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The Path to the Space Shuttle: The Evolution of Lifting Reentry Technology

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AIR FORCE FLIGHT TEST CENTER
EDWARDS AFB, CA

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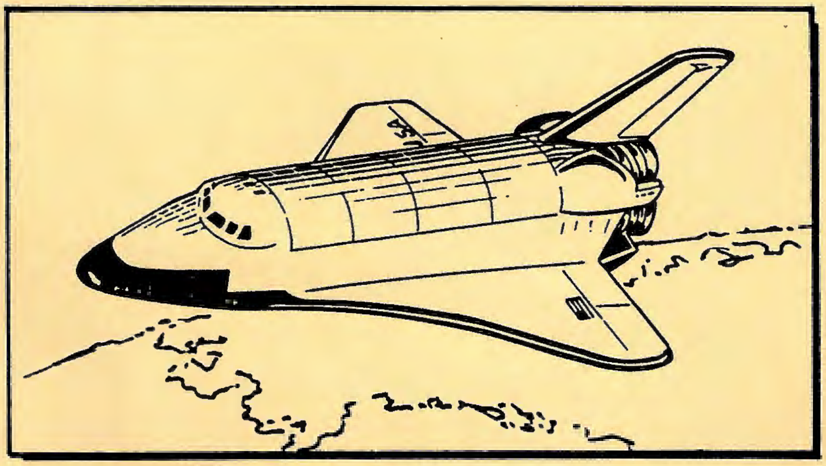
THE PATH TO THE SPACE SHUTTLE



The Evolution of Lifting Reentry Technology

by

DR. RICHARD P. HALLION

AIR FORCE FLIGHT TEST CENTER
HISTORY OFFICE

THE PATH TO THE SPACE SHUTTLE: THE EVOLUTION OF LIFTING REENTRY TECHNOLOGY

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An AFFTC Historical Monograph

History Office

Air Force Flight Test Center

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FOREWORD

Few concepts in the two hundred year history of aerospace development have held greater fascination than that of flying into space and returning to earth following a lifting reentry through the atmosphere: and few concepts have faced so profound a series of technical challenges. Long before the developers of the present-day Space Shuttle first set drafting pens to paper, the concept of lifting reentry had already sparked controversy and generated a number of occasionally contradictory proposals for actual spacecraft. The evolutionary path to the first winged reentry spacecraft is marked by numerous false starts, roads not taken, innovative decision-making, and carefully thought-out analysis of just what such spacecraft should be expected to do.

It is hoped that this historical monograph will improve understanding of how and why Shuttle came to be, and that it will serve to promote further research on the evolution of manned spaceflight in the twentieth century and the continuing relationship between government and industry in fostering aerospace development.

Comments are welcomed, and should be addressed to the AFFTC History Office, Stop 203, Edwards AFB, CA 93523.

Richard P. Hallion

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Introduction

When the Space Shuttle *Columbia* thundered into orbit in April 1981, it fulfilled a dream of a half-century: The development of a reusable manned spacecraft that could land like a conventional airplane. That this elusive goal proved within grasp stemmed from the efforts of an international community of engineers and scientists who worked to make it reality, for the technology base that Shuttle drew upon was both multinational and interdisciplinary in scope. The Shuttle represented the confluence of several broad technical streams, ranging from rocket aircraft, lifting body, and blunt-body spacecraft research through hypersonic aerodynamics, the development of large solid and liquid-fuel rocket engines, and, finally, experience acquired in previous manned spacecraft programs. Technology, however, does not proceed in isolated fashion, separated from the surrounding social, cultural, and economic environment, and the Shuttle offered no exception to this. The planned sophistication and capabilities originally expected of the Shuttle reflected the nature of contemporary 20th century technology, with its buoyant self-confident optimism. However, the existing political and economic climate forced planners to redefine its mission goals which, in turn, influenced its configuration and performance capabilities.

Origins to 1945

The origins of the Space Shuttle date to the beginning of the twentieth century, though earlier impractical suggestions for reaction-powered aircraft had been advanced by such nineteenth century space futurists as Charles Golightly, Werner von Siemens, and Hermann Ganswindt. In 1903, Konstantin Tsiolkovskiy, a Russian school teacher, published an article forecasting the eventual development of rocket-propelled space vehicle. Slightly later, Robert H. Goddard, the father of the liquid-fuel rocket, independently reached similar conclusions, as did Hermann Oberth, about the time of the First World War. These three men, generally considered (in the words of rocketry pioneer and historian G. Edward Pendray) "the three great progenitors of the modern space age," were followed by a host of individuals who focused on specific problems and technical questions. One of these early spaceflight advocates, German rocket enthusiast Max Valier, believed that the manned spaceship would evolve from the all-metal airplane. For experience, Valier suggested that, at first, rockets be added to conventional airplanes such as the Junkers G-23 transport. Later, designers could add more rockets and reduce the craft's wingspan. Finally, an entirely new design would be undertaken, one with six rocket engines (three in each short-span wing) and a pressurized cabin. Capable of high-speed flight into the stratosphere, this latter craft could lead to intercontinental rocket-propelled airliners. Beyond this, Valier rejected winged configurations in favor of the ballistic rocket. In conjunction with Fritz von Opel and Alexander Lippisch, Valier conducted actual rocket-propelled glider experiments in 1928-1929, but his research ended with his death in a laboratory accident in 1930, when an experimental rocket engine exploded on a test stand, and shrapnel severed his aorta.[1]

In 1925, two years after Oberth published his classic treatise Die Rakete zu den Planetenraumen (The Rocket into Planetary Space), and a year after Valier first gained attention with his book Der Vorstoss in den Weltenraum (The Advance Into Space), Walter Hohmann, a German civil engineer, published Die Erreichbarkeit der Himmelskörper (The Attainability of Celestial Bodies). Whereas previous writers had considered the problem of spaceflight in general, Hohmann exained one aspect in particular: the derivation of optimum transfer trajectories for flights from the earth to other planets. (The term "Hohmann Transfer" is now generally accepted world-wide). Hohmann also examined the problem of returning to earth, recognizing the value of using deceleration devices, and considering the related problem of aerodynamic heating. He theoretically examined the air drag forces acting on a reentering spacecraft at altitudes of 75 to 100 km. Though not per se concerned with the technology of reentry but rather with its mechanics, Hohmann nevertheless thought that returning spacecraft should use parachute-like brakes or perhaps variable-incidence wings. His research predated later ballistic and lifting reentry studies, but, sadly, he himself failed to see the fruition of his work, for his health deteriorated rapidly from overwork during the Second World War, and he died in 1945 at the age of 64.[2]

The work of Oberth, Valier, and Hohmann inspired Eugen Sänger, a young Viennese engineer, to undertake his own studies of rocketry and spaceflight, and he became the first major figure to advocate a Space Shuttle-type vehicle as it is now envisioned. Sänger conceived of such a spacecraft while a doctoral candidate at the Technische Hochschule of Vienna in 1929. He proposed examining the possibility of developing a winged spacecraft that would boost into earth orbit and rendezvous with a space station, followed by reentry and a glider-like descent to landing. His instructors suggested a more traditional doctoral thesis instead, and Sänger received his doctorate for studying the structure of multi-spar wings. He did not forget his conception, however, and pursued it vigorously; indeed, it became an obsession with him, and he lyrically dubbed the concept the "Silbervogel" (Silver Bird). He unveiled his concept in 1933, advocating the design of a winged aircraft propelled by a liquid-fuel rocket engine burning a mixture of petroleum and liquid oxygen, and capable of reaching Mach 10 flight speeds at altitudes in excess of 100 miles. Sänger elaborated upon this concept in his book Raketenflugtechnik, one of the major early texts of astronautical engineering, which he published privately that same year at great personal expense. Though he was deliberately vague about the geometric configuration of the vehicle, believing that configuration conceptualizations were beyond the scope of the book, he did select a general shape having (in his own words) a "spindle-shaped" fuselage, straight wings of low aspect ratio having sharp leading edges, a wedge airfoil section, and moderate leading edge sweepback, with a rocket engine buried in the tail section of the vehicle. He considered this design quite conventional, but by the standards of the early 1930's, it was, in fact, a radical shape more typical of the configurations that marched across drafting tables in the late 1940's and 1950's. The next year, 1934, he again elaborated upon the design of such an aerospace aircraft. Assuming a lift-to-drag ratio of 5, Sänger predicted that the craft could attain a flight speed of approximately Mach 13 at the moment of fuel exhaustion, followed by a deceleration to steady supersonic cruise conditions of approximately Mach 3.3 at an altitude of around thirty miles, giving a total flight length of over 3,100 miles. Sänger next discussed less ambitious, but no less radical, concepts for single-seat rocket-propelled interceptors, and bombers.[3]

Sänger devoted the next decade to working on rocket propulsion, developing regeneratively cooled rocket engines. His major goal remained hypersonic boost-glide aircraft. In 1937, he began a collaborative research effort with his future wife, mathematician Irene Bredt. By late 1938, Sänger-Bredt had conceptualized an aircraft having a half-ogive fuselage shape, giving the vehicle the appearance of a laundry iron--which is what his research assistants nicknamed it. It retained the wedge-profile thin wings, but with a greatly reduced aspect ratio; it had endplate vertical fins on its horizontal stabilizer instead of the large single vertical fin of earlier studies. Sänger-Bredt estimated that this craft would have a supersonic L/D of 6.4, and subsonic testing revealed a L/D of 7.75. They proposed launching this craft from a Mach 1.5 rocket sled. The "Silver Bird" would have had a 100 ton thrust rocket engine for its main propulsion, operating at a chamber pressure of 100 atmospheres (exceeded in actual subsequent development only by the present-day Shuttle's own engines). Sänger-Bredt dubbed this craft the "Rocket Spaceplane," and foresaw it performing orbital missions with a one-ton payload (based on 2½ orbits) or a four-ton payload (based on a single orbit), or delivery of up to a 8 ton payload at an antipodal point halfway around the world from its launch site.

After the craft was boosted to lift-off velocity from the rocket-propelled sled, it would coast upwards and the pilot would then ignite its large rocket engine, boosting into space and attaining a peak velocity of approximately Mach 24. The vehicle would then reenter in a semiballistic manner, "skipping" off the denser atmosphere like a stone skipping off water, in a series of shallower and smaller skips, until, finally, it would enter a terminal supersonic glide. (Subsequent analysis has indicated that this planned flight path is undesirable from an aerothermodynamic loads standpoint, as each skip induces high thermal loads and prolongs the heat-soaking of the structure. A more acceptable approach is a steady descent and deceleration followed by a hypersonic/supersonic glide, the approach currently taken by the Space Shuttle.)

Obviously, following Nazi Germany's decision to go to war in September 1939, the Rocket Spaceplane could not be pursued as extensively as in the pre-war years, for Nazi Germany now required immediate technical developments of benefit to its war machine. Sänger and Bredt shifted the project's emphasis from space transportation to a global rocket bomber (Rabo, for Raketenbomber) in a bid to receive continued official support. In December 1941, Sänger-Bredt submitted a draft report on the Rabo for approval by the Reichsluftministerium (RLM: the German Air Ministry), but RLM officials were understandably cool--if not annoyed--to such a distant scheme at a time when Nazi Germany for fighting for its existence in a war of its own making. A few months later, the Luftfahrtforschungsanstalt Hermann Göring (LFA: Hermann Göring Aviation Research Institute) rejected the report for publication, and Sänger, embittered and angry, joined the staff of the Deutsche Forschungsanstalt für Segelflug (the German Institute for Soaring Flight: DFS), at Ainring, in Bavaria, where he worked on ramjet propulsion schemes for high-speed airplanes. The DFS did publish an abbreviated and classified report on the Rabo project in 1944, and, after the war, copies of this report reached the highest councils of Allied technical intelligence teams, as will be seen.[4]

The Rabo thus remained an intriguing paper study, but another Nazi boost-glide effort actually reached the hardware stage. At about the time that Sänger-Bredt were vainly trying to win official approval for the Rabo, members of Wernher von Braun's Peenemünde rocket development team were busily studying methods of increasing the range of ballistic missiles by adding sweptwings enabling them to glide to their targets. Under the direction of Ludwig Roth, team members developed a winged derivative of the V-2 (A-4) ballistic missile. At an early stage in the development of the A-4, the Peenemünde team had embarked on a more ambitious venture, design of a long-range missile system capable of hurling a one ton high-explosive warhead 3,000 miles. Using a large booster designated the A-10 as the first-stage booster, planners envisioned a winged second stage, designated the A-9 that would fire into a ballistic trajectory and then transition to a terminal glide before impacting in the target area at about Mach 3.5 to 4.0. Because the Peenemünde facility could not support both the A-4 (V-2) effort and the ambitious A-9/A-10, work on the latter project continued at a slow pace; even study efforts on sweptwing variants of the A-4 itself were terminated in 1943. In 1944, however, in the face of intensive Allied air attacks on proposed and actual V-2 launch sites, worked resumed on a winged A-4 derivative, for a winged A-4, having increased range, would obviate the necessity of locating V-2 firing batteries within easy strike range of Allied aircraft. Batteries instead could be located closer to the Nazi Reich's heartland. The winged A-4, designated the A-4b, had a range of 270 miles compared to 150 miles for the purely ballistic V-2 then just entering service. Roth's team built two A-4b test articles and launched the first of these on January 8, 1945, but its control system failed just after launch. A second, launched on January 24, was more successful, transitioning to a Mach 4 supersonic glide from a ballistic reentry, but during the glide, a wing experienced structural failure, and the A-4b broke up. This was, incidentally, the first time that a winged vehicle had exceeded the speed of sound; the A-4b remained the fastest winged vehicle flown until the introduction of the X-15 research airplane. The rapid disintegration of the Eastern Front brought any further plans to test A-4b missiles to a halt.[5]

There was always a small coterie of space enthusiasts at Peenemünde who had to keep their more visionary projects out of sight of the more pragmatic ordnance experts of the Wehrmacht. One of these was for a piloted version of the A-9, with a pressurized cockpit and a retractable tricycle landing gear, to be launched vertically and then landed powerless on a conventional runway, much as the present-day Shuttle. It could fly 400 miles at an average speed of Mach 2+. Beyond the A-9/A-10, the von Braun team had even conceptualized an advanced A-11, a three-stage vehicle whose final stage--a development of the A-9 boost-glider--would enter earth orbit. An "A-12," consisting of a large first-stage booster, an A-11 second stage, and a winged A-10, was forecast for delivering up to thirty tons into earth orbit, permitting the construction of a space station. These futuristic schemes collapsed amid the rubble of the Third Reich, before rising, Phoenix-like, in the postwar world.

