BEN EVANS

The Space Shuttle: An Experimental Flying Machine

Foreword by Former Space Shuttle Commander Sid Gutierrez

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Thirty Years of Challenges

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To my wife, Michelle, for everything

Foreword

Experimental Flying Machine is a meticulously researched and beautifully written narrative of the Space Shuttle Experience. Ben Evans weaves together the technology trades, the political influences and the real human beings who created and flew this amazing vehicle. If you ever wondered why the Shuttle looked the way it did, Ben explains it in a way everyone can understand. Most engineering efforts are a compromise and the Space Shuttle is the prime example.

Ben Evans reminds me of Stephen Ambrose. Ambrose was able to get World War II veterans to open up about their experiences in books like The Band of Brothers. In the same way Ben Evans has been able to get the normally tight-lipped cadre of astronauts to open up about their personal experiences in the high risk, high stress environment flying the Shuttle. Their excitement, frustrations and fears. And our fears were well founded. The author describes the many close calls – red flags – that exposed the vulnerabilities and razor thin margins that foretold the Challenger and Columbia accidents. Much of what you will learn has only been available to those who lived the experience – passed on by word of mouth or buried in obscure government reports. But Ben ties it all together in a narrative that is fascinating, thought provoking and informative. I was surprised at how much I learned and I lived it.

Experimental Flying Machine should be a required read for every engineering and management student. It is not an engineering book, but it explores the decisions engineers and managers must make and exposes the consequence of those decisions including their human impact. Ben Evans presents a perspective on the Space Shuttle that is far different than the finely honed narrative you have heard from NASA Public Affairs. It is a book I could not put down.

Sidney M. Gutierrez (Colonel, U.S. Air Force, Ret.)
NASA Astronaut 1984-1994
Pilot, STS-40 (June 1991)
Commander, STS-59 (April 1994)

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Author's Preface

Astronaut Steve Hawley once remarked that the Space Shuttle was a feat of such technical enormity that simply launching it was nothing less than a minor miracle. It required thousands of people to work together to ensure that millions of discrete mechanical and electronic parts operated perfectly and in tandem. Several hundred of those parts, indeed, were so critical to the safety of the crew and the spacecraft that their single-point failure could spell disaster. The Shuttle required a winged vehicle, awkwardly bolted onto an immense fuel tank and a pair of boosters, to launch like a rocket, fly like a spacecraft, then descend back to Earth like an aircraft to a smooth runway landing…and then, after a period of refurbishment, repeat the achievement again and again. It required perfect weather conditions at its launch site and at several emergency landing sites around the world. It required precise control over huge amounts of volatile propellants and a computing power smaller than can be found in one of today's mobile phones. And with survivability and emergency escape provisions which many astronauts found questionable at best, it required steely-eyed bravery on the part of the men and women who dared to fly this most experimental of experimental flying machines.

I grew up with the Space Shuttle. It made its first flight over the California desert when I was a few months old, it first launched into space as I attended nursery, it triumphantly repaired the Hubble Space Telescope as I finished high school and it began building the International Space Station when I graduated from university. Over its 30 years of active operational service – first launched on 12 April 1981 and last landed on 21 July 2011 – this fleet of five winged orbiters flew an impressive 135 times. Fleet leader Discovery completed 39 missions, Atlantis made 33, Columbia made 28, Endeavour made 25 and Challenger made ten. Crews as small as two and as large as eight launched and repaired satellites, carried out scientific research and built and maintained space stations. Across that bundle of years, the Shuttle achieved unimaginable dreams and opened space exploration to more walks of life than ever before. The descendants of its technology continue to live and breathe as America prepares for its next great step into deep space. Modified versions of its engines, its boosters and its pressure suits will power the next generation of human explorers to the Moon and back.

But the Shuttle was from the outset, and remained to the very end, a highly dangerous vehicle to fly. Even late in life, with substantial safety improvements having been made, the risk of a launch disaster was predicted to be one-in-500; by the end of the program, that figure was refined to no better than around one in a hundred. In its original form, the Shuttle was intended to be the spacefaring equivalent of a commercial airliner, capable of carrying passengers and payloads into space regularly, reliably and cheaply and flying dozens of times each year. But as the vehicle's design morphed in response to external political and military pressures, it grew gradually more complex. When it eventually flew, it required far too much attention after each mission to ever come close to achieving those early dreams. And in any case, few people intimately involved in the program ever considered its politically mandated goals to be realistic.

The Shuttle's fallibility was tragically exposed on two occasions. In January 1986, a failure of one of its boosters resulted in the deaths of seven astronauts. And in February 2003, a failure of its fuel tank and critical damage to its thermal protection system claimed another seven lives. Both failures traced their cause to human as well as technical shortfalls. And betwixt those two dates, numerous other missions came within a hair's breadth of disaster: from aborted launch attempts on the pad to in-flight engine failures and from heat shields suffering severe damage to maddening computer malfunctions.

This book was written on the eve of the 40th anniversary of the first Shuttle flight, by which time the surviving members of the fleet had been retired for almost a decade. It offers a glimpse at the inherent dangers of this reusable spacecraft, whilst at the same time offering the reader a perspective of some of its successes. Of course, to trace every single problem faced by the Shuttle – every single weather delay, every time a Reaction Control System (RCS) thruster failed, every time a computer conked out, every time the toilet broke – would require a book far larger than this, and as such the troubles described in these pages are far from exhaustive. But *Experimental Flying Machine* seeks to offer a snapshot of some of the Shuttle's most visible technical and human challenges over its three astonishing decades of service.

