA officials believe that Shuttle reliability was improved after the loss of *Challenger* because some failure modes were eliminated.[12] However, NASA has not estimated **how much** reliability has been improved, because NASA does not routinely estimate Shuttle reliability quantitatively,[13] although it has done so for planned missions that will employ nuclear power systems.[14]

Estimates based partly on judgment vary widely. For example, the late Richard Feynman, a member of the Presidential Commission appointed to investigate the *Challenger* accident, called the Shuttle”. . . relatively unsafe ..., with a chance of failure on the order of a percent, ’ adding ‘It is difficult to be more accurateo15 A NASA contractor estimated that *post-Challenger* Shuttle reliability would be between 97 and 98.6 percent, with most failures caused by propulsion failures during ascent.[16] And while one NASA division estimated that on the Galileo mission the orbiter will have a 99.361 percent probability of remaining intact until deployment of the Jupiter-bound Galileo space probe begins,[17] another NASA division estimated the probability would likely lie between 1 in 36 (97.2 percent) and 1 in 168 (99.4 percent). *g

The uncertainty in Shuttle reliability on past missions may be expressed in terms of statistical confidence bounds. In essence, for each of several possible values of reliability (called a lower confidence bound), one calculates a confidence level on the probability that more failures would have occurred than the number that did occur.[19] If the confidence level for a lower confidence bound exceeds 50 percent, it is improbable that the observed number of successes would have occurred unless the reliability exceeded the lower confidence bound, This approach is objective[20] and takes into account all factors, including human factors, that may not affect the reliabilities of engines or other components during ground tests. On occasion, NASA has used confidence bounds.[21]

The method of confidence bounds possesses the shortcoming that, even if reliability is high, many launches are required to provide high statistical confidence that it is. **The 29 Shuttle launches to date provide only 50 percent statistical confidence that Shuttle reliability has been at least** 94.3 **percent. If the reliability is now actually 94.3**

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[11] The probability of safely recovering the crew may differ from orbiter recovery reliability, because the Crew might Survive Situations in which the orbiter would be lost (e.g., main engine shutdown followed by crew bail-out and ditching of the orbiter at sea).

[12] However, potential new failure modes were introduced. For example, radial bolts have been added to the nozzle-to-case Joint in the SRBs, creating new possibilities for blow-by or crack propagation. See Richard DeMeis, ‘‘Shuttle SRB: NASA’s Comeback Bid,” *Aerospace America,* April 1987, p. 32 ff.

[13] James H. Fletcher, ‘ ‘Risk Management Policy for Manned Flight Programs, ’ NASA Management Instruction NMI 8070.4, effective Feb. 3, 1988; Trudy E. Bell and Karl Esch, “The Space Shuttle: A Case of Subjective Engineering, “ *IEEE Spectrum,* June 1989, pp. 42-46.

[14] General Electric Astro Space Division, *Final Safety Analysis Report //for the Galileo Mission,* doc. 87 SDS4213 (Valley Forge, PA: General Electric Astro Space Division, August 1988).

[15] *Report of the Presidential Commission on the Space Shuttle* Challenger *Accident,* App. F. (Washington, DC: U.S. Government printing Office, 1986); R.P. Feynman, *What Do You Care What Other People Think? (New* York, NY: W.W. Norton& Co., 1988), p. 236.

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

[17] General Electric Astro Space Division, op. cit., NASA supplied no rationale for its estimates Of failure probabilities from which General Electric calculated this probability, and NASA specifications had the effect of masking the overall uncertainty.

[18] NASA, Code @, cited in chapter 2. The probability of orbiter recovery after the Galileo mission would be comparable to the mission success probability, because the most likely causes of a mission failure would probably destroy the orbiter.

[19] Y. Fujino, “Approximate Binomial Confidence Limits, ” *Biometrika, vol. 67, No. 3,* 1980, pp. 677-681; see also C.R. Blyth and H.A. Still, “Binomial Confidence Intervals, “ *Journal of the American Statistical Association, vol. 78, No. 381,* March 1983, pp. 108-116.

[20] Subjective methods, if logically consistent, can also be Valuable See M.G. Morgan and M. Henrion, *Uncertainty* (Clarendon, England: Cambridge University Press, in press).

[21] See, e.g., Jerry J. Fitts, NASA Transportation Services Office, ‘‘Payload Backlog, Flight Rate Capability, Reliability and Downtime—Briefing for Dale Meyers, ” Nov. 5, 1987, rev. Dec. 9, 1987.

percent, there would be a better than even chance of losing at least one orbiter on the next 12 flights (figure 3-5).[22]

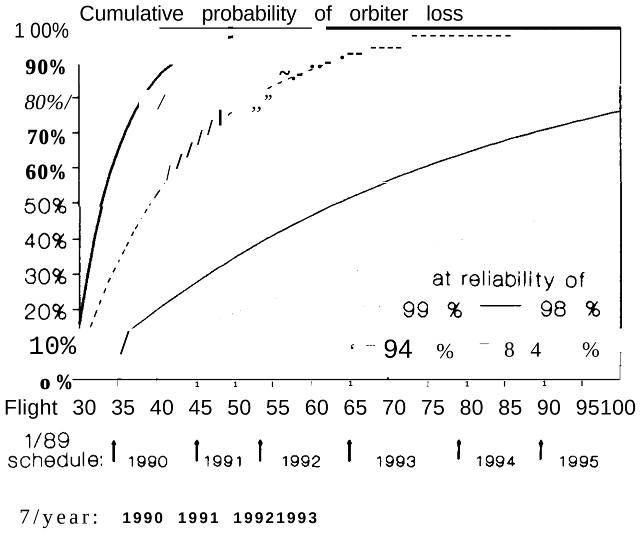
If reliability is, or becomes, higher, additional flights will eventually provide greater statistical confidence that is. But if it is judged more important to have four orbiters in the mid-1990s than to have high launch rates now, conservative planning would allow for the possibility that reliability might be lower than 94.3 percent by ordering one or more additional orbiters as soon as possible and limiting Shuttle launch rates until the first one becomes operational. Even if reliability is 98 percent, launching Shuttles at the rates now planned would make it unlikely that Space Station assembly could begin before another orbiter is lost (see box 3-A and figure *3-6).*