From A-4b to Dyna-Soar

The immediate postwar challenge facing aeronautics was that of manned supersonic flight. Despite ballistic and shell data, real doubts existed whether a manned aircraft could successfully traverse the transonic tangles and traps and attain sustained supersonic flight. Could, for example, the problems of high-drag rise, trim changes, and changes in control effectiveness be overcome? These critical questions remained unanswered at war's end. Indeed, a considerable body of evidence, accumulated from the wreckage of conventional aircraft lost in high-speed flight from "compressibility" effects, seemed to indicate that such problems could not be overcome, at least in the foreseeable future. The lack of reliable ground research methods (the slotted throat wind tunnel being a thing of the future), and the inadequacy of existing free-flight techniques using falling bodies, rocket-propelled test models, and wing-flow research methods, caused the United States to embark on an ambitious program of manned transonic and supersonic flight research using specially designed and instrumented research airplanes. This marked the birth of the so-called "X-series" of postwar research aircraft. As seen from a late 1950's perspective, there were three discernable phases to the X-series program. The first, dubbed "Round One" by engineers of the National Advisory Committee for Aeronautics (NACA--the predecessor to NASA), consisted of the Bell XS-1 (later X-1) series, the Bell X-2, the Douglas X-3, the Northrop X-4, the Bell X-5, the Douglas D-558-1 Skystreak and D-558-2 Skyrocket, and the Convair XF-92A. Three of these, the Bell X-1 series, the Bell X-2, and the Douglas D-558-2 Skyrocket, were supersonic rocket-propelled aerodynamic research aircraft air-launched for maximum performance from modified B-29 and B-50 carrier aircraft. The rest served to evaluate specific aerodynamic configurations, such as swept, tailless, and delta wing planforms. The second X-series phase was "Round Two," the North American X-15 project, directly inspired by the studies of Sänger and Bredt. The third phase, sequentially known as "Round Three," was the abortive Boeing X-20A Dyna-Soar project, inspired jointly by the early work of Sänger and Bredt, as well as later indigenous American studies.[6]

The "Round One" research aircraft accomplished the world's first manned Mach 1, 2, and 3 flights. The age of supersonic flight became a reality on October 14, 1947, when the first Bell XS-1, piloted by Capt. Charles E. Yeager, USAF, exceeded Mach 1, attaining Mach 1.06 (700 mph) at approximately 43,000 feet. On November 20, 1953, NACA pilot A. Scott Crossfield made the first manned flight at Mach 2, twice the speed of sound, while flying the second D-558-2 Skyrocket. Nearly three years later, on September 27, 1956, Capt. Milburn G. Apt reached Mach 3 while flying the first Bell X-2, unfortunately losing his life when the aircraft went out of control. Though these early X-series aircraft were, per se, benefiting the design of conventional aircraft that followed, they nevertheless contributed to a general base of knowledge that supported studies of more exotic hypersonic boost-glide vehicles. The X-2, for example, was the first aircraft that required a structure designed to withstand the problems of aerodynamic heating. During flight testing, it pointed to the need for reaction controls in order to maintain a desired attitude at high altitudes and low dynamic pressures, and reaction controls subsequently underwent evaluation on an advanced X-1, the X-1B. These early X-series aircraft generally derived data that led to greater understanding of how wind tunnel information should be interpreted, aerodynamic heating at supersonic speeds, transonic and supersonic lift and drag, transonic and supersonic flight loads, transonic and supersonic stability and control (including understanding of such phenomena as exhaust jet impingement effects on stability, inertial coupling, directional instability), reaction controls, and requirements for flight crew physiological protection at high altitudes. Engineers also gained confidence operating with complex reusable man-rated rocket propulsion systems.[7]

The Sänger-Bredt report fell into Allied hands with the collapse of Germany in May 1945. It immediately excited great interest, and was soon translated in French, Russian, and English. It so impressed Josef Stalin that he sent a team to Western Europe to locate the Sängers (who had gone to France) and persuade them (by any means) to work in Russia (the plan failed). Walter Dornberger, who was aware of Sänger's work, subsequently joined the staff of the Bell Aircraft Corporation, where he championed development of a series of Rabo-like proposals, one of which (like its German counterpart) was known as ROBO--for Rocket bomber. The most important contribution of Sänger's work was its impact upon the NACA. It focused attention on the potential of winged hypersonic cruise aircraft, paving the way for the X-15, and inspired a number of studies of Sänger-Bredt type hypersonic aircraft.[8] In 1949, Hsue-shen Tsien of the California Institute of Technology proposed a Mach 12 "transcontinental rocket liner" powered by liquid oxygen and liquid hydrogen. He optimistically concluded that "the requirements of a transcontinental rocket liner [are] not at all beyond the grasp of present-day technology."[9]

The first call for an X-15-class research vehicle came from Robert J. Woods, a colleague of Walter Dornberger, during a meeting of the prestigious NACA Committee on Aerodynamics on October 4, 1951. He reiterated his support for such a vehicle during subsequent meetings and, as a result, the NACA committee passed a motion on June 24, 1952 that charged the agency to expand its research aircraft program to include studying the problems of manned and unmanned flight at altitudes between 12 and 50 miles, and velocities of Mach 4 to Mach 10, as well as devoting "a modest effort" to study exoatmospheric flight from Mach 10 to escape velocity. The major NACA field centers exchanged various paper plane proposals. NACA engineers L. Robert Carman and Hubert Drake of the High-Speed Flight Station drew up configurations for Mach 3+ launch aircraft carrying small hypersonic research aircraft including, in August 1953, a five-phase proposal culminating in the design of an orbital air-launched hypersonic boost-glide winged vehicle. The NACA shelved this bold proposal as too futuristic, which it was; its advocacy of a "two-stage to orbit" research vehicle was one of the earliest of the "piggyback" concepts predating the current Space Shuttle. The NACA, like other federal and private organizations, favored a more modest approach. In October 1953, the Air Force's Scientific Advisory Board recommended development of a Mach 5-7 research aircraft, and at the same time, the Office of Naval Research had funded the Douglas Aircraft Corporation to study the feasibility of a Mach 7+ rocket-propelled research airplane, informally referred to as the D-558-3.[10]

During 1954, the NACA, in partnership with the Air Force and Navy, further explored the hypersonic aircraft concept. The agency's Langley laboratory (later NASA's Langley Research Center) had formed a hypersonic study team comprised of chairman John V. Becker, Maxime Faget, Thomas Toll, N. F. Dow, and J. B. Whitten, and this group subsequently evolved a baseline design that closely resembled the ultimate X-15 configuration. Their conception incorporated Inconel alloy heat-sink construction, had a cruciform tail configuration, a wedge vertical fin for increased directional stability, and similar weights and specifications as the final aircraft. In December 1954, the NACA, Air Force, and Navy agreed to undertake joint development of the proposed hypersonic research aircraft, and in January 1955 it received the designation X-15. That same month, the Air Force (which administered the design and construction phases of the project) held the first briefings for potential contractors. This culminated in a competition between North American, Bell, Douglas, and Republic, which North American won on September 30, 1955. The Bell entry, which featured a novel form of "double-wall" construction, reflected the firm's obsession with Sänger-like boost-gliders (indeed, in April 1952, Bell's Dornberger had journeyed to France in a vain attempt to convince Sänger and his wife to join the company), and had no real hope of winning. The subsequent technical development of the North American X-15 went smoothly, with the exception of its rocket powerplant, which generated great concern before it, too, reached fruition.[11]

The X-15, "Round Two" in the parlance of the NACA, had many features that separated it from the previous rocket research aircraft and placed it at an intermediate level between the purely supersonic aircraft (such as the X-1) and the purely winged reentry vehicles (like the proposed "Round Three" Dyna-Soar and the eventual Space Shuttle). For example, it incorporated a reaction control system of hydrogen peroxide rocket thrusters for keeping the aircraft under control at high altitudes; the pilot wore a full-pressure pilot protection suit (the Clark MC-2) having provisions for physiological monitoring. It was the first flight vehicle to blend the application of hypersonic aerodynamic theory to an actual aircraft. It incorporated high temperature seals and lubricants, and had a "Q-ball" flow direction sensor capable of operating with stagnation air temperatures of 3,500 deg. F. The pilot relied on inertial flight data systems developed especially for operation under space-like conditions. The X-15's Inconel structure was the first reusable super-alloy structure capable of withstanding the temperatures and thermal gradients of hypersonic reentry. Subsequently, during its flight program, the X-15 spawned development and application of a refurbishable ablative heat-protection system (the Martin MA-25S).[12]

The X-15 spanned 22 ft. 4 in., and had a length of 50 ft. 9 in. It utilized a Thiokol (Reaction Motors Division) XLR-99 throttleable rocket engine, burning a mixture of anhydrous ammonia and liquid oxygen. (Delays in the development of this engine forced North American to install two XLR-11 engines in the X-15's during 1959, before beginning the research program, for purposes of checking out the aircraft and its systems; the first XLR-99 flight did not come until November 15, 1960). The three X-15 aircraft quickly established a number of speed and altitude marks, which often obscured the less glamorous but occasionally more important work they accomplished in mapping out the frontiers of hypersonic flight. By the end of 1961, the X-15 had achieved its Mach 6 design speed, and had reached altitudes in excess of 200,000 feet. On August 22, 1963, NASA research pilot Joseph Walker reached 354,200 feet in the third X-15 aircraft, still a record for winged vehicles. X-15 testing revealed a number of interesting conditions about hypersonic flight, including the discovery that hypersonic boundary layer flow is turbulent and not laminar, that turbulent heating rates were lower than predicted by theory, that supersonic skin friction was likewise lower than predicted, that local surface irregularities generated hot spots (in one notable case, aerodynamic heating caused buckling of the wing skin behind leading edge heat expansion slots), and that the cruciform tail configuration created a serious adverse roll problem at high angles of attack during atmospheric reentry (NASA cured this by removing the jettisonable lower half of the craft's ventral fin). The flights demonstrated that a pilot could successfully transition from aerodynamic to reaction controls and back again, function in a weightless environment (which became an academic question after Vostok and Mercury), control a rocket-boosted vehicle during atmospheric exit, and use energy management techniques to make a hypersonic/supersonic reentry and glide approach to a precision landing. The X-15 eventually made reentries at angles of attack up to 26 deg. and at flightpath angles as low as -38 degrees at Mach 6 flight speeds.[13]

As with the previous "Round One" rocket research airplanes, the X-15 was airlaunched, being dropped from a modified Boeing B-52 jet bomber. The flights were made over a specially instrumented 485-mile-long 50-mile-wide flight test corridor stretching from Nevada to Edwards Air Force Base in California. Following a landing accident with the second X-15, the Air Force and NASA authorized the manufacturer to modify it as a special testbed for NASA's planned Hypersonic Ramjet Experiment. North American lengthened the aircraft, making numerous modifications to it, and added provisions for two large jettisonable external tanks. Thus equipped, the aircraft, designated the X-15A-2, was capable of Mach 7 flight speeds, if equipped with a proper thermal protection system. NASA finally selected Martin to develop a suitable ablator, and that company derived the MA-25S, an ablator mix consisting of a resin base, a catalyst, and a glass bead powder. Hopes that such ablators could enable designers to build refurbishable spacecraft that could be stripped and recoated after each flight proved ill-founded, however. On October 3, 1967, the X-15A-2 attained Mach 6.72 (over 4,520 mph), while piloted by Air Force Maj. William J. Knight. Unfortunately, the plane landed in extremely worn condition--a dummy ramjet had melted off the craft, in fact--and the ablator would have required massive cleanup efforts prior to reapplication. North American repaired the craft and returned it to NASA, but it never flew again.