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A Troubled Childhood

FIRST MOTIONS

As clocks across Florida struck eight on the last Monday of 1980, a new era began. In the early morning gloom, the doors of the Vehicle Assembly Building (VAB) – a 53-story sugar-cube of a structure which stood dominant over the marshy flatness of the Kennedy Space Center (KSC) on Merritt Island – clanked ajar to reveal a spacecraft like no other. It shimmered in the rays of the newly risen sun as the warming fingers of dawn gently caressed its flight surfaces and picked out its textures and contours in stark relief. The first Space Shuttle, named 'Columbia' in honor of the female personification of the United States, was on the move, bound for the launch pad. And after a troubled decade in development, the greatest experimental flying machine in history was about to spread its wings.

Clearing the confines of the VAB and emerging into the salty Florida air, this 56-meter behemoth cannot have failed to impress those who were there to see it on 29 December 1980. It surely caused many a jaw to drop in astonishment. A tight knot of engineers and managers attired in suits and ties, shirts and jeans, watched agape, some with hands stuffed into pockets, others conversing in hushed tones as Columbia made her creaking departure. When they saw her next in this building, she would be a 'used' spacecraft, having circled the globe 36 times, spent two days in orbit and deep into processing for another mission. Indeed, the central tenet of the Shuttle concept was that its fleet of winged 'orbiters' (of which Columbia was one) were fully reusable, capable of lifting more people into space more frequently than ever before and drawing down the immense cost of doing so.

Yet cost was not the Shuttle's only immense feature; so too was the spacecraft itself. Everything about it shrieked 'huge'. And whilst we dwellers of the 21st century may scratch our heads over the physical dimensions of this Great Pyramid of

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our age, it is difficult to grasp in a few sentences its sheer scale and monumentality. Even the tracked ‘crawlers’ which hauled the 2-million-kilogram Shuttle ‘stack’ along a roadway of Alabama and Tennessee river-gravels from the VAB to one of two pads at KSC’s historic Launch Complex 39 – a distance of some 5.6 kilometers – were a marvel of industrial engineering. To this day, they remain the largest self-powered land vehicles in the world, tipping the scales at 2.7 million kilograms. With a Mobile Launch Platform (MLP) and fully laden Shuttle atop them, the crawlers lumbered along at a glacial pace of just 1.6 kilometers per hour.

Unsurprisingly, not all went according to plan and between October 1983 and December 2010 a total of 18 missions were not only ‘rolled out’ to the launch pad, but also ‘rolled back’ to the VAB. The finger of blame often pointed squarely at Florida’s intractable weather, with the Shuttle ordered off the pad and back to the safety of the assembly building in response to the ravages of Tropical Storm Klaus in October 1990, Hurricane Erin in August 1995 and Hurricanes Bertha and Fran in July and September 1996. On one occasion in August 2006, threatened by severe approaching weather from Tropical Storm Ernesto, one Shuttle was rolled off the pad and was partway back to the VAB when conditions began to improve. The rollback was halted on the crawler roadway and the stack returned to the pad. But most problems which enforced rollbacks over the years were in response to technical difficulties not easily accessible or fixable in a vertical configuration at the pad: a suspect booster nozzle, the replacement of engines following a pair of aborted launch attempts, an issue with a primary payload, hydrogen leaks, cracked fuel-line door hinges and even – as will be discussed in Chapter 4 – attacks by hailstones and woodpeckers. Nor was the MLP and crawler hardware itself immune to difficulties. During one rollout in January 1997, a crack 7.3 meters in length was spotted on the MLP deck, whilst faulty bearings in the steering linkage on one of the crawler’s four trucks and hydrogen leaks conspired against other missions. These problems provided a stark and constant reminder that nothing about this endeavor was routine.

As Columbia moved, the onlookers continued to watch and chat. A helicopter fluttered overhead, filming the proceedings for posterity. Technicians in hardhats, wearing headsets and clutching walkie-talkies, plodded alongside the crawler’s huge tracks, their eyes and ears attuned to the slightest hint of damage or structural wear. Minutes ticked into hours as the morning chill gave way to a fine Florida afternoon. Eventually, the “big bird” (as Shuttle commander Jack Lousma once described it) reached its destination and set about navigating the upward slope to the concrete surface of Pad 39A. This was hallowed ground in America’s space program, having already been added to the National Register of Historic Places (NRHP) in 1973. A decade before the arrival of Columbia, it had seen off most of the mighty Saturn V rockets on their Apollo expeditions to the Moon and it was also from here that America’s first space station, Skylab, speared into orbit. Steeped in history, Pad 39A now stood proud for a new and very different chapter in its life.

Fig. 1.1 Displaying its unusual "butterfly-and-bullet" configuration, Columbia reaches Pad 39A atop the Mobile Launch Platform (MLP) and crawler on 29 December 1980. Clearly visible are the white-painted External Tank (ET) and twin Solid Rocket Boosters (SRBs).

Sophisticated levelling machines kept the Shuttle perfectly upright as it inched its way up the incline. And having set its precious cargo securely onto the concrete pedestals of the pad surface at three in the afternoon, the crawler withdrew. It left behind an ungainly machine utterly at odds with how a rocket 'should' look. For unlike all rockets before it, the Shuttle was no pencil. Two reusable Solid Rocket Boosters (SRBs), each 45.5 meters tall, flanked the stack like a pair of great Roman candles, providing the lion's share of the thrust (about 80 percent, or 2.5 million kilograms) at liftoff. A bulbous External Tank (ET), measuring 47 meters long and discarded after each flight, carried the liquid oxygen and hydrogen propellants to feed the Shuttle's cluster of three main engines which delivered a total of 535,000 kilograms of thrust. As for the orbiter itself, in size and shape it was not dissimilar to a DC-3 jet airliner: 37.2 meters long and spanning 27.8 meters between the tips of its delta-shaped wings. These constituent parts forged a flying machine which astronaut Story Musgrave likened to a butterfly that was awkwardly bolted onto a bullet.