Obsolescence

After sufficiently many flights, an orbiter's airframe could be so weakened by fatigue as to be unsafe. Replaceable parts may also wear out; when they do, replacement parts may no longer be available from manufacturers. The manufacturers that built them originally may have stopped making such parts, the tooling used to build them may have been destroyed, and the skilled workers who made them may have left or retired. If sufficient spare parts have not been stockpiled, replacement parts may have to be custom-made, and this may require new tooling, training of workers, extra expense, and delay.

Existing Shuttle orbiters will be at least 15 years old in the mid-1990s, when Space Station operations are scheduled to begin. By that time, the designs of most Shuttle systems will be 25 years old, On occasion, it will be economical to replace some systems before they wear out, because redesigned systems would be so much less expensive to operate that the cost of upgrading would be justified. Eventually, it will be economical to replace the entire orbiter fleet with a fleet of newly designed vehicles that can be operated at lower life-cycle cost.

Figure 3-5-Effect of Flight Rate on Shuttle Orbiter Attrition



"Compare expected attrition at a launch rate of seven per yr

These graphs show the cumulative probability that at least one orbiter will not be recovered after a flight, starting with flight 30, for four possible values of orbiter recovery reliability: 84%, 94.3%, 98°/0, and 99%. The actual value of orbiter recovery reliability is uncertain. 84% is the lower confidence bound on post-Challenger reliability at a confidence level of 50%. 94.3% is the lower confidence bound on reliability at a confidence level of 50%, based on all flights to date. 98% is the nominal post-Challenger reliability estimated by L Systems, Inc., and 99% is consistent with a NASA estimate of Shuttle reliability on the *Galileo* mission (see text).

Reducing the flight rate would slow the growth of the cumulative probability of orbiter loss. For example, reducing the flight rate from that scheduled by NASA in June 1989 to a rate of five flights per year beginning 1990 would reduce the probability of orbiter loss by 1995 from about 70 percent to about 44 percent, if the orbiter recovery reliability were 98 percent.

SOURCE: Office of Technology Assessment, 1989.

NASA is now estimating the costs of operating improved Shuttle orbiters and newly designed vehicles that would be used in an Advanced Manned Launch System. NASA, the Air Force, and their contractors are also estimating the costs of operating spaceplanes that could be built using technology to be demonstrated by the experimental X-30 spaceplane. When these estimates are completed, comparisons of cost-effectiveness can be made to forecast economically optimal dates for phasing out orbiters of existing design and introducing improved Shuttle orbiters, a Personnel Launch System, an Advanced Manned Launch System, and/or operational spaceplanes incorporating X-30 technology.

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[22] The four post-*Challenger* launches to date, all successful, provide only 50 percent confidence that post-*Challenger* reliability has been at least 84 percent. If the reliability is 84 percent, there would be a better than even chance of losing an orbiter on the next four flights.

NEAR-TERM OPTIONS

In the near-term the Nation could choose one or more of the following options:

- purchase additional orbiters--either copies of the orbiter (OV-105) now being built, or improved orbiters;
- improve existing orbiters;
- improve other Space Shuttle elements or facilities; or
- develop Space Station escape capsules or a Personnel Launch System to complement the Shuttle fleet.

The following sections discuss the first three options. The last one is discussed in chapter 6.

Option 1: Buy Additional Orbiters

Buying more orbiters would increase the resiliency of the Space Shuttle system, i.e., its ability to recover rapidly from loss of an orbiter or any other event that delays launches. As noted in earlier sections, the Shuttle orbiter fleet is likely to continue to suffer occasional attrition.[23] Loss or prolonged unavailability of one orbiter would throw NASA’s plans for Space Station assembly and servicing into disarray and could lead to loss of life.[24]

The Shuttle prime contractor, Rockwell International, argues that the Shuttle system could still be flying in 2020. Although this is theoretically possible, it may not be desirable, primarily because of obsolescence. The Shuttle will remain the crew-carrying workhorse well into the next century, but other more cost-effective options will also be pursued.

The company also believes that even in the absence of attrition, the percentage of time the orbiters are likely to spend being inspected, modified, or refurbished requires NASA to maintain five orbiters in order to assure use of four.[25] Rockwell officials similarly argue that having a slightly larger fleet, or ‘fleet margin’ would allow for unexpected contingencies and unscheduled downtime, ‘

Box 3-A-Shuttle Attrition and Space Station Assembly

The Shuttle fleet now consists of three orbiters; a fourth is to become operational in 1992. All 4 orbiters will be needed to fly the missions now scheduled for 1992-95 and planned for 1995-97, when NASA plans (but has not yet scheduled) 21 Space Station assembly flights. Figure 3-6 shows the probabilities that all 4, or at least 3, orbiters will survive flights 30 to 200, if *post-Challenger* Shuttle reliability is 98 percent. ’ If NASA adheres to its current schedule through 1994 and flies 14 flights per year thereafter, Space Station assembly would begin by about flight 92 and be completed by about flight 134. There is little statistical confidence that orbiter recovery reliability is at least 98 percent—only 7.8 percent confidence based on the four post-Challenger flights, or 11.4 percent confidence based on all flights to date. (See text for a discussion of statistical confidence.)