The third X-15 made a number of notable high-altitude flights above 50 miles. Unfortunately, this aircraft was lost, together with pilot Michael J. Adams, on November 15, 1967.* The first X-15 completed its last flight, the 199th flight for the type, on October 24, 1968.[14]

Following awarding of the X-15 development contract, North American had considered a so-called "X-15B" orbital spacecraft (even before Sputnik), to be launched by two Navaho boosters and possibly carry a two-astronaut crew. After Sputnik, it went through a cycle of shelving and revival until finally overcome by the ballistic blunt-body spacecraft approach as taken by the McDonnell Mercury vehicle. The X-15 series itself, however, did perform a number of "Shuttle" like missions, for after 1962, the X-15 program switched concentration from hypersonic aerodynamics to using the vehicle as a testbed carrying a wide range of applications and experiments, such as insulation intended for the Saturn booster, and navigation instruments under development for Apollo. By 1964, fully 65 percent of all data returned from the X-15 related to follow-on programs, and this figure continued rising until the conclusion of the program in December 1968. NASA even briefly considered using the X-15 as a launcher for Scout rockets carrying small satellite payloads, the B-52/X-15/Scout becoming, in effect, one large booster, but after examining the idea, NASA rejected it on grounds of safety, cost, and practicality. Fittingly, in December 1968, the Deutsche Gesellschaft für Raketentechnik und Raumfahrt awarded John Becker and the X-15 team with the Eugen Sänger Medal, created

*See Appendix A for a roster of X-15 pilots to honor individuals and groups who have made special contributions to the field of recoverable spacecraft.[15]

Even before the X-15 had completed its maiden flight, devotees of winged reentry were studying a variety of proposals for orbital lifting reentry vehicles, and, indeed, even interplanetary ones. Some of these orbital studies were military ones, and eventually led into the Dyna-Soar program discussed subsequently. Others were civilian. Most were, in light of subsequent work, completely impractical, if visionary. In August 1952, the Executive Committee of the National Advisory Committee for Aeronautics appointed a hypersonic study group under the chairmanship of Clinton Brown. This body reported to NACA Headquarters in June 1953, recommending that the NACA undertake heating studies, and fire rocket-propelled hypersonic models. It optimistically predicted the future development of hypersonic boost-glide intercontinental aircraft. (Most technical studies in the 1950's suffered from an excess of optimism that the very real problems encountered in designing such craft could be quickly overcome). Even more ambitious and idealistic were the fantastic conceptualizations of Wernher von Braun and Walter Dornberger. Their work naturally drew upon the previous Peenemünde A-4b--A-12 studies. In a series of books published in the early 1950's, A-4b--like and similar craft routinely appeared performing a variety of space missions, usually in the exquisite and seductive paintings of Chesley Bonestell. In 1951, space travel buffs had organized a symposium at the Hayden Planetarium. Out of this enthusiastic meeting came a number of optimistic articles printed in Collier's magazine, and later reprinted in a single volume, Across the Space Frontier. In this work, von Braun described a theoretical three-stage launch vehicle capable of placing 36 tons in earth orbit. The third stage was a canard shuttle-like aircraft having five rocket engines fueled with nitric acid and hydrazine, with provisions for a pilot and crew, and having a retractable landing gear. It spanned 156 feet, with a length of 77 feet. Von Braun predicted that reentry heating would turn the craft cherry-red, but that this could be overcome by using steel. He elaborated upon this concept in a 1956 book, The Exploration of Mars. Here, von Braun and rocket enthusiast Willy Ley, conceived constructing a large flying-wing interplanetary spacecraft spanning 450 feet that could coast from earth orbit to Mars, then enter the Martian atmosphere and fly down to a landing. Its nose section was an ascent rocket that would return the crew to Martian orbit preparatory to the return to earth; the rest of the vehicle would be left on the surface of Mars. Von Braun also conceptualized the building of a smaller delta-wing passenger spacecraft that would support earth orbit operations; this craft looked much like an extrapolation of 1950's jet fighters such as the Convair F-102A and Gloster Javelin. Dornberger, meanwhile, had expanded upon his own boost-glide studies. In 1957, in collaboration with Krafft A. Ehricke, Dornberger conceived of a two-stage passenger-carrying Shuttle-like transport. The stages were mounted in piggyback fashion, the ventral stage having five rocket engines and the dorsal (passenger-carrying stage) having three. Each stage had delta wings for boost-glide flight. Dornberger and Ehricke anticipated that such a craft would take off with both stages firing, and 130 seconds after launch the lower stage would separate and glide back to land, piloted by its own crew. The smaller dorsal stage would continue onwards, reaching a peak altitude of 27.5 miles and crossing the United States in 75 minutes. Clearly, by the mid-1950's, then, a number of Sänger-like studies were underway. What remained to be done was for the industry and government to join forces on a suitable development program that could serve as an actual technology demonstrator. The result of all this was the abortive X-20A Dyna-Soar program, the "Round Three" that followed the X-15, and the most ambitious lifting reentry effort prior to the actual Shuttle itself.[16]

Dyna-Soar, Aerospace Plane, and the Lifting Bodies

The roots of Dyna-Soar stemmed from Sänger-Bredt's work, Dornberger's at Bell, and that of a group of NACA engineers and scientists, particularly John Becker, Eugene Love, Alfred Eggers, and H. Julian Allen. (Allen, the father of blunt-body reentry, inspired Eggers and Love on their own research which eventually resulted in the lifting body craft of the 1960's). In 1952, the Bell Aircraft Corporation had proposed their developing a boost-glide piloted bomber-missile dubbed BOMI for the Air Force. With further refinement, BOMI evolved into an intercontinental three-stage "piggyback" reconnaissance bomber similar to later Shuttle "Triamese" configurations. At Air Force suggestion, Bell advanced a two-stage Mach 15 reconnaissance vehicle, System 118P, and both BOMI and 118P influenced Bell's next design effort, a reconnaissance system known as BRASS BELL. Receptive to these studies, the Air Force next funded a number of industry investigations of reconnaissance and strike boost-gliders. In 1956, the Air Force Air Research and Development Command launched a feasibility study of an orbital winged rocket bomber nicknamed ROBO. To support ROBO and the earlier BRASS BELL, the service proposed developing a piloted boost-glide research aircraft known as HYWARDS. Contractors working with the Air Force on these efforts included Bell, Boeing, Convair, Douglas, North American, and Republic. In November 1956, the Air Force asked the NACA to review the service's boost-glide aircraft studies. In response, NACA Director Hugh L. Dryden formed a "Round Three" steering committee which evaluated the various projects and then recommended to the Air Force, in September 1957, that the service sponsor development of a flat-bottom hypersonic delta glider. On October 4, 1957, the Russians launched Sputnik; on October 10, the Air Force consolidated ROBO, BRASS BELL, and HYWARDS into a single three-phase research program called Dyna-Soar, for "dynamic soaring," what Sänger had termed skipping reentry. On October 15, a "Round Three" conference opened at NACA's Ames Aeronautical Laboratory, and conferees eventually endorsed the recommendations of the Dryden steering committee. A minority favored a purely ballistic Allen-type blunt body design having nonlifting characteristics;

this marked the genesis of what eventually evolved into the Mercury spacecraft. Another minority favored development of an Eggers or Love lifting-body spacecraft. (Eventually, as the studies of the 1960's clearly reveal, all three paths, ballistic, winged, and lifting body, would be pursued by government and industry enthusiasts). On December 21, 1957, the headquarters of the Air Force's Air Research and Development Command (ARDC) issued System Development Directive 464L for development of Dyna-Soar's first phase, envisioned as a simple delta-wing single-seat boost-glider technology demonstrator.[17]

Nine contractor teams eventually responded with proposals, and the respondents represented essentially a Who's who of American aviation: Bell, Boeing, Chance Vought, Convair, General Electric, Douglas, Lockheed, McDonnell, Martin, North American, Northrop, Republic, and Western Electric. Of these teams, however, only a Boeing entry and a Martin-Bell team entry proposed a fully orbital vehicle for meeting the development directive; all others envisioned a long-range boost-glider that would eventually evolve into an orbital system. The Air Force directed Boeing and Martin-Bell to proceed with additional detailed studies, and, as a result, Boeing was declared the winner on November 9, 1959. Martin was selected to develop the launch booster, a modified Titan ICBM. Bell, the firm that had inspired the whole program, wound up with nothing but some subcontracts.[18]

Eventually, Dyna-Soar emerged as a radiative-cooled slender delta having a flat Sänger-like bottom, a rounded and tilted nose, and twin endplate vertical fins. The glider utilized a René 41 nickel superalloy primary structure, a columbium alloy heat shield, a graphite and zirconia nose cap, and molybdenum alloy leading edges. Unfortunately, the program suffered from a lack of clear definition of what its goals should be. At the highest levels of the Air Force, and within the prestigious Aerospace Vehicles Panel of the USAF Scientific Advisory Board, disagreements existed over what role Dyna-Soar should play in the steadily growing American manned spacecraft effort. Critics of Dyna-Soar were quick to point out that semi-ballistic or ballistic spacecraft (such as growth versions of the planned Gemini spacecraft) could carry a much larger useful payload into orbit. In June 1962, the Air Force designated Dyna-Soar as the X-20A, primarily to emphasize its research function. Despite this, some proponents still attempted to transform it into an operational military system. It quickly became obvious that Dyna-Soar would be less than fully successful in any none-research role, especially in any role involving orbital supply of a space station. For a while, X-20A faced criticism from partisans within the USAF Space Systems Division (SSD) favoring development of a small piloted lifting body for satellite inspection and space logistics known as SAINT II, but though it weathered this storm while SAINT II itself succumbed, it was clear that Dyna-Soar was losing its appeal. Eventually planned for launch from the large parallel-burn Titan IIIC booster, Dyna-Soar grew appreciably in weight and complexity, raising questions whether or not its metal thermal protection system could withstand the higher heat pulse during reentry generated by the higher weights. Privately, Secretary of Defense Robert S. McNamara's senior advisors concluded that Dyna-Soar's research objectives could be most expeditiously, safely, and economically met by firing small delta-wing reentry models from Thor,Thor-Delta, and Atlas launch vehicles. Dyna-Soar's support weakened rapidly over the fall of 1963, and McNamara cancelled it on December 10, 1963, in favor of proceeding with a "blue-suit" spin-off of the Gemini effort, the planned Air Force Manned Orbiting Laboratory program. (Ironically, MOL itself collapsed subsequently).* At the time of its cancellation, the X-20A was about 2½ years and an estimated $373 million away from its first flight. $410 million had already been expended. The cancellation decision is one that is still hotly debated; in any case, Dyna-Soar greatly accelerated progress in hot structures technology, the aerodynamics of delta reentry shapes, hypersonic design theory, and other information directly applicable to the present Shuttle. It was, therefore, a generally useful exercise despite its termination.[19]

Even as Dyna-Soar tottered on towards cancellation, another Air Force study was underway on an orbital aircraft. But this study differed dramatically from the simple X-20A boost-glider. Dubbed Aerospaceplane, this conceptual project envisioned an aircraft that would takeoff horizontally, like a conventional airplane, accelerate to hypersonic speeds at

*See Appendix A for a roster of X-20A and MOL crewmen high altitudes by using a radical air-breathing propulsion system, and then, by either using liquified air combined with a propulsion fuel, or by using stored rocket propellants, boost into a 300 mile orbit, place a payload in space, and then reenter the atmosphere, and make a powered descent and landing at a conventional airfield. Such a craft would have been huge, and would have posed enormous technical development problems. While most attention focused on trying to design the radical air-recovery propulsion system, structural problems were no less significant. The projected weight of the craft's structure plus heat shielding came to approximately 46% of its landing weight, a small percentage when compared to that of Dyna-Soar, in which 60% of its landing weight was accounted for by structure and the thermal protection system. To achieve such a favorable structural and TPS weight to landing weight ratio would have demanded the highest of engineering standards. Also, debate existed whether Aerospaceplane should be a single or a two-stage craft, and one scheme even called for design of a Mach 6 tanker that would air-refuel the Aerospaceplane orbiter at Mach 6 before it fired into orbit! At an early stage in Aerospaceplane studies, the Air Force had determined that it should have a large payload bay on the order of 10 ft. x 25 ft. x 40 ft., though the Aerospace Vehicles and Propulsion panel of the USAF Scientific Advisory Board later stated that such a specific requirement was "premature," given the tentative state of the project. There was general enthusiasm over the concept, largely because such a reusable launch system seemed to offer great flexibility for a variety of military missions including orbital supply and strike, enhanced safety, and a more economical method of boosting payloads into space than with expendable throwaway boosters. (The goals of reducing payload-to-orbit costs, mission flexibility--though not including orbital strike--and orbital supply were all ones that reappeared subsequently in discussions of the planned Space Shuttle). Essentially the same group of contractors who had been involved in Dyna-Soar's gestation participated in studies of Aerospaceplane, with the exception of Bell; for that pioneering firm, Dyna-Soar had been its last fling at lifting reentry and hypersonic flight. But Aerospaceplane increasingly ran into difficulties, as well. As early as December 1960, the Scientific Advisory Board had warned that it was "gravely concerned that too much emphasis may be placed on the more glamorous aspects of the Aerospaceplane resulting in neglect of what appear to be more conventional problems." In October 1963, Aerospaceplane was at the end of its tether, and the SAB had completely lost faith in the program. SAB damned the program in no uncertain terms:[20]

> The difficulties the Air Force has encountered over the past three years in identifying an Aerospaceplane program have sprung from the facts that the requirement for a fully recoverable space launcher is at present only vaguely established, that today's state of the art is inadequate to support any real hardware development, and the cost of any such undertaking will be extremely large. While these factors dominate the picture, the Air Force must focus on advancing the important technical fields involved and prepare themselves for the time when the projected total payloads into orbit per year will increase to the point where such recoverable launching systems are competitive.

The report also stated that the SAB's Aerospace Vehicles and Propulsion panel[21]

> feels that the so-called Aerospaceplane program has had such an erratic history, has involved so many clearly infeasible factors, and has been subjected to so much ridicule that from now on this name should be dropped. It is also recommended that the Air Force increase the vigilance that no new program achieves such a difficult position.

Aerospaceplane's demise removed the Air Force from the Shuttle logistics field just as Dyna-Soar's cancellation ended the service's immediate interest in piloted lifting reentry. The next stage belonged to the lifting bodies.