"The Shuttle is an asymmetric vehicle," remembered Neil Hutchinson, ascent flight director in Mission Control for Columbia's maiden voyage. "It doesn't look like it ought to launch right because it's not a pencil. Some of us in the early days wondered how that was going to work, not being an aerodynamicist. In fact, the Shuttle…it's a very tricky vehicle to launch. It has to be pointed carefully in the right direction at certain times or you'll tear the wings off or tear it off the External Tank. It is not a casual launch process." The Shuttle, therefore, was highly problematic in terms of its aerodynamic behavior and although hundreds of engineering tests and launch abort simulations and computational fluid dynamics models were conducted before its first flight, the unknowns remained. "I'm not sure that we have risk-takers in NASA these days," Hutchinson added, "that would take that kind of risk."

A REUSABLE SPACESHIP

For three decades, from April 1981 to July 2011, five Shuttle orbiters – Columbia, Challenger, Discovery, Atlantis and Endeavour – launched 135 times, traveled 873 million kilometers, spent 1,323 days circling the Earth a total of 21,030 times, and carried 357 individual men and women from 16 sovereign nations. More than two-thirds of that number launched and landed on the Shuttle at least twice, with a handful doing so as many as six and even seven times. All told, Discovery flew 39 times, Atlantis 33 times, Columbia 28 times, Endeavour 25 times and Challenger ten times. Across that bundle of years, the Shuttle attained the loftiest of heights and achieved the most unimaginable of dreams: launching and retrieving satellites, performing cutting-edge research across multiple scientific disciplines, revealing the home planet in unprecedented detail and building and restocking the International Space Station (ISS). But it did so at the cost of two appalling human tragedies and many other brushes with misfortune and near-disaster. Right from the start, in fact, the Shuttle was a direct consequence of political and military compromise.

Indeed, Richard Nixon harbored no innate love of space. He entered office as the 37th U.S. president in January 1969 with a full plate of political priorities upon which America's space aspirations held comparatively little sway. Ending an unpopular war in Vietnam and solving problems of civil unrest, student protests and racial division at home were in no shape or form dependent upon a multi-billion-dollar space program, which Nixon felt contributed little to the average man or woman in the street. At its genesis, the stated intent of Project Apollo – the national drive to land a man on the Moon – was purely to beat the Soviet Union. Nixon's predecessors in the White House, John Kennedy and Lyndon Johnson, had pushed through this aggressive goal to demonstrate technological and ideological might over a Cold War foe. And in July 1969, when Neil Armstrong and Buzz Aldrin walked on the Moon's Sea of Tranquility, Nixon had little interest in further space spectaculars.

Fig. 1.2 The sheer size of the crawler is visible as it withdraws in June 2011, after depositing STS-135, the last Space Shuttle, on the launch pad.

But he did acquiesce that America needed a future in space. In February 1969, the Space Task Group (STG) convened within the remit of the National Aeronautics and Space Council (NASC). Chaired by U.S. vice president Spiro Agnew, its mandate was to chart the United States' space-flying course after Apollo. The group proposed four options to the White House: an advanced base on the Moon, a manned voyage to Mars, an Earth-circling space station or a reusable winged 'shuttle' which could visit space more reliably, frequently and cheaply than ever before. Only the latter piqued Nixon's interest. A machine capable of launching and landing again and again, like an airliner, and with similar levels of frequency and low cost, might give it the chance to compete with (and perhaps replace) the United States' fleet of eye-wateringly-expensive disposable rockets. The Space Shuttle was glowingly endorsed by the American Institute of Aeronautics and

Astronautics (AIAA) and the President's Science Advisory Committee (PSAC), which pointed out that its "early goal of replacing all existing launch vehicles" not only promised to deploy and recover satellites and build a space station, but also achieve a "radical reduction in unit-cost of space transportation".

Ideas for a reusable winged spacecraft, even at this historical juncture, were far from new. As early as the 1930s, the German aerospace engineer Eugen Sänger conceptualized a rocket-propelled aircraft capable of velocities over ten times the speed of sound and altitudes as high as 70 kilometers. He found that adding wings enhanced the potential of such machines and the 'lift' thereby generated during re-entry allowed them to 'skip' off the atmosphere, adding the capability to circle the globe and land back at their launch site. Within a few years, dreams morphed into reality when Chuck Yeager piloted the rocket-powered Bell X-1 'Glamorous Glennis' aircraft through the sound barrier in level flight in October 1947. At those velocities, aerodynamic heating was not yet a substantial obstacle, but as the U.S. military focused upon the practicalities of sending heavy warheads across intercontinental distances, speed and stability attained new heights of importance. In 1952, the National Advisory Committee for Aeronautics (NACA) – forerunner of today's National Aeronautics and Space Administration (NASA) – began work on an aircraft capable of exceeding Mach 5 (the generally recognized lowermost velocity for 'hypersonic' flight) and set about considering how to achieve enhanced stability and better thermal protection.

If the aircraft re-entered the atmosphere with its nose oriented in the direction of flight, its streamlined shape could induce catastrophic overheating and destructive aerodynamic loads. But re-entering with the nose positioned at a slightly higher angle-of-attack (and with its flat belly presented to the hypersonic airflow) offered a more manageable approach, permitting it to bleed off speed in the rarefied high atmosphere, minimizing overheating and reducing aerodynamic stress. Yet temperatures remained far more extreme than anything previously experienced in aviation. Bell was already working on a chrome-nickel alloy called 'Inconel-X', which, when combined with stainless steel 'shingles', could radiate heat away from the airframe in conjunction with water-cooling at the leading edges of the wings.