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

Rockwell estimates that, starting from scratch, an orbiter could be built in about 6 years. If some structural spares are available, the time could be reduced by about a year. Thus, if a new orbiter (OV-106) were needed by, say, 1996, the decision to build spares would have to be made in 1990. A decision to purchase OV-106 could be delayed until fiscal year 1991. Major structural components for the Shuttle can take 4 to 5 years to produce. Space Shuttle Main Engines (SSMEs) now require 4 years. Orbiter OV-105,[26] ordered to replace the *Challenger,* was begun in 1987 and is scheduled for completion late in 1991.[27] It will be ready in such a relatively short time because major components

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[23] *Post-Challenger* Assessment of Space Shuttle Flight Rates and Utilization, National Research Council (Washington DC, Nationat Academy Press, October 1986); Report of the Committee on the Space Station of the National Research Council (Washington DC: National Academy Press, September 1987). See atso L-Systems, Inc., “Shuttle/Shuttle-C Operations, Risks and Cost Analyses,” El Segundo, CA, LSYS-88-008, July 21, 1988, which analyses the probability of supporting Shuttle commitments under differing assumptions of fleet size, flight rates, and reliability.

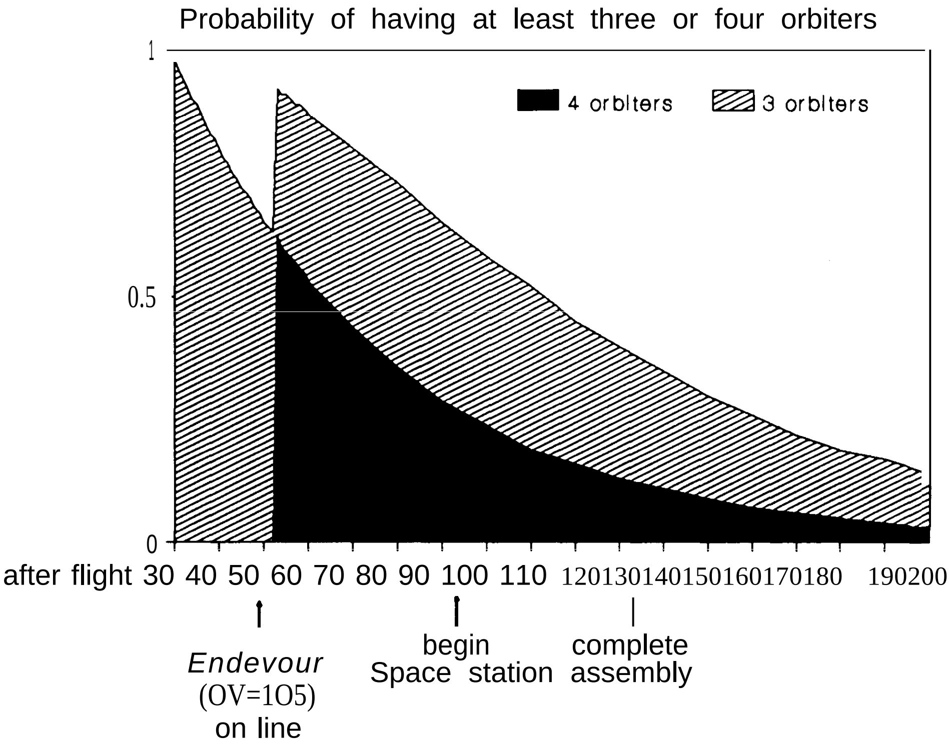
[24] Loss of life could occur if resupply *to the* Station is late.

[25] Rockwell presentation t. OTA, Nov. 15, 1988, p. 20. The L-Systems report also makes a compelling case for replacement and spare orbiters.

[26] In May 1989, President Bush named this ncw Space Shuttle orbiter *Endeavour,* after the first ship commanded by James Cook, the British explorer who was the first European to discover Hawaii.

[27] First flight is expected early in 1992.

Figure 3-6--Shuttle Attrition if Orbiter Recovery Reliability is 98 Percent



SOURCE: Office of Technology Assessment, 1989

already existed as spares. If too long a period passes between major component buys, some of the expertise and physical plant required for manufacture could be lost, leading to even longer lead times.

If Congress decided to proceed with building a new orbiter, it has three basic options. Congress could direct NASA to construct an orbiter:

- that is a copy of OV-105;
- designed for increased safety, performance (e.g., endurance), and economy; or
- with reduced weight to increase payload capability or with other improvements (e.g., an improved escape system).

Build a Copy of OV-105 *(Endeavour)*

OV-105 is itself a greatly upgraded vehicle compared with its predecessors and includes:

- addition of an escape hatch, with an extended pole to allow crew members to slide down and parachute to safety;
- external changes including improved heat absorbing tiles, changes to the landing gear, strengthening of the wing structure and engine pod; and
- more than 200 internal changes including electrical rewiring and changes in the braking and steering systems. Because of these improvements, building OV-106 identical to OV-105 would still represent considerable modernization of the fleet.

Improve Safety, Performance, and Economy

For the second option, a large number of potential new upgrades have been identified by the orbiter prime contractor, Rockwell, and are shown in table 3-1. These have been categorized into the three basic areas of safety and reliability, cost reduction, and performance, although each change has benefits in several categories. Orbiter upgrades are being continually defined and evaluated so that the list itself is dynamic. NASA/JSC is studying the costs and benefits of possible improvements with a view to identifying the most important improvements.

The orbiter cockpit could be made into a crew escape module to allow the crew to escape in some situations in which the existing escape pole system[28] is unusable. However, a crew escape module would be heavier and more costly;[29] *developing it would be* a very difficult project and its utility is the subject of considerable debate.