Unlike the abortive Dyna-Soar and Aerospaceplane programs, actual hypersonic lifting body shapes were built and flown. In 1951, NACA engineer H. Julian Allen had conceived the blunt-body reentry principle as a means of getting a thermonuclear warhead through the intense heating of atmospheric reentry. He found that a blunt nose shape generated a strong detached shock wave that served to give the warhead excellent thermal protection. In contrast, a sharply pointed nose--the darling shape of science fiction authors--formed an attached shock that quickly melted the reentry body down. Allen's work first appeared on the nuclear warhead of the Atlas missile. A blunt body shape had a very low lift-to-drag ratio, far less than one, and thus had an essentially ballistic flight path. Allen and Alfred Eggers, together with other NACA engineers, were convinced that the lifting body shape could be tailored in such a way to produce an acceptable lift-to-drag ratio of about 1.5, reducing reentry loadings from the approximately

8g experienced by a blunt-body ballistic shape to 1g, and giving a cross-range maneuvering "footprint" in excess of 1,500 miles from the initial point of atmospheric entry. Eggers led a team that derived a series of shapes culminating in the "M2" configuration, a modified half-cone having a rounded nose, a hypersonic lift-to-drag ratio of 1.4, and--after much configuration work--acceptable supersonic, transonic, and subsonic stability. The M2, Ames laboratory's contribution to lifting body research, was complemented by a Langley-inspired design, the HL-10 of Eugene Love, which was first known as the MLRV (for Manned Lifting Reentry Vehicle; HL stood for Horizontal Landing). The HL-10 was basically a fattened and rounded delta wing with sharply upswept tips and a central vertical fin. The Air Force had watched the NACA's lifting body work with interest, as evidenced by the START II concept, and an ambitious study by the Space Systems Division in May 1961 for a manned lunar landing expedition, LUNEX, incorporating a three-man M-2 type lifting body for the return to earth. This plan, of course, was rejected as posing too many technical uncertainties, and NASA's lunar mission planners opted instead for a more traditional shape as ultimately selected for the Apollo Command Module. Though the two-man Gemini and the larger and more refined three-man Apollo CM had modest lifting characteristics, they remained basically ballistic vehicles.[22]

The conclusion of Dyna-Soar and Aerospaceplane did not spell a total end to Air Force lifting reentry research, for three programs, START, ASSET, and PRIME, served to fill in for these abandoned efforts. ASSET and PRIME, in particular, were most influential in the field of winged and lifting body reentry from space. ASSET, for Aerothermodynamic/Elastic Structural Systems Environmental Tests, began in the 1959-1960 time period as a support program for Dyna-Soar, but without using X-20-dedicated monies. In May 1961, the Air Force Flight Dynamics Laboratory contracted with the McDonnell Aircraft Corporation for six experimental ASSET delta gliders, closely resembling the shape of the X-20 (but without its vertical fins). The ASSET craft measured over five feet in length, and were designed for launch on Thor and Thor-Delta boosters. Eventually, during tests between September 1963 and March 1965, they reached speeds of between 10,000 and 13,500 mph while making lifting reentries from 200,000 feet over the South Atlantic; all survived, though some were lost at sea before recovery crews could pick them up. After the cancellation of Dyna-Soar, Gen. Bernard Schriever, commander of Air Force Systems Command (AFSC), launched a successor to ASSET, the PRIME program, to demonstrate Precision Recovery Including Maneuvering Entry using pilotless lifting body shapes. (To coordinate this new program, plus the remainder of ASSET, a general program, START, was established, for Spacecraft Technology and Advanced Reentry Tests). PRIME got underway in November 1964, when AFSC contracted with the Martin Company for the design of a maneuvering lifting body to demonstrate whether, in fact, a lifting body could be guided from a straight course and returned back to that course. Martin responded by developing the SV-5D, an 890 lb. aluminum lifting body having an ablative heat shield for thermal protection. The company built four of these heavily instrumented bodies, which the Air Force designated as the X-23A. Three of the four were fired over the Western Test Range between December 1966 and mid-April 1967 using Convair Atlas ICBM's as boosters. During their 15,000 mph reentry, the three flown performed so well during hypersonic maneuvering that the Air Force, for reasons of economy, so no need to proceed with launching of the fourth. PRIME confirmed that a lifting body could indeed successfully alter its flight path during reentry. Though the service did not believe that it should immediately move towards the development of a manned lifting body using the SV-5 body shape, tests of this shape by PRIME and other subsonic model trials were so encouraging that the Air Force and Martin embarked upon PILOT (for Piloted Lowspeed Tests), an effort to build a piloted rocket-boosted lifting body capable of supersonic speeds just to demonstrate that such a craft could execute a precision powerless approach and landing after boosting to high altitude, and to verify the predicted supersonic, transonic, and subsonic performance and handling qualities of the design. Martin designed and manufactured the SV-5P aluminum lifting body (which the Air Force flew subsequently as the X-24A) under the aegis of the PILOT program.[23]

In fact, the X-24A was but one of four lifting body configurations actually flown in piloted tests. The first, a wooden-shell M2 glider dubbed the M2-F1, had been built by NASA's Flight Research Center as a private venture, and first flown by NASA pilot Milton Thompson on August 16 1963, when towed aloft from Rogers Dry Lake by a C-47 transport to an altitude of 10,000 feet and then released. The M2-F1, strictly a low-speed testbed, had a fixed tricycle landing gear. These first flights lent confidence to advocates who wished to proceed with development of "heavyweight" rocket-propelled aluminum-structure lifting body shapes that could be flown at supersonic speeds down to landing. Because the desirable hypersonic body shapes for atmospheric reentry often conflicted with what was desirable for supersonic and transonic flight, it was imperative that designers know whether or not a suitable hypersonic configuration could also be tailored to have acceptable supersonic, transonic, and subsonic behavior. The result was the NASA/Northrop M2-F2 and HL-10 programs. In a sense, this represented a competitive "fly-off" between the Ames M2 approach and the Langley HL-10 approach. In June 1964, NASA's Flight Research Center awarded a development contract to Northrop for one example of each configuration. Like the X-15, they would be air-launched from a modified B-52. Though first flown as gliders, each would have provision for a single XLR-11 rocket engine (like the Air Force Martin SV-5P) for supersonic excursions. Northrop completed the M2-F2 in June 1965, and followed this with the HL-10 in January 1966. Martin followed with the Air Force-sponsored SV-5P/X-24A in July 1967.[24]

The "heavyweight" lifting bodies flew with varying degrees of success. Of the initial three (the M2-F2, HL-10, and X-24A), the HL-10 had superior ratings from its test pilots. When the M2-F2 was modified as the M2-F3, its performance and handling characteristics approached that of the docile HL-10. Later, when the Air Force modified the X-24A as the X-24B, the X-24B surpassed the HL-10 as the pilots' favorite.* The M2-F2 was the first "heavyweight" to fly, making its maiden flight on July 12, 1966. Unfortunately, the M2-F2 had extremely poor lateral-directional stability characteristics at low angles of attack, and these undesirable traits contributed to a serious landing accident on May 10, 1967 that critically injured research pilot Bruce Peterson and resulted in the craft being so badly damaged as to require virtual rebuilding. Subsequently modified with an additional vertical fin to act as a flow fence and improve the craft's lateral control characteristics, the lifting body--now designated M2-F3--made a number of transonic and supersonic flights, boosting to Mach 1.6 on one occasion before beginning its low lift-to-drag landing approach. Altogether the M2-F2/M2-F3 completed 43 flights before being retired at the end of December 1972. The HL-10, a product of Eugene Love's research at Langley, encountered serious flow separation problems on its maiden flight on December 22, 1966, leading to redesign of its outer vertical fins. Thus modified, the HL-10 subsequently flew very well, indeed. It eventually completed approach and landings from speeds up to Mach 1.86 and altitudes of up to 90,303 feet, making it the fastest and highest-flying lifting body built to date. The

*See Appendix A for roster of lifting body pilots.

Martin X-24A fell somewhat between the M2-F2/M2-F3 and HL-10. Though it had no major vices, it did have one performance quirk that bothered researchers: it exhibited a pronounced nose-up trim change that prevented the craft from attaining low angles of attack during powered flight. The trim change stemmed from the effects of the exhaust plume impinging upon the craft, and warned designers of the Space Shuttle to beware similar problems with that ambitious project, for though such trim changes seem innocuous, they could impose additional aerodynamic loads on the Shuttle during its boost to orbit, endangering the mission.[25]

All of the lifting bodies demonstrated that shuttle-type hypersonic vehicles could successfully fly at supersonic speeds and make precision unpowered landings without needing auxiliary turbojet engines. This had been a point of serious contention during the initial stages of Space Shuttle conceptualization, and many advocated developing the Shuttle with auxiliary landing engines to permit power-on landing approaches. However, the experience with the Round One and Round Two rocket research airplanes, as well as with the lifting bodies, indicated to NASA flight researchers that proper energy management techniques obviated the need for power approaches. Indeed, powered landing trials with the HL-10 (the best flying of the lifting bodies, prior to the X-24B), indicated that powered approaches put a much greater workload on a pilot, since the pilot had more difficulty determining the landing point, and the higher approach speed aggrevated control sensitivity problems. Whether it had landing engines or not, a Shuttle would have to be maneuvered unpowered close to its landing site before its auxiliary engines could be started, as the engines had to be operated at subsonic speeds, and because only limited fuel would be available. Air Force and NASA pilots believed it "ridiculous" to have to maneuver the Shuttle into a position where it required power to reach the runway.

A little-known but most important series of tests conducted by the Air Force Flight Test Center using modifed General Dynamics F-111A and Boeing NB-52B aircraft dramatically demonstrated both the ability of a Shuttle-like craft to complete an unpowered approach to landing, and its ability execute such an approach using precision navigation and guidance. These tests further encouraged development of a Shuttle craft unencumbered by an awkward landing engine installation. In the summer of 1969, project pilot Maj. Peter C. Hoag began a series of flights in a F-111A variable-wing sweep aircraft to simulate the approach characteristics of a lifting reentry spacecraft descending from Mach 2 and 50,000 feet and utilizing a variable sweep wing configuration for approach and landing.* These tests were intended to evaluate terminal energy management and landing characteristics typical of several new classes of variable-sweep reentry craft then on the drawing boards at the Air Force Flight Dynamics Laboratory, especially the FDL-5, FDL-7, and FDL-8 shapes. The F-111, because of its then-novel variable sweep wing planform, was an ideal simulation tool for such craft. Very quickly, however, the thrust of the program changed to address a much more significant problem: low lift-to-drag

*See Appendix A for a roster of personnel involved in these tests.

ratio approaches under instrument-flight conditions, in contrast to the traditional "eyeballs" or "blue skies" clear visibility approaches utilized previously. Because of its sophisticated inertial navigation system (INS), the F-111 was also an ideal testbed for this aspect of the program. Approaches were flown under various L/D and power conditions using a "funnel" type approach with the right-seat occupant handling the terminal area navigation problem and the pilot flying the aircraft from the left seat. Terminal area guidance had not previously been a problem in the American space program, because of the semi-ballistic nature of the returning spacecraft. It was, of course, critical to a shuttle craft maneuvering to a horizontal landing on a predetermined runway. The display fed the pilot distance, bearing, glide slope, and course to an aim point, and a precision low altitude radar altimeter furnished reliable height information. As flown, the F-111 entered an "energy dissipation phase," following a descending, circling path and decelerating from supersonic to subsonic speeds. Then the pilot banked to enter an initial approach phase, using monitoring of distance measuring equipment (DME) to determine when to bank to a final approach phase, using glide slope and course deviation displays, coupled with inputs from the radar altimeter. At a predetermined height, the pilot would flare the F-111, decelerating to landing with a shallow glide angle of less than 1 deg. For greater fidelity, pilots flew "hooded" instrument approaches as well as visual ones, the pilot removing the hood at the start of the landing flare and then decelerating to landing. These F-111 tests demonstrated the ability of trained test crews to make unpowered instrument approaches from Mach 2 and 50,000 feet down to a precision runway approach. A series of follow-on tests using an NB-52B which had general handling characteristics more closely approximating a Shuttle-size craft confirmed that the instrument landing system (ILS) type approach flown with the F-111 testbed was more suitable than the ground controlled approach (GCA) flown by the NB-52B. The most important assessment from these tests, of course, was the conclusion that "unpowered instrument landing approaches for the Space Shuttle are both feasible and practical, and should be considered for normal flight operations of this vehicle."[26]

Unpowered landing advocates gained further confidence from the flight trials of the X-24B, a modified airframe built on the earlier X-24A. The X-24B evolved from the Flight Dynamics Laboratory's FDL-7 body shape having a hypersonic L/D on the order of 2.5 and large internal volume, suited to hypersonic aircraft capable of flight from Mach 4 to orbital velocities, though tailored for aircraft in the Mach 8 to 12 range. The Air Force hoped that these shapes could be used for both sustained airbreathing hypersonic cruise aircraft, as well as for unpowered orbital reentry spacecraft capable of landing at any convenient airfield. In January 1969, the Air Force proposed modifying an abortive Martin jet-powered lifting body trainer (the SV-5J) into a testbed for one of these advanced body designs. The company planned taking the SV-5J and gloving an FDL-7 body shape around the craft, giving it a new composite shape that the Flight Dynamics Laboratory designated the FDL-8.

Further analysis led to the decision, in July 1971, to modify the X-24A itself (which had the same basic shape as the SV-5J) into the FDL-8 shape, the new vehicle to be designated the X-24B. The X-24B, which Martin delivered back to NASA and the Air Force in the fall of 1972, had a 78 deg. double-delta planform, a flat bottom, "boat-tailing" for good subsonic lift-to-drag characteristics, and a sloping 3 deg. nose ramp for hypersonic trim. It retained the X-24A's XLR-11 rocket engine. Overall, the X-24B was 9 ft. greater in span, and 14.5 feet longer than the earlier X-24A. It weighed 13,800 lbs. at launch. It was, altogether, a much more pleasing and rakish "flat iron" shape than the potato-like SV-5 shape housed within it. The X-24B completed its maiden flight on August 1, 1973; on October 24, 1975, Air Force test pilot Michael Love flew the craft to Mach 1.76, 1,164 mph, then made an unpowered descent and landing from altitude. The X-24B demonstrated superlative handling qualities, and may be considered indicative of the shape of future delta planform hypersonic lifting bodies. Pilot Jerauld Gentry had strongly advocated lifting body runway landings in support of Shuttle development, and now, as a result of the X-24B's fine flying qualities, NASA pilot John Manke and Air Force pilot Love proposed executing approach and landing tests to the 15,000 foot concrete runway at Edwards AFB, similar to what would be required of the Rockwell Space Shuttle then under development. The joint NASA-USAF X-24B research subcommittee approved the proposal in January 1975, and on August 5, 1975, Manke made an unpowered approach and landing to the Edwards runway from an altitude of 60,000 feet, touching down precisely on the planned landing spot. Two weeks later, Love duplicated the feat. Indeed, it could have been accomplished with any of the other lifting bodies, though more easily with the X-24B. The X-24B flew better, and, more importantly, had nosewheel steering, which the other vehicles, designed to land on the vast surface of Rogers Dry Lake, did not have. The X-24B made its last flight on November 26, 1975, bringing America's postwar rocket research aircraft program to a close.[27]

Early Formulations in America and Abroad

The present Space Shuttle represents the outcome of a tradition of lifting reentry design approaches, beginning with the work of Sänger-Bredt in Germany and continuing with the "paper plane" proposals of the 1950's, the X-15, the X-20A, and the lifting bodies. It comes as the fourth major American manned spacecraft venture, following on the heels of Projects Mercury, Gemini, and Apollo. Because of expediency, as well as the understandable desire to build upon an existing technology, these preceeding efforts had used ballistic or semi-ballistic blunt-body reentry vehicles to return the astronaut crews through the atmosphere to earth. Yet even here attempts had been made to give these vehicles some favorable lift-to-drag ratios permitting limited maneuverability. While Mercury was purely ballistic, the two-man Gemini spacecraft produced a small amount of lift at hypersonic speeds, having a lift-to-drag ratio of 0.25, permitting limited maneuvering.