In 1954, the Aircraft Panel of the Scientific Advisory Board advocated the field of hypersonic flows to be a principal research and development goal for the next decade, telling U.S. Air Force chief of staff Nathan Twining that "much of the necessary physical knowledge still remains unknown at present" and cautioning that "an ingenious and clever application of existing laws of mechanics is probably not adequate". The board considered the time to be ripe for a new aircraft to surpass Mach 5 and reach altitudes up to 150 kilometers. The result was the single-seat North American X-15, which flew 199 times out of Edwards Air Force Base in California in 1959–1968, reaching the highest speed ever recorded by a crewed, powered aircraft of 7,274 kilometers per hour (almost Mach 5.9) and an altitude of 107.8 kilometers. Two of its missions exceeded 100 kilometers, surpassing the 'Kármán Line' which is accepted by the Fédération Aéronautique Internationale (FAI) as the edge of space. Not only did it push velocity and altitude to new heights, the X-15 also trialed a throttleable rocket engine (the XLR-99), which laid the groundwork for the Shuttle's main engines.

Elsewhere, significant strides were being made in the adjunct field of manned lifting bodies and in 1963–1967 the U.S. Air Force flew a series of small unmanned hypersonic gliders – the Aerothermodynamic/elastic Structural Systems Environment Test (ASSET) and Precision Recovery Including Maneuverable Entry (PRIME) – at speeds of up to 25,000 kilometers per hour and achieved a cross-range capability of over 1,000 kilometers. Neither ASSET or PRIME could land on runways and instead parachuted back to Earth, but they showcased supreme maneuverability and could endure the furnace-like temperatures of atmospheric re-entry at hypersonic velocities. Their findings paved the way for the M2-F1, M2-F2, HL-10 and X-24 lifting bodies, flown out of Edwards in 1963–1975. These lifting bodies proved that human pilots (including future Shuttle commander Dick Scobee) could land wingless vehicles whose very shape provided the same aerodynamic lift as wings.

Even as Agnew and the STG labored on a 'road map' for space exploration, NASA was considering an "integral launch and re-entry vehicle" and initiated a four-phase solicitation process for U.S. industry to analyze, define, design, produce and operate a new spacecraft after Apollo. Study contracts were awarded to Lockheed, General Dynamics/Convair, McDonnell Douglas and North American Rockwell in February 1969 for what became 'Phase A' of the Shuttle. STG board member Robert Seamans (a former NASA deputy administrator and since January 1969 the secretary of the Air Force) noted that this attracted "considerable military interest".

It was an interest which grew (for good or ill) to define the size, shape and capabilities of the new vehicle. Concurrently, NASA formed a Space Station Task Group (SSTG) in May 1969, led by the agency's associate administrator for spaceflight George Mueller, which raised the Shuttle's payload-to-orbit capability from 11,300 kilograms to 22,600 kilograms to suit growing calls for it to be a 'truck' for a future space station and a satellite launcher. Its 'payload bay' was set at 6.7 meters in length and discussions with the Department of Defense led to an August 1969 decision that it would not use expendable boosters, but would instead be a fully reusable, two-stage system. Although 'partial' reusability was considered an appropriate means of minimizing development costs for a space truck, it was not anticipated to work as well if the Shuttle were to take on a broader role with a correspondingly higher flight rate. And whilst full reusability would increase development costs, like an airliner it promised lower operational running costs in the longer term.

Fig. 1.3 The eventual Shuttle system adopted a ‘parallel-burn’ architecture, with the three main engines (seen here in the process of ignition on STS-51) and twin Solid Rocket Boosters (SRBs) both started and verified as healthy whilst on the launch pad.

This multi-purpose role for the Shuttle, as the SSTG told the STG in June 1969, now encompassed several mission types. As well as supporting a future space station, it could also deploy, retrieve, refuel and repair satellites and perform research. NASA recognized that building a vehicle flexible enough for these applications (whilst remaining sufficiently economical to fly) put serious demands on a fully reusable system. Potential 'trades' included piloted flyback boosters, off-the-shelf engines, a vertical rather than horizontal takeoff profile and igniting the engines 'sequentially' during ascent, rather than in 'parallel' on the ground. Very soon, however, the Air Force weighed in with its own demands for a cross-range capability of 2,780 kilometers, enabling the Shuttle to rapidly return to secure military airfields. "The military was interested in a great cross-range," said Caldwell Johnson, chief of NASA's spacecraft design division at the time, "so they could land where they wanted to in one orbit at any given time and get back." It also wanted a cargo capacity of 29,500 kilograms and payload bay length of 18.2 meters to accommodate its large reconnaissance/intelligence satellites. This was significantly greater than the 6,800-kilogram cargo capacity that NASA desired.

"What the Air Force had in mind for the Shuttle and what NASA had in mind for the Shuttle were two different animals," said former North American Rockwell chief program engineer Alan Kehlet. "One was an elephant and the other one was a gigantic elephant. The Air Force wanted a big payload bay. NASA wanted a small vehicle to refuel the space station and the two of them can't meet. You had these conflicting requirements which determined the size of the vehicle and the booster."

But the Shuttle was in for a rude awakening. In September 1969, Agnew's STG submitted its report to Nixon. It pointed out that the reusable spacecraft offered substantial improvements over NASA's current way of doing business through reduced costs and higher operational flexibility, as well as supporting "a broad spectrum" of missions. The STG offered three long-range plans for America. The first, costing $10 billion per year, envisaged a space station in Earth orbit (serviced by the Shuttle), plus a lunar-orbiting complex and manned voyage to Mars. A second, at $8 billion per year, deleted the lunar complex. And a third at $5 billion per year kept the space station and the Shuttle.

Nixon rejected all three.