Space Shuttle main engine improvements that would increase engine life and reliability are already under way. They include improved welds, improved manufacturing techniques, improved nondestructive testing, improved heat exchangers, improved controllers, improved power head, engine health monitoring,[30] alternate turbopump development (see box 3-B), and a technology test bed.[31]

The on-board computers of future launch vehicles, or existing orbiters, could consist of identical computer modules "mass-produced" for economy (possibly even commercial modules) and connected by optical fibers for reduced susceptibility to electromagnetic interference.[32] *Computers* with a high degree of fault-tolerance would also allow the launch of a vehicle with a known fault rather than holding the launch to replace a failed module and retest the system.

The length of time an orbiter can remain in orbit could be extended.[33] NASA states that "extended duration orbiters' will allow NASA to fly missions lasting 16 to 28 days (current orbiters are limited to 7 days). This would be useful for SpaceLab and for tending the Space Station in the crew-tended phase, or servicing commercially developed space facilities.[34] It would also provide experience in technology areas beneficial for future space operations.

A Shuttle orbiter could be given the capability to fly an entire mission automatically, as the Soviet shuttle *Buran* did on its first flight. Without a crew, an automatic orbiter could carry extra payload. With a crew, such an automatic orbiter could land even if Shuttle pilots were incapacitated (e.g., by a depressurization accident).

Table 3-I-Selected Possible Upgrades for New Orbiters

Safety & reliability:
- Assured *crew* return
- Simplified hydraulics
- Increased strength skins
- Improved attitude control
- Suppressed helium overpressure

Cost reductionms:
- Simplified cooling
- Modernized crew displays
- improved tile durability
- Modernized telemetry

Performance:
- Extended duration orbiter
- Weight reduction
- ***Local*** structure strengthening
- Global Positioning Satellite (GPS) receiver-computer for navigation

SOURCE: Rockwell International Corp.

Reduce Weight

The third option would involve significant weight reduction of the airframe. Orbiter airframe weight reductions of 8,000 to 10,000 pounds for both retrofittable and nonretrofittable structures could be achieved through the use of composite materials, alloys, intermetallics, and high-temperature metallies. This would allow payload capability to be increased by the amount orbiter weight is reduced (i.e., up to 10,000 pounds) or allow an improved escape system or other systems to be installed without sacrificing payload capability. About 10$000 pounds of weight reduction would provide the equivalent of one extra launch of 60,000 pounds of payload in one and one-half year of OV-106 flights (approximately six launches). The choice of specific airframe structural modifications would depend on cost-benefit analyses.

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[28] The escape @e system is only good under stable flight conditions al relatively low speeds.

[29] George Marsh, ''Eject, Eject, Eject,' *Space,* January-February 1988, pp. 4-8.

[30] In other words, being able t. diagnose engine operation when it *is* firing. This leads to improved performance and potentially can signal if engine shutdown is necessary to avoid catastrophic failure.

[31] J.W. Smelser, MSFC, presentation to OTA, Sept. 21, 1988.

[32] *Reducing Launch operations Costs,* op. cit., footnote 3, p. 63.

[33] Dwayne Weary, JSC, presentation to OTA, Sept. 22, 1988.

[34] It would generally be useful for a whole class of experiments. See OTA's Space Station study: *Civilian Space Stations and the U.S. Future in Space* (Washington, DC: U.S. Congress, Office of Technology Assessment, OTA-STI-241, November 1984).

Box 3-B—Alternate turbopump Development

Improving the lifetime of the SSME is a good example of a significant incremental improvement. NASA has a $228 million contract with Pratt and Whitney to build an alternate fuel and oxidizer turbopump that will be more durable and reliable than the existing ones.[1] Pratt and Whitney will attempt to bring the engines closer to their intended 55 missions (approximately 7.5 operating hours), between costly teardowns.[2] NASA's design goals call for 30 missions before removal for minor seal and bearing replacements, and another 30 missions before major overhaul. This would cut SSME refurbishment time and operational costs. These turbopumps are designed to be completely interchangeable with the existing Rocketdyne pumps, have more benign failure modes for greater safety, and will have only 4 welds compared to the present 297. The table below lists some of the ATD enhancements and advantages to date. The new turbopump borrows heavily from Pratt and Whitney's experience building the T800 helicopter engine; additional development is required for withstanding the harsh operating environment of ultra-high pressures, cryogenic temperatures, and possible hydrogen embrittlement.

Benefits of Alternate turbopump Development

Principle:

- Design for producibility utilizes precision castings and new processes and materials, thereby minimizing number of welds, parts, and coatings.

Results to Date:

- Number of welds reduced from 297 to 4.
- Rotor stack details reduced from 80 to 39
- No coatings in hot turbopump sections

Benefits:

- Improved turbomachinery quality
- Improved part-to-part repeatability
- Improved durability
- Reduced machining requirements
- Reduced manufacturing lead time by 20 months
- Reduced turbomachinery cost ($3 million per pump set)

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[1] Frank Colucci, "Space Power From Florida,'' *Space*, Nov-Dec 19S8, pp. 10-12; Edward H. Kolcum, "Pratt and Whimey Engine Turbopumps Could Fly on Space Shuttle in 1992," *Aviation Week and Space Technology*, Feb. 27, 1989.

[2] Up to the present, the engines have had complete turbine blade inspections after every mission.

Some of these upgrades could not be retrofitted into existing vehicles because they would require extensive and expensive structural changes.

Option 2: Improve Existing Orbiters[35]

Redesign and improvement for all Shuttle systems is a continuing process.[36] However, NASA, through the Johnson Space Center, has begun to examine how best to improve the existing Space Shuttle system by making incremental changes. The first effort studies major evolutionary modifications that could be applied to the existing Shuttle fleet. This evolutionary path is becoming increasingly attractive to NASA because it would allow a phased implementation of improvements, is relatively low-risk, and would not require "new program" funding—funding that is often difficult to obtain, particularly when the overall U.S. budget is so constrained. Major upgrades to the existing fleet could be accomplished during the regularly scheduled structural inspection program (every 3 years), bringing the entire fleet up to improved levels. However, NASA would have to reduce its expectations for the Shuttle schedule in order to have enough time to make these modifications. As noted above, meeting the manifested launch rate of 14 flights per year presents a major challenge to NASA, even in the absence of major modifications to the Shuttle system.