The larger Apollo had a hypersonic lift-to-drag ratio of 0.6, though in practice, because of the precision guidance systems developed for the Apollo program, the spacecraft never required a ratio higher than 0.31. Though the later Space Shuttle drew upon a whole host of actual and theoretical winged spacecraft for its configuration and aerodynamics, the data base acquired from the Mercury, Gemini, and Apollo program was invaluable in such areas as propulsion, structures, guidance, instrumentation, and life support systems.[28]

In the early days of the space program, ideas abounded concerning ways of getting some limited cross-range travel following reentry into the atmosphere. In any case, the time-honored tradition of recovery at sea, with the heavy manpower and facilities requirements necessitated by such an approach (as well as the inability to reuse the recovered spacecraft) increasingly appeared as a liability to practical use of space travel. Dyna-Soar and the lifting bodies appeared as one way around this problem, as did other paper studies for more ambitious projects. Some other advocates suggested using stowed Rogallo wings and even rotors as a means of overcoming the problems of purely ballistic or semi-ballistic reentry flight. Gradually, however, the winged reentry approach appeared more acceptable. For one thing, the many aerodynamic heating problems expected with winged designs appeared less serious in light of new materials developments using high-temperature materials, ceramics, and composite structures. Thus, the pure blunt body, and such proposals as the M2 half-cone lifting body, lost much of their allure. Wings returned to favor. At the same time, the high reentry aerothermodynamic loadings imposed by a Sänger-type skipping reentry appeared undesirable: the prolonged heating of the flight structure was much greater (and thus a more significant problem) than if an orbiter simply made a single reentry approach, followed by a hypersonic and supersonic glide down to subsonic speeds prior to the approach and landing. Questions about the exact configuration of such a winged reentry shape, as well as its booster configuration, were too general as to yet have answers, as were such issues as an unpowered vs. powered landing approach. Disagreement existed over whether the craft should have a single delta wing, or a conventional straight or swept wing with tail surfaces, or whether the wings should be fixed or variable-geometry (that is, stowed during boost and reentry, and then deployed once the craft passed through peak aerodynamic heating and dynamic loadings), or whether it should be a radiative or ablative cooled vehicle. Disagreement existed over whether the craft should be vertically launched, or whether it should be horizontally launched off a sled, like the Sänger proposal.

The Space Shuttle program grew out of a perceived need for a logistical spacecraft to support orbital space stations, and was also influenced by growing fears that the space program had inadequate provisions for emergency space rescue. In the optimistic climate of the early 1960's, it seemed inconceivable that the nation would not immediately embark upon space station development after completion of Apollo. (This, of course, changed rapidly after July 20, 1969, and the successful completion of President Kennedy's lunar landing directive.) Lifting reentry spacecraft appeared to offer attractive alternatives to ballistic spacecraft, such as proposed derivatives of Gemini and Apollo hardware, for space rescue and supply.

As a result, all through the 1960's, NASA, primarily at its Houston and Huntsville centers, solicited a great number of industry feasibility studies directed towards two related goals: creation of orbiting space habitats, and development of either ballistic or lifting reentry logistical space shuttles to support operations of the orbiting space stations. However, the agency was adamant in its belief that while lifting reentry technology was desirable for earth-to-orbit logistical transports, such a technology was less than mature for application to military vehicles for such missions as orbital reconnaissance, and long range surface-to-surface hypersonic transports operating, say, from New York to Sydney, Australia. A staff report by NASA's Ad Hoc Committee on Hypersonic Lifting Vehicles with Propulsion, prepared in June 1964, stated that "the need for hypersonic military reconnaissance -type missions is indeterminate at this time, although the Air Force expresses interest in this mission if the technical problems can be solved. Thus a research and development program aimed solely at such an application would be highly questionable."[29] The report further concluded that the heating problems of a long-range surface-to-surface hypersonic transport would in turn generate profound technical difficulties, pushing the state of the art in a number of areas. But the earth-to-orbit vehicle seemed to be more practicable and attainable, so the agency recommended continuing study of such logistical spacecraft. The committee's research indicated that such a vehicle should have two stages; it would have mixed air-breathing and rocket propulsion systems; the all-rocket second stage would be launched in a near-vertical attitude at high altitude. Both the first and second stages would return to earth as fully reusable vehicles. NASA thought that "one of the most attractive approaches" would be to have a hybrid propulsion first stage that would take off using "turbojet engines similar to those that will be used in the supersonic transport" (i.e.: approximately 60,000 lbs. static thrust each). At Mach 3, the craft would switch from using these engines to using rocket propulsion, and at about Mach 6, during a vertical climbing maneuver, the second stage would fire into orbit. The committee questioned developing any less-capable vehicle as a first step, arguing that[30]

> There is reason to question the desirability of the frequently proposed development of a full-scale research or prototype vehicle for either of the possible applications at this time. The cost of such a vehicle would be exceptionally high and hence competitive with other programs. There is validity to the argument that such a program would provide a focal point for effort that would hasten progress. On the other hand, there are so many unanswered technical questions that a great deal of worthwhile progress can be made with programs confined for the present to research and analysis aimed at obtaining better definition of what is technically feasible and what development and operational problems and costs are likely to be encountered.

Coming approximately six months after the cancellation of the X-20A Dyna-Soar program, this pronouncement effectively ended calls within NASA for manned lifting reentry technology demonstrators. Calls for such demonstrators outside government circles continued, however. Northrop, for example, proposed building a man-carrying M2 lifting body and launching it using a modified Titan II ICBM; this scheme had considerable support among enthusiasts at NASA's Flight Research Center, but it did not win favorable endorsement from NASA Headquarters, in spite of its modest $200 million estimated price tag.

Instead of proceeding with demonstrators, then, NASA pursued development of a large multistage craft having genuine logistical capabilities. Many of these studies used the M2 and HL-10 configurations as baselines for further research, and almost all of these studies were linked to operating such craft in conjunction with an orbiting space station, then also in the design study phase. Companies involved in these NASA-solicited studies included Aerojet-General, Boeing, Douglas, General Dynamics, General Electric, Lockheed, McDonnell, Martin, North American, and Northrop; North American eventually became part of the larger Rockwell conglomerate, and Douglas eventually merged with McDonnell. Even within companies, a wide range of disparite views existed over the capabilities and configurations of these logistical vehicles. Companies would, for example, study both horizontally launched craft using rocket-boosted sleds, and vertically launched designs. The Lockheed company, for example, evolved the so-called

"Starclipper" configuration, a "1½ stage to orbit" approach consisting of a delta lifting body with two huge external fuel tanks mounted on the craft in such a way that it nestled between them in the crook of the large "V" that they formed. General Dynamics proposed the "Triamese" (a play on Siamese) approach: the Shuttle would consist of three stages, each having a basically identical configuration. The three stages would be mounted in parallel. During launch and the subsequent climb to orbit, two of the stages would separate and return to the launch point. The third stage would fire into orbit. All three had a lifting body shape with a stowed variable geometry wing that could be deployed once the craft survived reentry and decelerated to subsonic speeds. Also, the craft would have deployable turbojet engines so that it could cruise down to its landing site and make a conventional powered landing. Other companies recommended adopting existing launch systems such as the Titan or the Saturn IB boosters; while recognizing that Shuttle craft using these boosters would not be fully reusable, these designers hoped to reduce the great number of technical uncertainties in developing both piloted and winged orbiters and boosters. As it subsequently turned out, their more practical viewpoint played a significant role in determining the final configuration of the present-day Shuttle, though, as will be seen, the most crucial factors in the development of the actual Shuttle were its economics and its usefulness for Department of Defense-sponsored missions.[31]

Shuttle-related studies in the United States were mirrored by studies made abroad by European enthusiasts. These foreign advocates energetically pursued lifting reentry concepts, despite the economic posture of their nations, advancing ideas consistent with their national economic situation and technological capabilities. Great Britain, France, and Germany all developed orbiter configurations. As early as 1958, British advocates had been studying a rounded delta orbiter similar to the abortive Dyna-Soar. The Royal Aircraft Establishment studied two-stage horizontal takeoff transporters during the early 1960's, and the British Aircraft Corporation pursued the MUSTARD scheme (for Multi-Unit Space Transport and Recovery Device), a plan to build three lifting bodies shaped roughly like the HL-10 and launch them in a symmetrical cluster, or as a parallel back-to-belly-mounted "Triamese" approach. Hawker Siddeley examined two stage winged rocket boosters carrying orbiting lifting bodies.[32] In France, Dassault, Nord, Sud, SNECMA, ERNO, and ONERA worked singly and as a team on various studies of Shuttles and "Space Taxi" proposals. French studies, as evaluated by the Centre National d'Etudes Spatiales, fell into two catagories: large payload haulers and small "taxi" vehicles to transfer personnel and for space rescue. Dassault started studies in 1963, eventually developing a series of multi-stage configurations making use of a large delta wing Mach 4 launch aircraft powered by turbo-ramjets (this craft was elegantly shaped, and reminiscent of the Concorde SST then under development). This craft would then launch a small "space taxi" propelled by an expendable booster stage. The booster stage would fire and be jettisoned, and the space taxi would continue into orbit, returning through the atmosphere, and then deploying variable sweep wings and tail surfaces and firing up a turbofan engine before landing. Nord Aviation proposed the so-called "Mistral" project, a generally similar scheme to that of Dassault, though the orbiter, in this case, was a large lifting body similar in configuration to the Langley HL-10 concept. Sud Aviation also pursued this concept, but generally favored much more sharply swept delta planforms for the launch aircraft. In support of all of these efforts, ERNO ran model drop tests of proposed orbiter shapes from Luftwaffe Transall transport aircraft over the Baltic and Mediterranean. Additionally, Nord proposed development of an X-15-class hypersonic test bed called VERAS (Vehicle for Experimentation and Research in Aerothermodynamics and Structures) to develop the requisite technology base for further studies on hypersonic lifting reentry from space leading to construction of a spacecraft.[33]

In Germany, Messerschmitt-Bölkow-Blohm and Junkers examined various lifting reentry concepts and derived suitable configurations. German postwar work had begun in 1962 as a result of active lobbying by pioneer Eugen Sänger; it represented this remarkable man's last efforts, for he died soon thereafter, in 1964. Between 1962 and 1969, the Federal Republic of Germany expended approximately 16.5 million DM on Shuttle-related studies, to (in the words of the West German Minister for Education and Science) "prepare German industry for future possible bilateral or multilateral international cooperative projects and to build up active teams."[34] Like French advocates, German supporters believed that there was a need for a mix of large and small payloads (ranging between 6,000 and 50,000 lbs. to orbit), and that any such craft should be partially expendable to reduce costs and development uncertainties, though they conceded that a partially expendable spacecraft could be regarded as only an interim solution for the "final space transport." Messerschmitt-Bölkow-Blohm (MBB) investigated many possible configurations, finally selecting a two-stage approach with a winged boost vehicle and a modified HL-10-class orbiter mounted piggyback. Junkers, working closely with Sänger, postulated a winged booster and winged orbiter for their RT-8-01 Raumtransporter (space transport) study, completed in 1964. The RT-8-01's orbital craft closely resembled the cancelled X-20A Dyna-Soar, and also clearly revealed its Sänger origins.[35]

The Soviet Union's work is obscure; apparently, as early as 1962, some Soviet studies on Raketoplan (rocket aircraft) were underway under the direction of Artem Mikoyan, who himself used the term Kosmoljot (spacecraft) to describe the project. As elsewhere, Soviet studies were directed towards ascertaining whether such craft should be multi-stage, should employ vertical or horizontal launch, and what its mission capabilities should be. Speculative art by well-known Soviet space artist Andrei Sokolov shows one configuration that may have represented serious Soviet thought: a two-stage craft consisting of a lifting body orbiter fired from the back of a winged booster. The painting in question showed the orbiter firing into space as the booster, obviously piloted, peeled away in a rolling turn for its own return to earth.[36,*]

The broad range of European studies reflected the vigorous interest displayed by European enthusiasts of lifting reentry and Shuttle-related technology. In tacit recognition of this, by the end of 1970, working partnerships had developed between American and European firms engaged on Shuttle-related research. North American-Rockwell, McDonnell-Douglas, and Grumman negotiated with diverse European aerospace concerns, forming organizational ties to such groups as the British Aircraft Corporation, Messerschmitt-Bölkow-Blohm, ERNO, Aerospatiale, Dornier, Dassault, and Hawker-Siddeley, further emphasising not only the multidisciplinary but multinational character of Shuttle development.[37]

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*In 1978, the aviation trade press announced that a Soviet lifting reentry spacecraft had been drop-tested in a manner similar to the American M2, HL-10, and X-24 lifting bodies, from a modified Tupolev Tu-95 Bear mothership. Popular accounts at the time stated that the craft had a similar overall configuration and size to that of the abortive X-20A Dyna-Soar. But the precise nature of Soviet work in this field remained unclear until the launch in 1982 of a subscale delta wing lifting reentry vehicle resembling Dyna-Soar, and with characteristics similar to the American ASSET and PRIME spacecraft launched nearly a decade earlier. Clearly it can be anticipated that future Soviet lifting reentry research will build upon this effort; in any case, the Soviet Union has demonstrated its desire to embark on an active lifting reentry research and development program leading to Shuttle-class vehicles. Unclassified reports in 1983 were indicating that the Soviet Union was embarked upon a program to build a heavy-lift Shuttle capable of placing up to a 60,000 kg. payload into a 180 km. orbit, using a parallel-burn launch system similar in concept to the American Space Shuttle. See Department of Defense, Soviet Military Power, 2nd ed. (Washington, D.C.: GPO, 1983), pp. 66, 68.