WINNING THE PRESIDENT'S EAR

NASA now sat in the unenviable position of having to build political support to get the Shuttle approved. In October 1969, the Phase A industrial teams submitted their orbiter/booster concepts. North American Rockwell (which ultimately won the contract to build the Shuttle) proposed a straight-winged orbiter, 61.5 meters long with a 44.5-meter wingspan, mounted slightly forward of the booster. In keeping with Air Force requirements, its payload bay was 18.2 meters long and 4.5 meters wide but could still only lift 6,800 kilograms. Powered by a pair of boost engines and four turbojet engines, it carried two pilots and up to ten passengers. The booster was 85.3 meters long with a 73.4-meter wingspan. The orbiter/booster would take off vertically and execute a 90-degree roll at high altitude, before parting company at 70 kilometers. The orbiter would then propel itself firstly into a 185-kilometer ‘parking’ orbit and then a 500-kilometer ‘phasing’ orbit. Meanwhile, the booster would land on a runway, as would the orbiter at the end of its mission. North American Rockwell expected to build six vehicles and fly 50 missions per year.

In May 1970, the four companies were winnowed down to two, with North American Rockwell and McDonnell Douglas selected for definition and preliminary design studies in ‘Phase B’. By this stage, the Shuttle’s maiden voyage was scheduled for 1977 with an expectation that two orbiters would be built. The first was a straight-winged vehicle with a low cross-range of 370 kilometers, the other a delta-winged vehicle with a high cross-range of 2,780 kilometers. Inclusion of a delta-wing in the design of the high-cross-range orbiter afforded it better aerodynamic lift over the broad Mach range as it decelerated through hypersonic and subsonic flight regimes. Added to the complexity was the need to use different control modes to manage the vehicle through conditions of minimal atmospheric drag into full aerodynamic flight with the support of rudders and ailerons and from orbital velocities of 28,200 kilometers per hour to land at about 370 kilometers per hour. “You had to transition your control systems as they became functional and transition ‘out’ the ones that were no longer functional,” said NASA aerospace engineer Emery Smith. “The guidance had to make sure you were targeted so you didn’t burn the vehicle up. We had contractors all over the country at that time working on the same problem.”

Under the terms of the design requirements, each orbiter could remain in space for a week at a time and fly 25–75 missions per year, with landing-to-launch turnaround times of only 14 days. But the payload capacity of 6,800 kilograms still fell far short of Air Force requirements. Moreover, the booster – which would lift the orbiter not only to 70 kilometers but also to a speed of 11,200 kilometers per hour at ‘staging’ – would be the biggest, heaviest and fastest aircraft ever made. Twenty-five percent larger than a Boeing 747 and ten times faster, it would weigh 1.4 million kilograms when fully fueled. And although clever design of its cryogenic tanks would permit them to carry some of these weights and aerodynamic loads, there remained an acute risk of stress-related fractures, leaks and a potentially catastrophic build-up of gaseous hydrogen under its skin during re-entry.

However, a multitude of other troubles faced NASA when it became obvious that the agency’s funding outlook through the mid-1970s was effectively flat. The

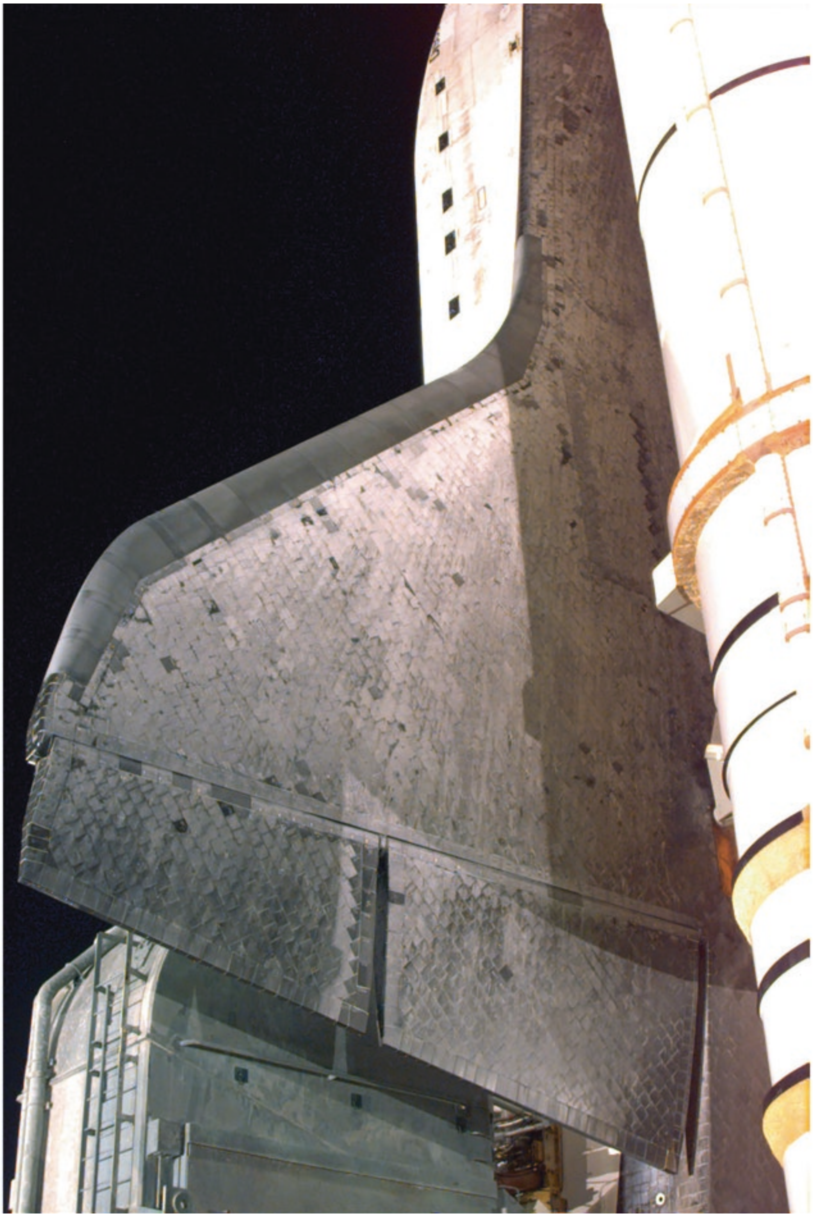

Fig. 1.4 The Shuttle's delta-shaped wing, pictured here as Discovery stood poised to launch STS-96 in May 1999, permitted greater aerodynamic 'lift' over a much broader Mach-range during the passage from the hypersonic through subsonic flight regimes.