Improved Space Shuttle main engines and computers, discussed above, could be installed on existing orbiters.

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[35] See also Gene Austin, MSFC, "Shuttle Evolution/Follow-On," Sept. 21, 1988, and C. Teixeira, JSC, Sept. 22, 1988.

[36] Because of the modular nature of the Space Shuttle system, some changes can take place outside of orbiter changes.

Reduce Airframe Weight

The airframe weight of existing orbiters (or OV-105) could be reduced, but not by as much as the airframe weight of a new orbiter could be reduced. This would allow payload capability to be increased by the amount orbiter weight is reduced, or allow an improved escape system or other systems to be installed without sacrificing payload capability.

Crew Escape Module

The cockpit of an existing orbiter could be made into a crew escape module to allow the crew to escape in some situations in which the existing escape pole system would be unusable. A crew escape module would be heavier and more costly; installation on an existing orbiter would be more costly, in terms of payload capacity sacrificed, than would installation on a new orbiter, because the airframe weight of a new orbiter could be reduced by a greater amount.

Automatic Orbiter Kit

An existing Shuttle orbiter could be given a capability to fly an entire mission automatically. This would require installation of a kit consisting of additional automatic control equipment (in the orbiter galley) and cables. Rockwell International estimates that it would take 2 years and cost $200 million to automate a first orbiter and $30 million to $40 million each for successive orbiters. Rockwell designers estimate the most difficult problem will be steering and braking after landing.

Extending Duration in Orbit

An existing Shuttle orbiter could also be made an Extended Duration Orbiter by installing fuel cell pallets in the payload bay, and additional life support supplies.

Option 3: Improve Other Space Shuttle Elements or Facilities

Space Shuttle elements other than the orbiter could also be improved, or replaced by newly designed elements.

Continue Development of Advanced Solid Rocket Motors [37]

The *Challenger* accident was caused by a failure in a solid rocket motor.[38] After the accident, NASA redesigned the solid rocket motors (SRMs) to improve reliability; these redesigned solid rocket motors (RSRMs) have been used on all subsequent Shuttle flights. Seeking even higher reliability, as well as higher performance, NASA has also initiated development of Advanced Solid Rocket Motors (ASRMs). They are to weigh less than RSRMs but produce more thrust, allowing Shuttles to carry up to 12,000 pounds of additional payload to orbit. Figure 3-7 illustrates the expected improvement in ASRM payload capability with respect to the present RSRM. Some NASA officials have expressed concern over whether the full additional lift capability of 12,000 pounds will be achieved. Their concerns are the result of past experience with launch systems.[39] Program officials at Marshall are confident that the 12,000 pound lift increase for the ASRMs can be achieved, as they have incorporated a lift margin to allow for weight growth of the solids. Many also feel that even if the lift increase goal is not completely met, that the other advantages of the ASRMs such as increased reliability, reproducibility, and a second supplier for of solids will make them worthwhile. NASA expects that the ASRM program will promote a competitive solid rocket motor industry and encourage commercial initiatives.[40] NASA has estimated the cost of the ASRM program at $1.3 billion, of which $1 billion would be for ASRM design, development, testing, and evaluation, and the rest for facility construction.

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[37] See also, U.S. Congress, Office of Technology Assessment, *Launch Options for the Future: A Buyer's Guide,* pp. 27-28.

[38] *Challenger* was launched in weather much colder than the solid rocket motors were certified to tolerate.

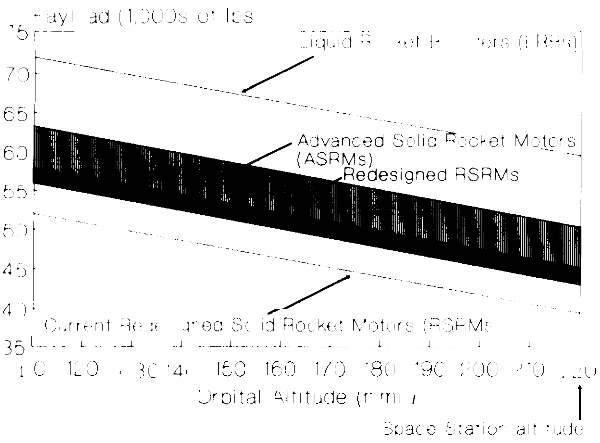
[39] For example, as noted earlier, the original Shuttle performance goal was 65,000 pounds to 110 nmi, 28.5 degrees. But the existing Shuttle only achieves 52,000 pounds to this orbit. This decrease in lift capability arose from weight growth of the Shuttle itself and lower than expected performance from the propulsion systems.

[40] NASA, "Space Shuttle Advanced Solid Rocket Motor—Acquisition Plan," Mar. 31, 1988, P. 3.

[41] Aerospace Safety Advisory Panel, op. cit., p. 3, and press briefing, Mar. 28.1989.

[42] Ibid., loc. Cit. See also, Eliot Marshall, "Shuttle Rocket Plan Under Fire, *Science,* vol. 244, pp. 135-136.

Figure 3-7--Expected Shuttle Payload Capability With Proposed Boosters



SOURCE: Office of Technology Assessment,1989.