The uncertainties confronting Shuttle advocates concerning the shape and purpose of such spacecraft continued as the 1960's progressed, even as support for the development of winged spacecraft continued to increase. This did not mean that partisans of developing ballistic logistical supply spacecraft were pushed entirely to the background of Shuttle development; nevertheless, as the 1960's progressed, there was a marked decrease in interest in utilizing ballistic spacecraft such as the proposed "Big G" (a Gemini derivative carrying a payload of nine astronauts), or ballistic spacecraft that would utilize a stowed Rogallo wing or paraglider lifting system for gliding to a landing following a ballistic drop through the atmosphere. In September 1966, the joint NASA-Department of Defense Aeronautics and Astronautics Coordinating Board (AACB) issued its summary report on the status of reusable launch vehicle technology. The AACB report concluded that numerous cost uncertainties and technical risks required resolution. Numerous other factors, however, encouraged reusable launch vehicle development, particularly an expected increase in manned earth orbital flight activity. At the time, the AACB's panelists could not identify one single concept capable of satisfying both NASA's and DoD's perceived future needs. Thus, the AACB examined and summarized a variety of proposed systems, including ones utilizing horizontal and vertical takeoff and landing, lifting bodies, winged spacecraft, single vs. multi-stage configurations, air launching, and craft blending air-breathing and rocket propulsion.[38]

The Path to the Space Shuttle

To help refine its own concepts for Shuttle vehicles, NASA created a Space Shuttle Task Group (SSTG) under the direction of L. E. Day to evaluate both the agency's needs and system concepts. In February 1969, the agency took the first step towards what eventually emerged as the Space Shuttle with the award of four study contracts to Lockheed, General Dynamics, McDonnell-Douglas, and North American-Rockwell for what were designated Integral Launch and Reentry Vehicles (ILRV). Five months later, in July 1969, the SSTG issued a summary report of its own efforts, concluding that an ILRV-class vehicle should be capable of performing six major space missions:

*Logistical support of a space station
*Orbital placement and retrieval of satellites
*Delivery of propulsive stages and payloads in space
*Propellant delivery to orbit
*Satellite servicing and maintenance
*Short-duration manned orbital missions.

The group did express a marked preference for a fully or near-fully reusable system, and endorsed the Shuttle as "the keystone to the success and growth of future space flight developments for the exploration and beneficial uses of near and far space."[39] NASA now turned to deriving an optimum design to satisfy these demanding missions.

Such a task, of course, was no easy one. Any one design capable of fulfilling all of these missions would require numerous design tradeoffs, some of which were:

*partially or fully reusable system
*"flyback" piloted booster vs. expendable unmanned booster

*winged vs. lifting body configuration

*if winged, whether delta, swept, straight, or variable-sweep

*off-the-shelf engines vs. new propulsion system

*vertical vs. horizontal launch

*low (200 nautical mile) vs. high (1,500 n.m.) cross-range

*small vs. large payload bay

*sequential staging vs. parallel-burn staging

To help resolve such questions, NASA held a series of meetings to address these and other issues, most notably a major international symposium on the Space Shuttle arranged by NASA and held at the Smithsonian Institution in October 1969. There were, however, two other major factors operating with less visibility behind the scenes: the state of the American space program after July 20, 1969, and the role of the Department of Defense.

On July 20, 1969, Apollo XI astronauts Neil Armstrong and Buzz Aldrin fulfilled President Kennedy's expectations of the Apollo program by walking on the lunar surface at Tranquillity Base while fellow astronaut Michael Collins remained in lunar orbit awaiting their return. NASA's space program beyond Apollo had always been nebulous at best, though planners at the Manned Spacecraft Center at Houston and the George C. Marshall Spaceflight Center at Huntsville had tried to crystallize the vague urges of space station advocates into hardware programs. Nevertheless, the national climate--and especially Congressional response to that climate after Apollo XI's triumphant journey--dictated a turning away from such ambitious (if ill-defined) plans. In 1970, the agency recognized that it could not have both the Shuttle and the station, and accordingly, shelved plans for the latter. The Shuttle, a more modest, attainable, attractive, and--most importantly--more defendable concept, survived, though its major justifications shifted from space station logistical support to its use as a more economical substitute for "throwaway" launch systems such as the Delta booster. The next year, 1971, the government's Office of Management and Budget (OMB) expressed its unwillingness to support NASA at budget levels above the space agency's 1971 annual figure of $3.2 billion. This placed Shuttle in serious jeopardy; program costs for the fully reusable two-stage Shuttle were already rising above an estimated (and now clearly unavailable) $10 billion. Though NASA planners still favored the fully reusable approach, economic considerations, supported by outside analysis, dictated otherwise. NASA now had to adopt a partially expendable booster system. That the Shuttle survived both the restructuring of the national space program and the secondary economic barrage from OMB was due, in no small measure, to quiet but strong support from the Department of Defense, particularly the United States Air Force. And this support played a profound role in shaping the final configuration and capabilities of the Space Shuttle.[40]

In his masterful study of the engineering and political influences affecting the design of the Shuttle from 1969 through 1972, Massachusetts Institute of Technology science and technology policy analyst Scott Pace identified five key issues affecting the ultimate design of the Shuttle:[41]

*determining the capacity and dimensions of the payload bay
*determining the optimum cross-range for the craft
*choosing a TAOS (Thrust-Augmented Orbiter Shuttle) design
*deleting plans to incorporate air-breathing "landing" engines
*selecting aluminum as the primary structural material

The first two questions were ones in which Department of Defense input was critical. The technical fall-out from these first two decisions influenced, together with other external factors such as those already discussed, the latter three questions as well. Although it is popular to describe the United States in the 1960's and early 1970's as having two space programs, one wholly dedicated to the civilian world (that of NASA) and the second dedicated to national defense related matters (that of the Department of Defense) there were, of course, areas of mutual interest. The early activities of the NASA-DoD Aeronautics and Astronautics Coordinating clearly demonstrate this dualistic approach to the utilization of space, particularly as questions concerning possible development of a Shuttle system were concerned. While the number of actual Air Force personnel involved in Shuttle studies was small during the late 1960's, senior NASA and Air Force representatives, such as Grant Hansen, the Assistant Secretary of the Air Force for R & D, and George Mueller, NASA's Associate Administrator for Manned Spaceflight, already were discussing the issue in both formal and informal sessions. In 1970, then-Air Force Secretary Robert Seamans and NASA Administrator Thomas Paine established a joint NASA-USAF Shuttle coordination board, the STS Committee, chaired by Hansen and NASA's Dale Myers, who had succeeded Mueller. The agreement stated that the Shuttle, now designated the Space Transportation System (STS), would furnish the United States with an "economical capability for delivering payloads of men, equipment, supplies, and other spacecraft to and from space by reducing operating costs an order of magnitude below those of present systems." For its part, the STS Committee would review the program and recommend decisions to ensure that the STS met both NASA and DoD needs; the recommendations of the committee would include such matters as "development and operational aspects, technology status and needs, resource considerations, and interagency relationships."[42]

Interestingly, the Air Force did not feel the acute need for the Shuttle system that NASA did. The service's own space programs were adequately supported by the use of expendable launch systems such as the Scout, and, above all, Titan III. Because of this, and perhaps because of the large expenditure of DoD funds with little return in the ill-fated Dyna-Soar and Manned Orbiting Laboratory programs, the Air Force was unwilling to support the actual development of the Shuttle with its own monies. Further, the late 1960's and early 1970's were a time period in which the service was increasingly concerned about the development of new aircraft systems such as what eventually emerged as the B-1, F-15, F-16, and A-10. Air Force Shuttle involvement centered on a new building program at Vandenberg AFB, California, so that Shuttle could be launched and recovered there on DoD missions, and developing a small booster, the Space Tug, to place DoD payloads in higher orbits than could be achieved by the low-earth-orbital STS. In brief, DoD, and the Air Force in particular, were willing to support the

Shuttle if it had utility for the defense community; NASA saw such support as vital if the STS were to withstand the attacks of critics questioning its need and rationale; and Air Force support for the STS hinged on two key areas: payload capacity and payload bay size, and the cross-range of the Shuttle orbiter.[43]

These two matters both pertained to the placement of Department of Defense satellite systems in orbit. Very quickly, the Air Force established the following criteria:

*A payload bay 60 ft. long and 15 ft. in diameter

*A payload capacity of 65,000 lbs. into a due east 100 n.m. orbit, and 40,000 lbs. into a polar orbit

*A cross-range of 1,500 n.m. (later changed to 1,100 n.m.)

The first two were required by the size and weight of planned DoD operational systems. The latter point was a necessary safety concern for a single-orbit Shuttle return to Vandenberg following launch from Vandenberg, placement of a satellite into polar orbit, and return to landing at Vandenberg, since the earth would have rotated sufficiently during the flight to require that the orbiter have a high crossrange so that it could adjust its course to reach the California base.

NASA's initial Shuttle configurations, the ILRV's, had been designed by Maxime Faget, and were straight-wing designs having low-placed horizontal stabilizers and a single large vertical fin. Their payload capacity was small, ranging from 12,500 to 25,000 lbs., and they had a cross-range on the order of 200 nautical miles. Such constraints were anathema to Air Force proponents, and, via the STS Committee, the Air Force quickly made its views known to NASA. Former Deputy Assistant Secretary of the Air Force

Michael Yarymovych went directly to NASA's George Mueller to state the Air Force position. As he recollected later, "NASA needed Air Force support, both for the payloads and in Congress. I told Mueller we'd support the Shuttle, but only if he gave us the big payload bay and the cross-range capability, so we could return to Vandenberg after a single orbit. Mueller knew that would mean changing Max Faget's beloved straight-wing design into a delta wing, but he had no choice. He agreed."[44] There were other reasons for rejecting the Faget orbiter and adopting a delta design, notably improved aerodynamic performance and improved stability and flight safety characteristics. In a major STS meeting between NASA, USAF, and industry representatives held on January 19-20, 1971, all of the Air Force requirements--the 15 x 60 ft. payload bay, 65,000 lb. east and 40,000 lb. polar payload, and 1,100 n.m. crossrange, were adopted as baseline design decisions, a major point.[45]

By this time, the NASA STS studies were in what the agency termed Phase B: Concept definition. Phase A (preliminary analysis) had begun with contracts to Lockheed, General Dynamics, McDonnell-Douglas, and North American-Rockwell in February 1969. The agency had followed these with Phase B follow-on study contracts to McDonnell-Douglas and North American-Rockwell awarded in July 1970. At the time of the Phase B study award, the agency and the contractors were generally unanimous in considering the design of very large, two-stage fully reusable craft, with fly-back piloted boosters and having orbiters that carried both their payload and fuel internally. As a hedge, at the same time that NASA awarded the

Phase B contracts, it also awarded two additional Phase A studies to a Grumman-Boeing team and to Lockheed for examination of partially expendable systems as alternatives to the more elaborate Phase B studies then undergoing evaluation. The downfall of the large fully reusable orbiters came with growing recognition that OMB's budgetary limitations upon NASA precluded their development, as well as a recognition that such vehicles would require extensive flight test and validation programs not only for the orbiter, but for the piloted booster as well. Expendable studies emphasized use of existing hardware, such as launching the orbiter using a derivative of the Saturn IB booster. But a growing school of thought conceptualized using a parallel-burn launch system, and reducing the size of the orbiter by removing its internal fuel and placing it in external propellant tanks. This orbiter, with external fuel pumped to its own engines, and with an assist from solid rocket boosters, was essentially a flying payload bay. Eventually, of course, following the evolution of the NASA 040 Shuttle configuration, the parallel-burn school carried the day, and the ultimate Shuttle came to be a derivative of the 040 class orbiter combined with a single large external fuel tank flanked by two solid fuel boosters. Before these final refinements to the Shuttle concept took place, allowing Shuttle proponents to freeze the design and proceed to hardware, the concept had to pass yet one more challenge: an OMB request to NASA to evaluate smaller and smaller Shuttle designs, including one having a payload weight as low as 30,000 lbs. for an eastern orbit, and a payload bay measuring only 30 ft. by 10 ft. NASA successfully defended the large Shuttle with its Air Force-sized payload bay and capacity as the "best buy" in a letter from NASA Administrator James Fletcher to then-OMB deputy director Caspar Weinberger on December 29, 1971.[46]

On January 3, 1972, NASA received Executive Branch authorization to proceed with development of the full-capability Shuttle; President Richard M. Nixon publicly endorsed its development two days later, and the STS was hailed in some quarters as potentially a "Space Age DC-3," an allusion to the airliner that revolutionized air transport in the 1930's. Of course, many design decisions remained to be worked out. In August 1971, NASA's Spacecraft Design Division at the Manned Spacecraft Center in Houston had derived the so-called 040 configuration. In short order it underwent progressive design refinement, from the 040A (September 1971) to the 040B (November 1971), and to the 040C (January 1972). The 040C orbiter roughly approximated the final STS configuration developed. A debate over whether Shuttle would utilize a recoverable liquid-fuel or solid-fuel booster was not resolved until March 1972, when the agency committed itself to a parallel-burn mix of solid and liquid fuel propulsion. Contractor Phase B studies proceeded through an additional Phase B' (Prime) and even a Phase B" (Double Prime) stage before, on July 26, 1972, Rockwell received a NASA go-ahead to undertake final Shuttle design following lengthy analysis of competitive designs submitted by Rockwell, Grumman, McDonnell-Douglas, and Lockheed by a joint NASA-Air Force Source Evaluation Board.[47] Shuttle entered Phase C: detailed design definition. Ahead lay Phase D, final design and development.

By May of 1973, the final configuration of the Shuttle had been set to paper; Shuttle now generally resembled the 040 configuration, but had grown more graceful, with a smoothing of its external lines and a "cranked" leading edge as well as gentle forward sweep of its trailing edge. The construction of the actual Shuttle vehicle began on June 4, 1974. Rockwell completed this first craft, OV-101, subsequently named the Enterprise, in September 1976, and it completed the type's approach and landing tests in 1977. Further difficulties involving development of the craft's propulsion, flight control, and thermal protection system delayed completion of the second Shuttle, OV-102 Columbia, until 1981, reaffirming the problems inherent in developing a complex reusable lifting reentry spacecraft.[48] In April 1981, piloted by astronauts John Young and Robert Crippen, Columbia completed the Shuttle's maiden orbital flight. Three more test flights followed before, in November 1982, Columbia flew with a four-man crew including two mission specialists, placing two satellites into orbit. When it journeyed into space of that historic first operational mission and--more importantly--returned to earth safely to be refurbished and flown again, it fulfilled the hopes and expectations of all those who had advocated the development of reusable reentry spacecraft, from Goddard, Tsiolkovskiy, Hohmann, Oberth, Valier, Sänger-Bredt, and all the rest of the many pioneers who had dreamed and worked to make that moment in time possible. That the United States now has a Shuttle is possible only because of this long heritage of effort; a heritage whose legacy is a new era in the exploration and utilization of space.