picture for Fiscal Year 1971 was barely $3.2 billion and the Office and Management and Budget (OMB) informed NASA that this was unlikely to change for five years. The result was that there would be sufficient funding to build a reusable orbiter, but not a reusable booster. Coupled with internal analyses that showed a fully reusable Shuttle was simply not competitive against expendable rockets, NASA's emphasis shifted once again to a partially reusable design. In June 1971, an earlier idea of the External Tank now re-entered consideration. This called for the liquid oxygen and hydrogen propellants for the Space Shuttle Main Engines (SSMEs) to be shifted outside the body of the orbiter and into a disposable piece of hardware.

Despite the estimated $740,000 cost of building a new tank for each mission, the design eliminated the need to refurbish the booster's thermal protection system and allowed the orbiter to be smaller and lighter, with a substantial reduction in its development cost. North American Rockwell's orbiter correspondingly shrank from 61.5 meters in Phase A to 58.5 meters in Phase B and eventually came in at 37.2 meters. Since the ET would not be reused, its own need for thermal protection was minimal. And the overall cost of producing tank after tank for mission after mission would gradually decline as flight rates increased and manufacturing efficiencies matured. The number of SSMEs on the Shuttle itself increased from two to three for added margins of safety. This reduced the risk of an outright 50-percent power loss in the event of a single engine failure. Furthermore, because the SSMEs could be throttled up in an emergency, three engines afforded greater flexibility in abort situations. NASA now began to consider a 'phased' approach, whereby the reusable orbiter would initially be tested alongside an interim expendable booster, with and expectation that "full-scale hardware development of a reusable booster" would commence later.

"The preferred configuration, which is emerging from the studies is a two-stage, delta-wing reusable system in which the orbiter has external propellant tanks that can be jettisoned," NASA administrator James Fletcher explained in June 1971. "Although our studies to date have mostly been based on a 'concurrent approach', in which development and testing of both the orbiter and the booster stages would proceed at the same time, we have been studying in parallel the idea of sequencing the development, test and verification of critical new technology features of the system. We now believe that a 'phased approach' is feasible and may offer significant advantages."

In July, four industry teams – North American Rockwell, McDonnell Douglas, Grumman Aerospace and Lockheed, together with Martin Marietta, General Dynamics and Boeing as major subcontractors – were selected to examine this phased approach. The boosters under consideration included the S-IC first stage of the Saturn V, an 'outgrowth' of the Titan III rocket, a single solid-fueled motor with a diameter of 6.6 meters or a cluster of solids, each with a diameter of 3–4 meters. Liquid-fueled boosters were flexible and 'throttleable' during flight, whereas solids delivered a harsher impulse and could not be turned off once ignited but were simpler to design and less risky to develop. Contracts were later extended to April 1972 as emphasis gravitated towards building the entire Shuttle in parallel. And hopes for a fully-reusable, two-stage vehicle vanished.

As the development process moved into 'Phase B Prime' in October 1971, the decision of exactly what type of booster to use remained an open question. So too did the issue of whether the Shuttle would adopt a 'sequential-staging burn' (in which the booster would ignite on the ground and the orbiter's engines would ignite in flight) or a 'parallel-burn' (with ignition of all engines on the ground). Advantages of the latter allowed the SSMEs to be verified as 'startable' and healthy before the stack went airborne. As a result, the Thrust Assisted Orbiter Shuttle (TAOS) concept had gained broad acceptance by the end of 1971. Its orbiter/ET combination would function in parallel from liftoff through to insertion into orbit, with the boosters – whether reusable or otherwise – providing added thrust for the first two minutes of ascent, prior to being jettisoned. The parallel-burn TAOS architecture was priced at approximately $6 billion over six years.

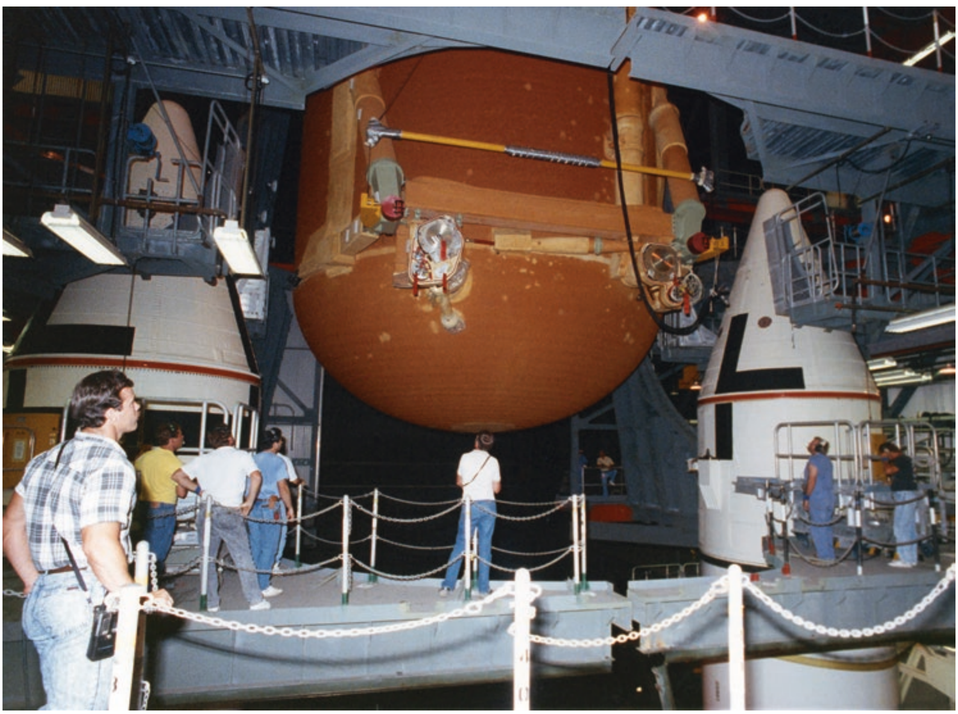

Fig. 1.5 From June 1971, the propellants for the Shuttle's three main engines were shifted outside the orbiter and into the External Tank (ET), the rust-colored base of which can be seen during installation onto the twin Solid Rocket Boosters (SRBs) in the Vehicle Assembly Building (VAB).