In March 1989, NASA's Aerospace Safety Advisory Panel (ASAP) announced its finding that "on the basis of safety and reliability alone it is questionable whether the ASRM would be superior to the RSRM . . . until the ASRM has a similar background of testing and flight experience. This may take as long as 10 years. . ."[41] The ASAP recommended "that NASA review its decision to procure the Advanced Solid Rocket Motor and postpone any action until other alternatives. . . have been thoroughly evaluated. "[42] NASA disagreed with the ASAP findings and, in late April 1989, it awarded two contracts to a partnership formed between Aerojet and Lockheed.[43] One contract is for design and development of the ASRM; the other is for the design, construction, and operation of an automated solid rocket motor production facility. NASA has designated Yellow Creek, Mississippi as its preferred GOCO (government-owned/contractor-operated) ASRM production site and the Stennis Space Center in Mississippi as the motor test location. ASRMs could be ready for a first launch in 1994 or 1995.

Improve Redesigned Solid Rocket Motors

The *Challenger* disaster was attributed to a failure of one of the Solid Rocket Motors.[44] This prompted a program that redesigned the motor's joints and made other improvements, some of which were in process even before the Shuttle explosion. Many of the improvements in the RSRMs relate to ablative and insulation materials processing and nondestructive testing techniques. As of May 1989, the RSRMs have now performed successfully on four Shuttle flights.[45]

The thrust of the RSRMs could be improved by 6,000 to 8,000 pounds by substituting a more energetic solid propellant and by performing other requisite changes to the motors.[46] The additional thrust would increase the Shuttle's payload capacity by the same amount but might decrease unreliability. NASA has not estimated the cost of such improvements, but qualification testing alone would require about 10 rocket firings at $10 million to $12 million per test. These improved thrust RSRMs would be ready for flight before 1995, which is when ASRMs are scheduled to replace the existing RSRMs. More extensive changes could give a payload increase of 13,000 pounds.[47]

Develop Liquid Rocket Boosters (LRBs)[48]

At the same time that NASA was planning its ASRM work, propulsion experts inside NASA and in the aerospace community began to reconsider the practicality of replacing the current SRMs with

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[41] Aerospace Safety Advisory Panel, op. cit., p. 3, and press briefing, Mar. 28, 1989.

[42] Ibid., loc. cit. See also, Eliot Marshall, "Shuttle Rocket Plan Under Fire, ' ' Science, vol. 244, pp. 135-136.

[43] Immediately after the ASAP annual review on Mar. 28, 1989, NASA Administrator James Fletcher announced to the press that NASA would award the ASRM Phase C/D contracts as planned, despite the ASAP concerns. One reason was that the funds had already been authorized.

[44] *Report of the Presidential Commission on the Space Shuttle Challenger Accident,* op. cit.

[45] *Discovery:* Sept. 29, 1988; *Atlantis:* Dec. 2, 1988; *Discovery:* Mar. 13, 1989; *Atlantis:* May 4, 1989.

[46] See response by Morton Thiokol, Inc. to NASA Marshall Space Flight Center request to provide candidate NSTS payload performance improvements directly related to RSRM changes. Memo L060-FY89-170, Apr. 3.1989.

[47] Ibid.

[48] *Launch Options for the Future: A Buyer's Guide,* op. cit., footnote 38, pp. 28-29.

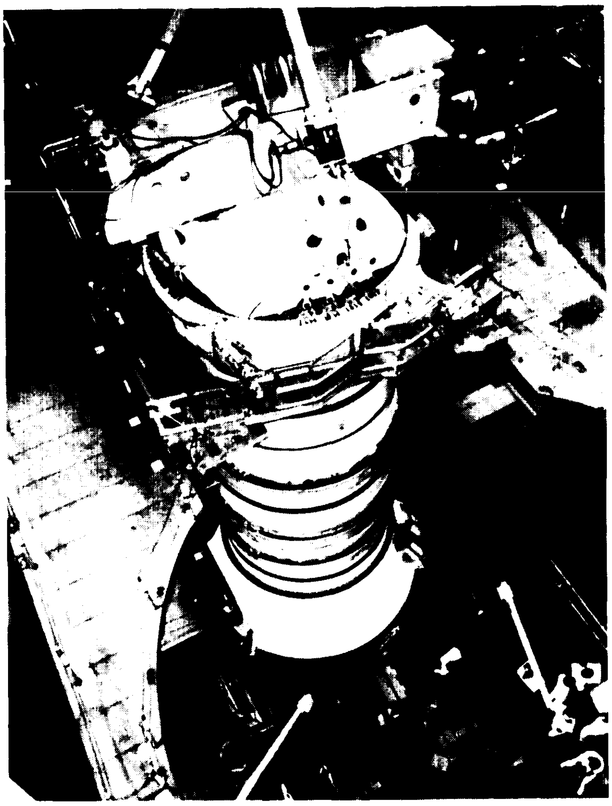

Photo credit: National Aeronautics and Space Administration

One of the Shuttle's redesigned solid rocket motors being attached to the mobile launch platform, Kennedy Space Center.

Liquid Rocket Boosters.[49] Initial studies indicate that LRBs could replace or complement the RSRMs or the ASRMs on the Shuttle, but would require some redesign of Shuttle and launch pad systems.[50]

NASA estimates that development and testing for the liquid booster alone would cost $3 billion spread over 8 years.[51] Pad modifications would cost $500 million. A conceptual drawing of the Shuttle atop LRB rockets (two pods of four liquid engines each) is shown in figure 3-8.

Figure 3-8-Space Shuttle With Proposed Liquid-Fuel Rocket Boosters (LRBs) (artist's conception)

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Pri ate e to n n LRB has been ub tan al Gene al Dynamı one o the LRB udy ontractors a was Martin Marı a has p po d Natıona L qu d Rock B o Program Th wou d de e op an LRB q d o g n/l qu d hydro g n fue ed n onȷ n tıon w h ped up ALS p opu on efforts n th ız hru and w gh qu rements fo both ng n are rtual y th am Poten al y arge o ng ou d ac u om

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[49] LRBs were originally studied at the inception of the Shuttle program but were rejected in favor of solids when it was estimated that LRB development would cost $500 million more and would take at least 1 year longer than solids. (U.S. Congress, House Committee on Science, Space and Technology, Subcommittee on Space Science and Applications, Space Shuttle Recovery Hearings, Apr. 29-30.1987, vol. I, p. 64; also Larry Wear, MSFC). Some cite this as another case where a decision based on a constrained budget led to a less than optimal choice of technology for the long-term.