APPENDIX A

X-15 Research Aircraft Pilots

Maj. Michael J. Adams, USAF

Neil A. Armstrong, NASA

A. Scott Crossfield, North American Aviation

William H. Dana, NASA

Maj. Joe H. Engle, USAF

Maj. William J. Knight, USAF

John B. McKay, NASA

Lt. Cmdr. Forrest S. Petersen, USN

Maj. Robert A. Rushworth, USAF

Milton O. Thompson, NASA

Joseph A. Walker, NASA

Maj. Robert M. White, USAF

X-20A Dyna-Soar Project Pilots

Maj. Albert H. Crews, Jr., USAF

Maj. Henry C. Gordon, USAF

Maj. William J. Knight, USAF

Maj. Russell L. Rogers, USAF

Milton O. Thompson, NASA

Maj. James W. Wood, USAF

Manned Orbiting Laboratory Project Crewmen

Maj. James A. Abrahamson, USAF

Maj. Michael J. Adams, USAF

Capt. Karol J. Bobko, USAF

Maj. Albert H. Crews, USAF

Lt. Robert L. Crippen, USN

Lt. John L. Finley, USN

Maj. Henry W. Hartsfield, USAF

Maj. Robert T. Herres, USAF

Maj. Robert H. Lawrence, USAF

Maj. Richard E. Lawyer, USAF

Maj. Lachlan Macleay, USAF

Maj. Francis G. Neubeck, USAF

Capt. Robert F. Overmyer, USMC

Maj. Donald H. Peterson, USAF

Maj. James M. Taylor, USAF

Lt. Richard H. Truly, USN

Lifting Body Pilots

William H. Dana, NASA

Einar Enevoldson, NASA

Capt. Jerauld Gentry, USAF

Maj. Peter C. Hoag, USAF

Lt. Col. Michael V. Love, USAF

John Manke, NASA

Thomas McMurtry, NASA

Lifting Body Pilots (cont.)

Bruce A. Peterson, NASA

Maj. Cecil Powell, USAF

Maj. Francis R. Scobee, USAF

Lt. Col. Donald Sorlie, USAF

Milton O. Thompson, NASA

Col. Charles E. Yeager, USAF

F-111A/NB-52B Terminal Area Energy Management Test Pilots

Capt. Nicholas H. Fritz, USAF

Maj. Gordon Fornell, USAF

Fitzhugh L. Fulton, NASA

Maj. Jerauld Gentry, USAF

Maj. Peter C. Hoag, USAF

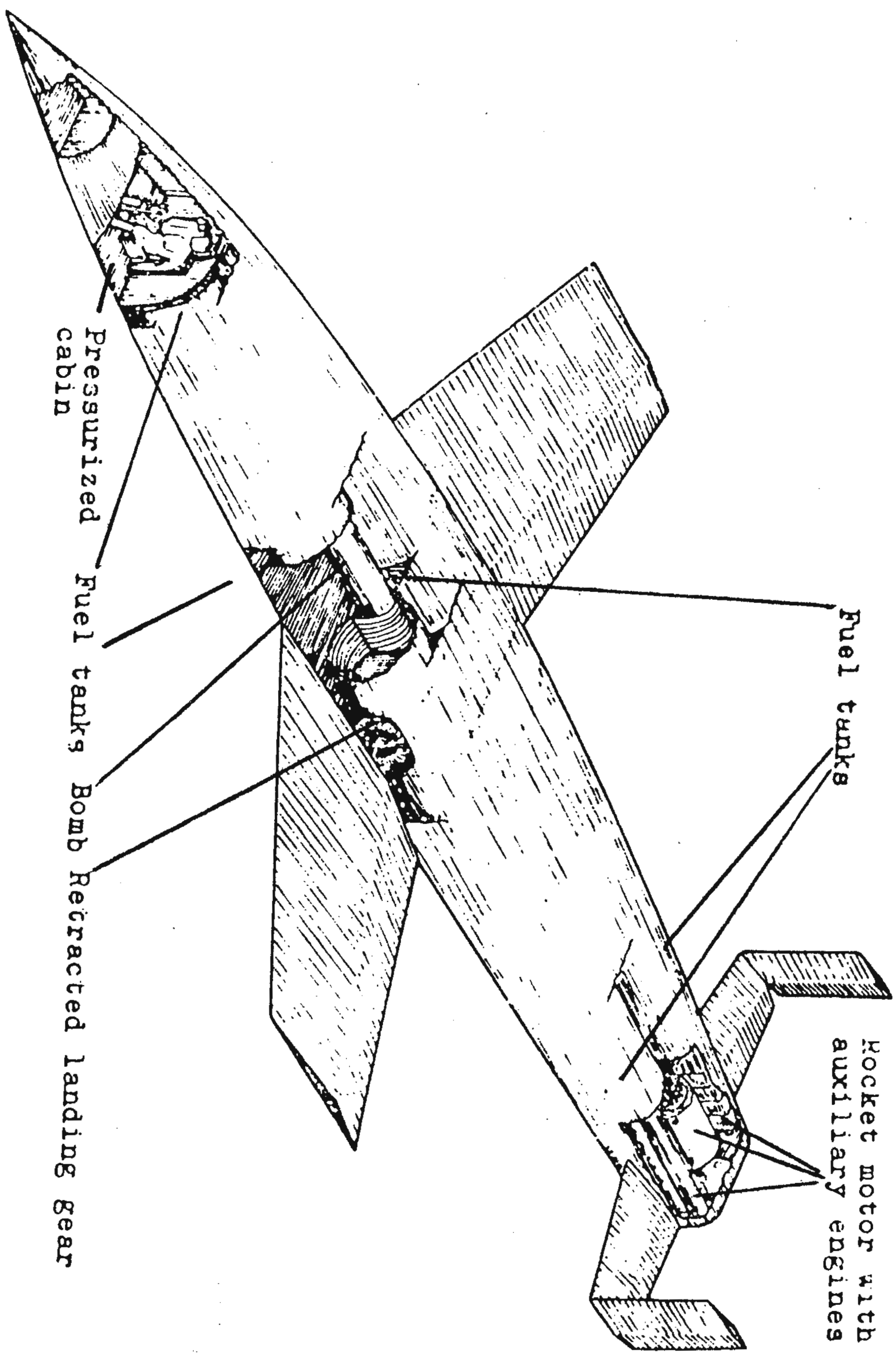
Maj. David W. Livingston, USAF

Capt. Michael V. Love, USAF

Maj. Norman L. Suits, USAF

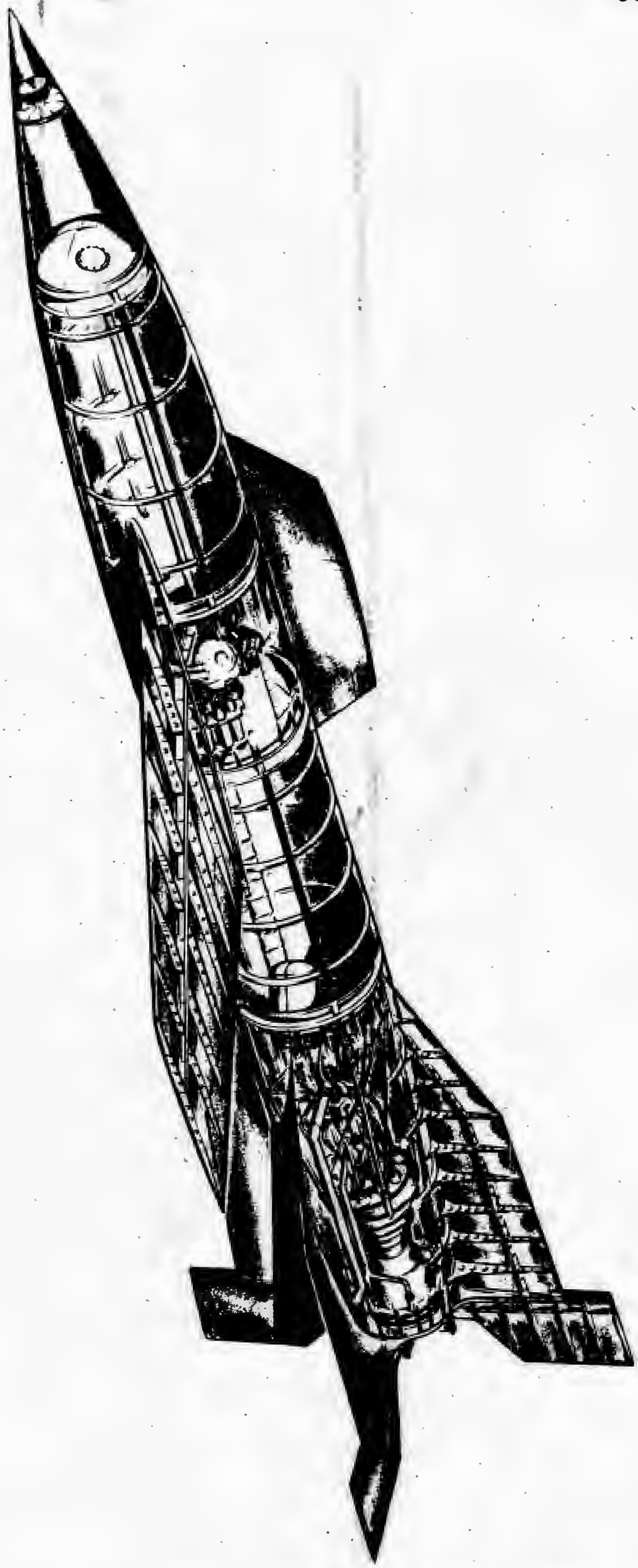
APPENDIX B

PHOTOGRAPHS AND DRAWINGS



THE SÄNGER-BREDT "SILBERVOGEL" ANTIPODAL AIRCRAFT OF 1944

Note: the drawing labels are from a postwar American translation of the Sänger-Bredt report.



A LIFTING REENTRY CRUISE DERIVATION OF THE GERMAN A-4 (V-2) MISSILE.
A PREDECESSOR, THE SIMILAR A-4b, FIRST FLEW IN 1945

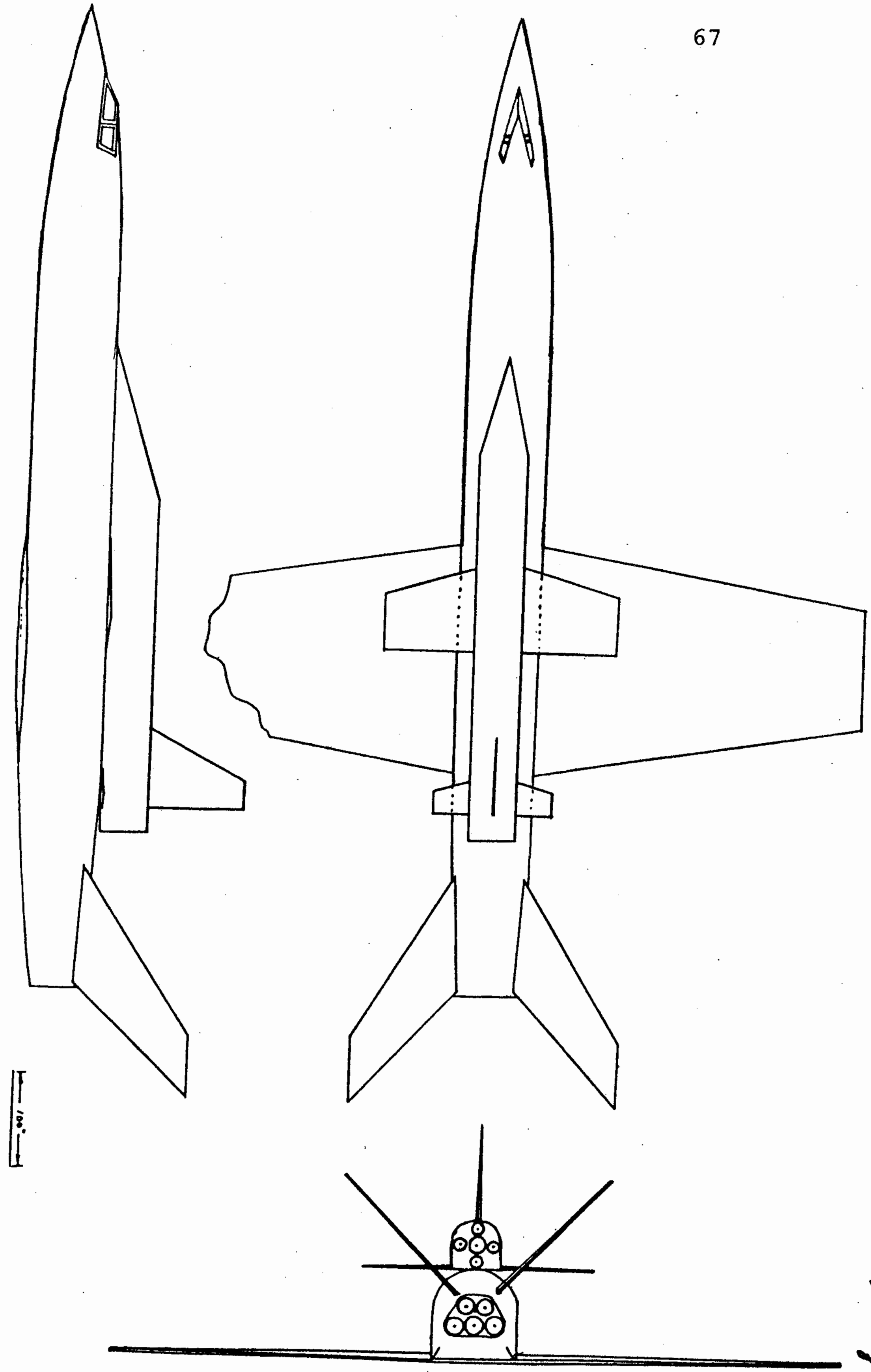
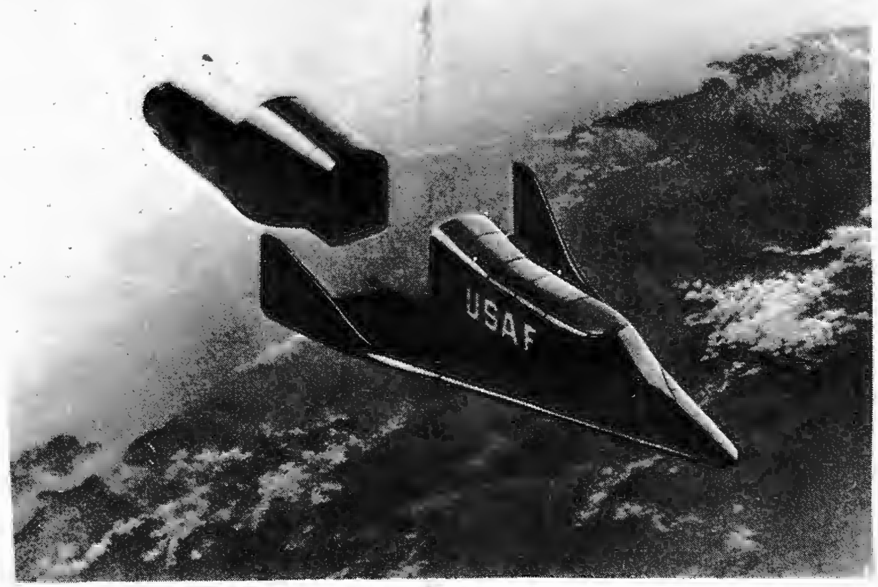