Still, it remained a problematic solution. "Before the Space Shuttle, we would have generally built launch vehicles…stacked like telephone poles; they were all in line," said former Space Shuttle program office manager Bob Thompson. "You've got a good thrust vector that goes right up the center of the backbone of the vehicle. You can drop off parts of the vehicle as you 'stage'. People wanted to put the booster rockets behind the orbiter and push it along the axis, but they weren't very practical if you wanted to burn the orbiter engines at liftoff. We very much wanted to turn those engines on before we lifted off to make sure they were working, so we wanted the orbiter down in the 'firepit'…where we could light off those engines." That requirement prompted additional decisions to use the ET itself as part of the structural backbone of the stack, onto which the boosters could be mounted, and played an integral role in creating its peculiar butterfly-and-bullet appearance.

But to gain Nixon's approval, Fletcher had to make concerted overtures to the Department of Defense to commit to using the Shuttle for all its launch needs; an estimated one-third of all future space traffic. This made it imperative that the spacecraft be able to fully accommodate the military requirements. The often-touted payload bay length of 18.2 meters and the capacity to put 29,500 kilograms into low-Earth orbit or 18,150 kilograms into polar orbit were non-negotiable. Moreover, the Air Force wanted to reach polar inclinations from Vandenberg Air Force Base in California to reach and service its classified satellites, then return to Earth after a single 90-minute orbit. On such missions, the landing site would appear to 'move' eastwards as the Earth rotated, necessitating a cross-range capability of up to 2,780 kilometers. This was greater than NASA's desire to land back at its launch site after 24 hours. Still, there were some corollary benefits for NASA in terms of launch aborts, including the ability to land the Shuttle at a downrange site or return home quickly after a single orbit.

As early as September 1970, NASA increased the Shuttle's payload capacity from 6,800 kilograms to 11,340 kilograms, although even this still represented less than half of the Air Force's requirement. The size of the payload bay remained critically important and in mid-1971 the Air Force's assistant secretary for research and development Grant Hansen told NASA's associate administrator for spaceflight Dale Myers that anything less than 18.2 meters meant that nearly half of all military cargoes would not fit the Shuttle. It is unsurprising that the Air Force's lack of total confidence prompted it to declare that it would continue developing its own Titan and Atlas expendable rockets. Its position softened in late 1971 with an agreement to continue purchasing existing designs alongside the Shuttle.

By New Year 1972, analysis fell in favor of two payload bay sizes. NASA refined its requirement to 13.7 meters and 18,150 kilograms, but the Air Force remained unflinching in its insistence for 18.2 meters and 29,500 kilograms. On 5 January, at the Western White House on California's picturesque San Clemente coast, Fletcher and NASA deputy administrator George Low presented Nixon with a model of the TAOS design and the president was visibly fascinated. He liked the fact that it would carry ordinary people into space, but other factors prevailed equally on his mind. Fletcher pledged that starting the Shuttle in 1972 would generate direct employment on the order of 8,800 people by the end of the year and 24,000 by December 1973. And as Project Apollo wound down and the Soviet Union's manned space program appeared on the ascendancy, the prospect of America having no capability to put people into space was unconscionable. Nixon therefore formally instructed NASA to "proceed at once" with building the Shuttle. He cared not a jot about whether the orbiter had a 13.7-meter payload bay or an 18.2-meter one, nor about its cargo-lifting credentials. His principal concern was that the United States retained a capacity to put people into space and that NASA did not exceed the fiscal ceiling of approximately $5 billion mandated by the OMB.

COMPETING PRIORITIES

With Nixon's approval in hand, decisions could at last be made about what form the Shuttle would physically take. Aluminum was selected for its airframe, based upon Air Force preferences and the fact that very few aerospace contractors possessed the requisite expertise with handling titanium. But this choice also made it likely that a complex and expensive patchwork of silica tiles would be needed for its Thermal Protection System (TPS) to protect it from the searing temperatures of hypersonic re-entry. A parallel-burn architecture was selected, in which all engines – those of the orbiter and the booster – would be ignited on the ground before liftoff. And the nature of that booster had also shifted definitively in favor of solids. Boeing's plan to modify its S-IC first stage could not be done cheaply enough to fit within OMB guidelines and, in any case, solids promised significant cost savings over the others. NASA's budgetary outlook raised the stature of solids even further. Their cost savings would allow any 'difference' to be kept in reserve for unexpected development problems. The decision to adopt solids came on 15 March 1972. Fletcher announced that they would have a diameter of 4 meters and could be made faster and $700 million cheaper than liquid-fueled boosters, bringing the Shuttle's overall cost down from $5.5 billion to $5.15 billion. It was noted that the boosters would be fully reusable, detaching from the stack at an altitude of 45.7 kilometers and parachuting to an oceanic splashdown, after which the orbiter would continue into space under the power of its SSMEs. Unsurprisingly, NASA agreed to meet all Air Force requirements. The payload bay would be 18.2 meters long and 4.5 meters wide and capable of lifting 29,500 kilograms into a 185-kilometer 'due-east' orbit.