[50] Lockheed Space @rations Co. report to KSC: Liquid Rocket Booster Integration Study, LSO-000-286-1410, November 1988.

[51] This includes the first flight article and operations costs for the first flight.

pared to developing each separately.[52] The Rocketdyne Division of Rockwell International has also worked on modifying some of their existing engine hardware into an "RSX" configuration (liquid oxygen/kerosene fueled) for use on art LRB.[53] Both firms feel that LRBs could be developed for substantially less than $3 billion.

LRBs could provide significant benefits in safety, performance, reliability, operations, environmental impacts, and the payload's physical environment, and offer important synergisms with other programs (table 3-2). However, they would also present higher risks, resulting from greater technical uncertainty, longer development times, potentially higher initial cost, and the need for launch pad modifications. Appendix A discusses the benefits and drawbacks of LRB development in more detail.

Develop Lightweight External Tank (ET)[54]

The emphasis on using improved materials in the Shuttle system has focused particularly on saving weight. For example, a 20 to 30 percent weight savings in the weight of the external tank could accrue from using aluminum-lithium (A1-Li)[55] alloy instead of the present aluminum alloy. If the external tanks were made of Al-Li and the intertanks (which hold the cryogenics) were made of graphite epoxy composite, the Shuttle would weigh 12,000 pounds less at lift-off. Because the external tank is carried nearly all the way to orbit, reducing the weight of the ET by 12,000 pounds would translate into almost 12,000 pounds of increased payload capability. Additional ET options, which could improve reliability and reduce costs, would involve increased use of robotics in manufacturing, nondestructive evaluation techniques, and thermal protection system improvements. Table 3-3 lists some typical materials improvements.

Table 3-2-Abort Mode Comparison of Shuttle/ Booster Configurations

Engine failure[a]		Abort mode		
Booster +	SSME	SRB	ASRM	LRB
0	1	RTLS	RTLS	TAL
o	2	Split-S or ditch	Split-S or ditch	Loft-return
o	3	Split-S or ditch	Split-S or ditch	Loft-return
1	0	None	None	ATO
1	1	None	None	RTLS
1	2	None	None	Loft-return
1	3	None	None	Loft-return
2	0	None	None	TAL
2	1	None	None	RTLS
2	2	None	None	Loft-return
2	3	None	None	Loft-return

[a] Assumes engines tail at liftoff.

KEY: ASRM=advanced solid rocket motor; ATO=abort to orbit; LRB=liquid rocket booster; RTLS=Return to launch site; Split-S=aircraft landing maneuver that utilizes banking to dissipate energy and slow down; SRB=solid rocket booster; SSME=Space Shuttle main engine; TAL=transatlantic abort.

SOURCE: General Dynamics

Improve Operations[56]

Introducing a number of new technologies and management strategies into Shuttle operations could make these operations more efficient, faster, and perhaps less expensive.[57] An excellent example of this is the Shuttle tile automation system described in box 3-C. NASA is also exploring the use of expert systems in Shuttle operations and making other efforts to "take people out of the loop' in order to reduce the number of human operations and decisions.[58] Its goals are to speed up shuttle turnaround and reduce costs.

A POSSIBLE SHUTTLE IMPROVEMENT PROGRAM

To recapitulate, there are several options for conserving, maintaining, and improving the existing Shuttle fleet. The fleet could be conserved by flying fewer Shuttle flights to reduce the expected attrition

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[52] "The Case for a National Liquid Rocket Booster, " General Dynamics Space Systems Division, March 1989.

[53] "U.S. Launch Vehicles—Planning for the Future, " Rocketdyne, May 3, 1989.

[54] *Launch Options for the Future: A Buyer's Guide,* footnote 38, p. 29.

[55] There has been some concern as to the impact resistance of Al-Li, but as with any new candidate materials, extensive testing and certification would be done before any actual use.

[56] *Launch Options for the Future: A Buyer's Guide,* footnote 38, p. 29; *Reducing Launch Operations Costs:* New *Technologies and Practices,* op. cit., footnote 3.

[57] *Launch Options for the Future,* footnote 38, p. 29.

[58] Care must be exercised, of course, t. not take this too far since many critical decisions require human judgment, based on the the b&st information available to the person at that time.

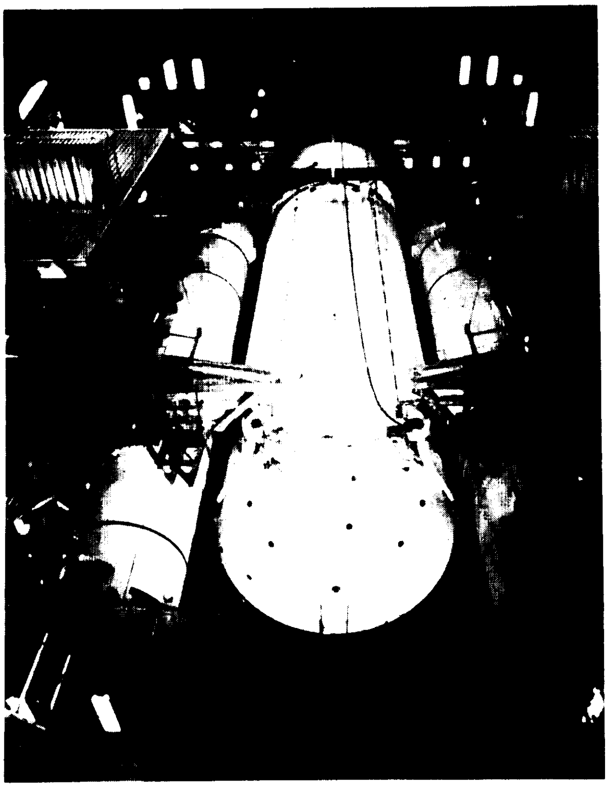

Photo credit: National Aeronautics and Space Administration

The external tank is lowered into place between the solid rocket motors in the Vehicle Assembly Building, Kennedy Space Center.

rate. To do this without reducing service, Shuttles could be modified to carry more payload, or complementary vehicles could be developed to fly missions that would otherwise require Shuttle flights, Shuttle fleet size could also be maintained, despite attrition, by ordering one or more additional orbiters now, as a hedge against attrition. If NASA waits until it loses an orbiter to order a replacement, the replacement might cost more and take longer to build than one ordered in the near future.

Table 3-3-Materials Improvements for Shuttle

External Tank:
- Use of robotics
- Nondestructive evaluation techniques
- Thermal protection system (TPS) Improvements/composite applications

***Rocket* Boosters:**
- TPS development
- High temperature sealant development
- Process improvements
- Advanced Thrust Vector Control (TVC) System evaluation development

solid ***Rocket*** Motors:
- Ablative and insulation process development and Nondestructive Evacuation techniques

Space ***Shuttle Main Engines (SSMEs):***
- Use of robotics
- Weld improvements
- Producibility

SOURCE: Rockwell International Corp.

Table 3-4 lists several improvements discussed above, and some discussed in the OTA technical memorandum *Reducing Launch Operations Costs,* which could be elected to increase payload, safety, economy, or utility. The list is illustrative, not exhaustive, and contains entries (e.g., improved RSRMs, ASRMs, and LRBs) with redundant benefits, because having a variety of booster options may improve resiliency, and it may be desirable to have both an early improvement in payload capability and a larger improvement later.

A program of this magnitude could cost as much as $8.5 billion. A 10-year program would therefore require average funding of $850 million per year, some of which (e.g., for ASRMs) NASA has already planned to spend. However, to fund such a program at a level that would make a marked improvement in Shuttle system safety and performance would require finding extra space program funding, scaling down the Space Station program, or deferring other programs.

Box 3-C-Shuttle Tile Automation System

Inspecting the some 31,000 thermal protection system (TPS) tiles on the Shuttle orbiters and repairing damaged ones is highly labor intensive. Automating the inspection procedures could reduce overall labor costs, and increase inspection speed and accuracy. In 1986 NASA began the Space Systems Integration and Operations Research Applications (SIORA) Program as a cooperative applications research venture among NASA-KSC, Stanford University, and Lockheed Space Operations Company. One of its initial tasks is to apply automation and robotics technology to all aspects of the Shuttle tile processing and inspection system.

The team is developing an automated work authorization document system (AWADS) that will enable the technicians to document the condition of each tile, determine any necessary repairs or replacement, and generate work instructions. With the automated system, the computer, which is programmed to recognize each technician's voice, prompts the technician to find the correct tile, enter its number, and report on its condition in a systematic way. The TPS quality control technician first inspects the tiles after each flight and enters the part number, location, and condition of each tile into a computer database by voice. The computer's central database automatically generates a problem report in electronic format, which a TPS engineer uses to identify and recommend proper repair procedures for the tile. The problem report proceeds through an electronic signature loop until final approval for the repair. Finally, the TPS technician uses the voice data entry method to indicate tile status as repair procedures are completed.

The AWADS system and other automated systems developed in the SIORA program use the Ada programming language,[1] the software environment that will be used in the Space Station and other large NASA programs in the future. It offers the advantages of excellent portability from one hardware system to another, a rich set of programming functions and tools, and a uniform code documentation.

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[1] Ada was originally developed for use by the armed services. It has become the DoD software standard.

Table 3-4-A Possible Shuttle Improvement Program

Options	cost	Benefit
Orbiter Improvements:		
Develop alternate turbopumps for Space Shuttle main engines	$228 million[a]	Safety and economy
Automate orbiter for unpiloted flight	$200 million[b]	Safety
Extend orbiter fight duration	$120 million	Utility
Built-in test equipment[c]	[?][c]	Safety and economy
Booster Improvements:		
Increase thrust of redesigned solid rocket motor.	$50 to $60 million	More payload
Continue to develop advanced solid rocket motor.	$1.3 to $1.8 billion	Safety and more payload
Develop liquid rocket booster	$3.5 billion	Safety and more payload
Other elements:		
Develop lightweight external tank	[7]	More payload
complementary Vehicles:		
Develop Shuttle-C	$1.5 billion	For cargo
Develop capsule or lifting body for Space Station escape.	$0.7 to $2 billion	Safety

[a] Already funded by NASA.

[b] Only $30M to $40M for each additional orbiter.

[c] See OTA-TM-ISC-28, *Reducing Launch Operations* Costs.

NOTE: Most of these options would increase Shuttle payload capability, but by different amounts; their other benefits and their dates of availability would differ (see fig. 3-9). Therefore, two or more options might be pursued, for example, ASRMs to increase Shuttle payload capability and LRBs for increased safety and reduced environmental impact. On the other hand, NASA could develop complementary vehicles (e.g. Shuttle-C) to carry large payloads to orbit and reduce the Shuttle flight rate, reducing Shuttle fleet attrition. The United States need not decide imminently whether to proceed with one or more of these options. However, if such improvements are desired, more benefit will be reaped if they are begun earlier.

SOURCE: Office of Technology Assessment, 1989.