Fig. 1.6 The sheer enormity of the External Tank (ET) and twin Solid Rocket Boosters (SRBs) is illustrated in this view of the STS-110 crew posing in front of 'their' vehicle in early 2002. The attachment points linking the boosters to the tank are readily apparent.

Two days later, on 17 March, NASA released its request for proposals to North American Rockwell, McDonnell Douglas, Grumman Aerospace and Lockheed, together with their major subcontractors Martin Marietta and Boeing. This 'Phase C/D' contractual element required each orbiter to have a 'useful' lifetime of ten years and a capacity to fly a hundred missions before major refurbishment. The Shuttle had to be able to return to its launch site after a single orbit, although its cross-range capability was (initially) left unspecified. North American Rockwell's revised design for the orbiter was 38 meters long with a wingspan of 24.3 meters. A bubble-like canopy over its flight deck improved the astronauts' visibility of the payload bay and its landing gear retracted into 'wheel wells' in the wings, rather than the fuselage.

On either side of the 'pyramid' of SSMEs were a pair of Orbital Maneuvering System (OMS) engines for use in space and two Abort Solid Rocket Motors (ASRMs) for use in the first 30 seconds of ascent to facilitate a 'meaningful' crew-escape capability in an emergency. Air-breathing engines were housed in the Shuttle's rear payload bay, with an air intake just underneath the vertical stabilizer. Both the air-breathing engines and the ASRMs were subsequently deleted to recover Air Force payload requirements. Additionally, the ASRM elimination saved $300 million and their usefulness, in any case, would only have been effective in the opening few seconds of a mission. The orbiter's wheels, brakes and tires were drawn in design from the B-1A Lancer bomber and a 'drag chute' to assist with deceleration on the runway came from the heritage of the B-52 Stratofortress. (Ironically, the drag chute, too, was deleted, although it would be reintroduced later in the Shuttle era.) North American Rockwell's concept for the ET envisaged a cylindrical structure, 64 meters long and 10 meters in diameter, with a retro-rocket 'pod' at its tip. Two solid-fueled boosters – equipped with fins for greater stability after staging – sat 18.3 meters aft of the ET's nose, their nozzles exhausting behind the trailing edges of the Shuttle's wings.

The proposals for the Shuttle were submitted by May and on 9 August 1972 NASA awarded North American Rockwell a $2.6 billion letter contract to begin developing two Shuttles. One of them (originally intended to be called 'Constitution' but eventually named 'Enterprise') would make a series of Approach and Landing Tests (ALTs) in the low atmosphere, before being modified for space missions, whilst the other ('Columbia') would be built for orbital flights from the outset. Of the four teams, North American Rockwell's proposal gained the highest scores in terms of mission suitability and the most lightweight design. NASA's Source Evaluation Board paid glowing tribute to its guidance, navigation and control architecture, which it regarded as clean and simplistic with minimal interfaces. Additionally, the company had excellent analyses of maintainability and turnaround, as well the lowest costs. Two space-rated orbiters, a full-scale Structural Test Article (STA) and a Main Propulsion Test Article (MPTA) were incorporated into the contract. And the Shuttle would fulfill the final round of Air Force needs with a cross-range capability of 2,035 kilometers. Frustratingly, this broad cross-range went largely unused. "Cussed a lot," remembered Bruce Jackson, former chief of NASA's engineering analysis division. "Their requirement was to have a certain cross-range and they never used it. The military requirement is what dictated the Shuttle configuration, not NASA's requirement. Configuration looks as it does simply because of the long cross-range requirement the Air Force placed on the configuration. That was a big expense."

From the outset, the contract required 50 percent in dollar-value to be subcontracted to other U.S. companies. In November 1972, North American Rockwell issued a solicitation for proposals to design and fabricate the spacecraft's wings, mid-fuselage and vertical stabilizer. Unfortunately, the Shuttle contract award came under immediate and sustained fire, not least because North American Rockwell was headquartered at Downey, in Nixon's home state of California (with its 55-vote monopoly in the Electoral College), and five members of its board had contributed thousands of dollars to his 1972 presidential re-election campaign. Jean Westwood, chair of the Democratic National Committee (DNC), harshly criticized the president's "calculated use of the American taxpayers' dollars for his own pre-election purposes". Moreover, NASA's Dale Myers had spent much of his early career with the company and hand-picked the members of the Source Evaluation Board. Thus began an ugly period of recrimination and not until April 1973 did 'Rockwell International Corporation' – the result of North American Rockwell's merger with Rockwell Manufacturing – sign the definitive Shuttle production contract with NASA.

Nevertheless, there were solid engineering reasons for not selecting the others. Lockheed's craft, for example, was considered heavy, "unnecessarily complex" (according to Fletcher) and left a minute-long duration in the ascent phase with no provision for an abort. In retrospect, this proved an ironic criticism, given that the eventual Shuttle design imposed two full minutes (during first-stage flight burning the solids) with no viable means of crew escape. McDonnell Douglas' proposal was deemed to be technically deficient and weak, whilst Grumman came second. Its presentation was impressive, identifying fundamental problems and offering good solutions, but struggled with costs and management. "I can't verify what happened in the final selection," said former Grumman president Joe Gavin, "but the gossip has it that Mr. Nixon put it in California and that's all I should say about it." Even North American Rockwell had several shortfalls, including a difficult-to-build crew cabin. One intriguing footnote is that its approach to hiring minorities garnered it something of an edge. By 1972, the company had more Black, Hispanic and Asian workers than the others. High scores and low costs, therefore, were the principal rationale behind the decision to pick North American Rockwell to build the Shuttle. In fact, when George Low asked the unsuccessful bidders to comment on the overall fairness of the contract award, all three considered it to have been one of the best and fairest competitions that they had participated in.