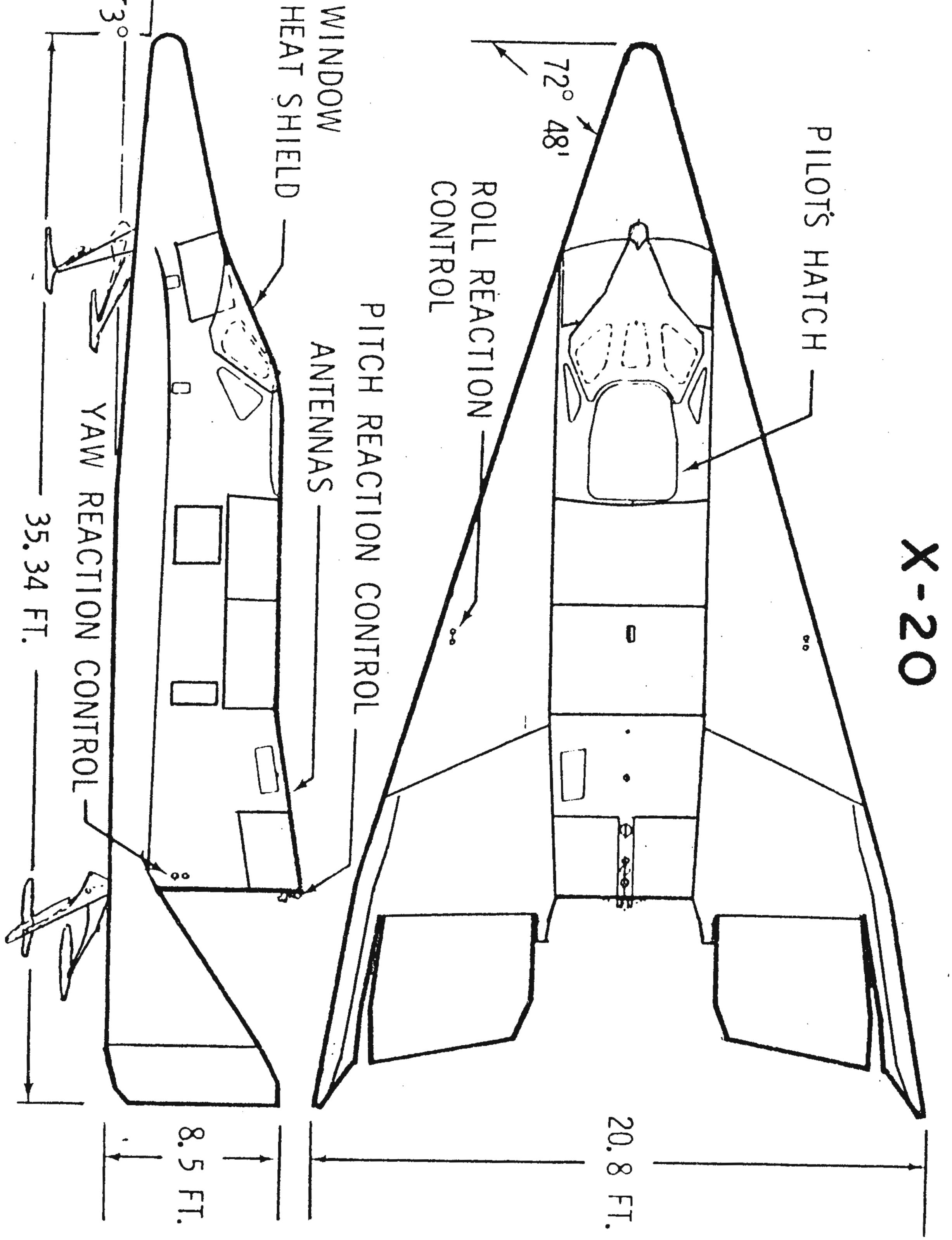
Figure 5. — Phase III airplane mounted on launcher

AN EARLY AMERICAN HYPERSONIC AIRCRAFT/ORBITER PROPOSAL: THE DRAKE-CARMAN COMPOSITE RESEARCH AIRCRAFT PROPOSAL OF 1953.

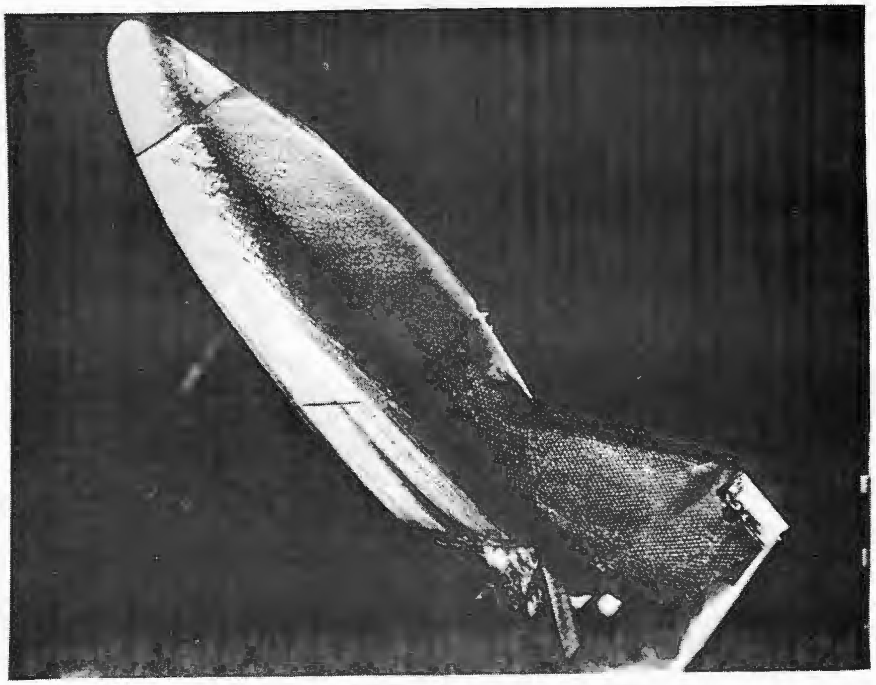
NORTH AMERICAN X-15A-2



BOEING X-20A DYNA-SOAR

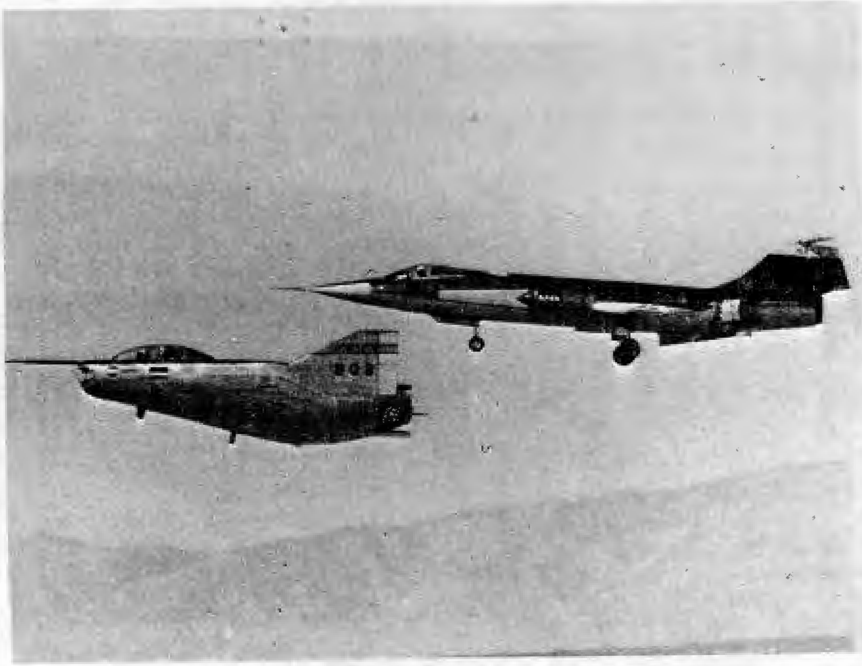


THE BOEING X-20A DYNA-SOAR ORBITAL SPACE GLIDER, 1963



MARTIN X-23A (SV-5D) PRIME FOLLOWING REENTRY

NASA FRC M2-F1

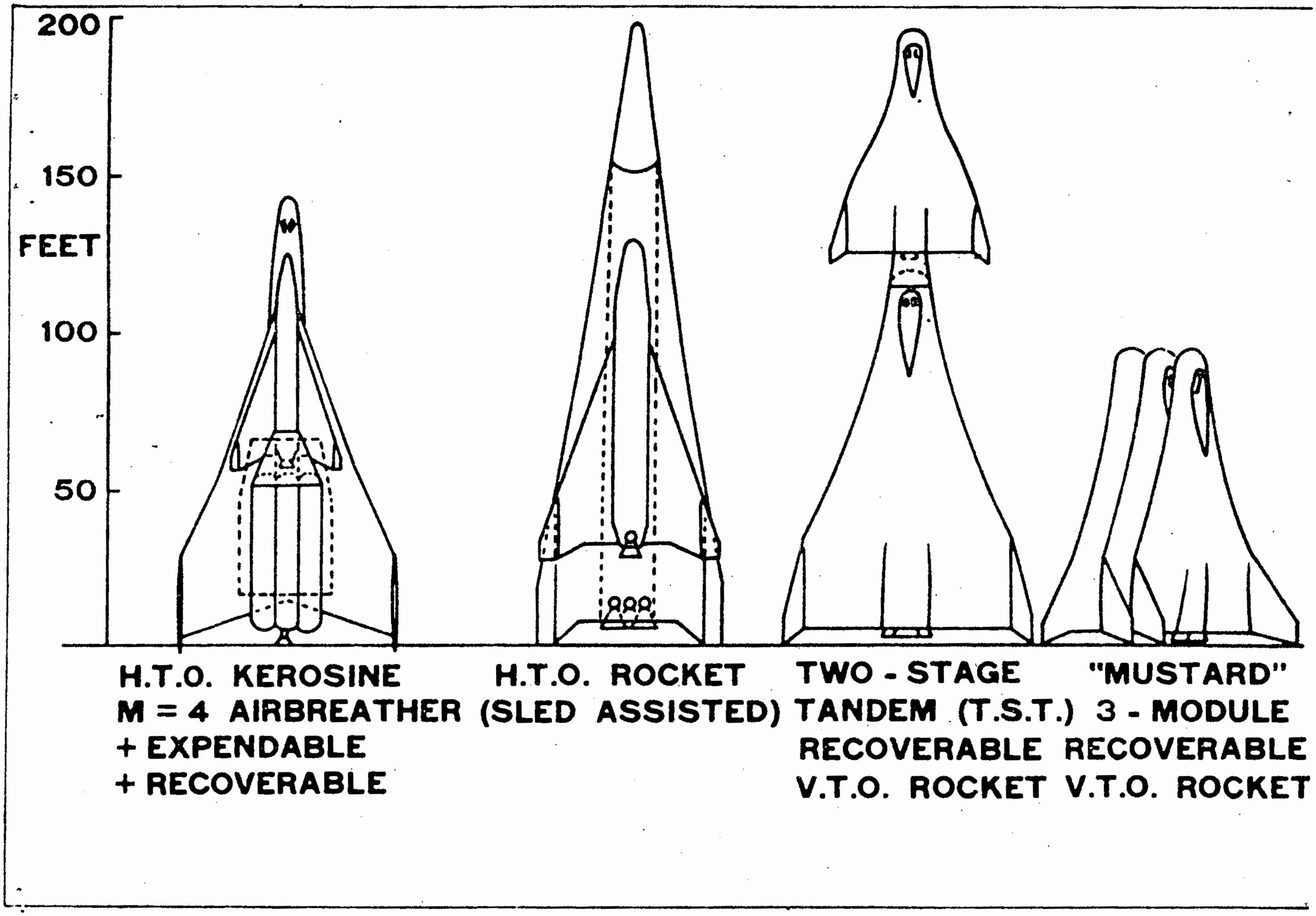


NORTHROP M2-F2 WITH LOCKHEED F-104 CHASE PLANE

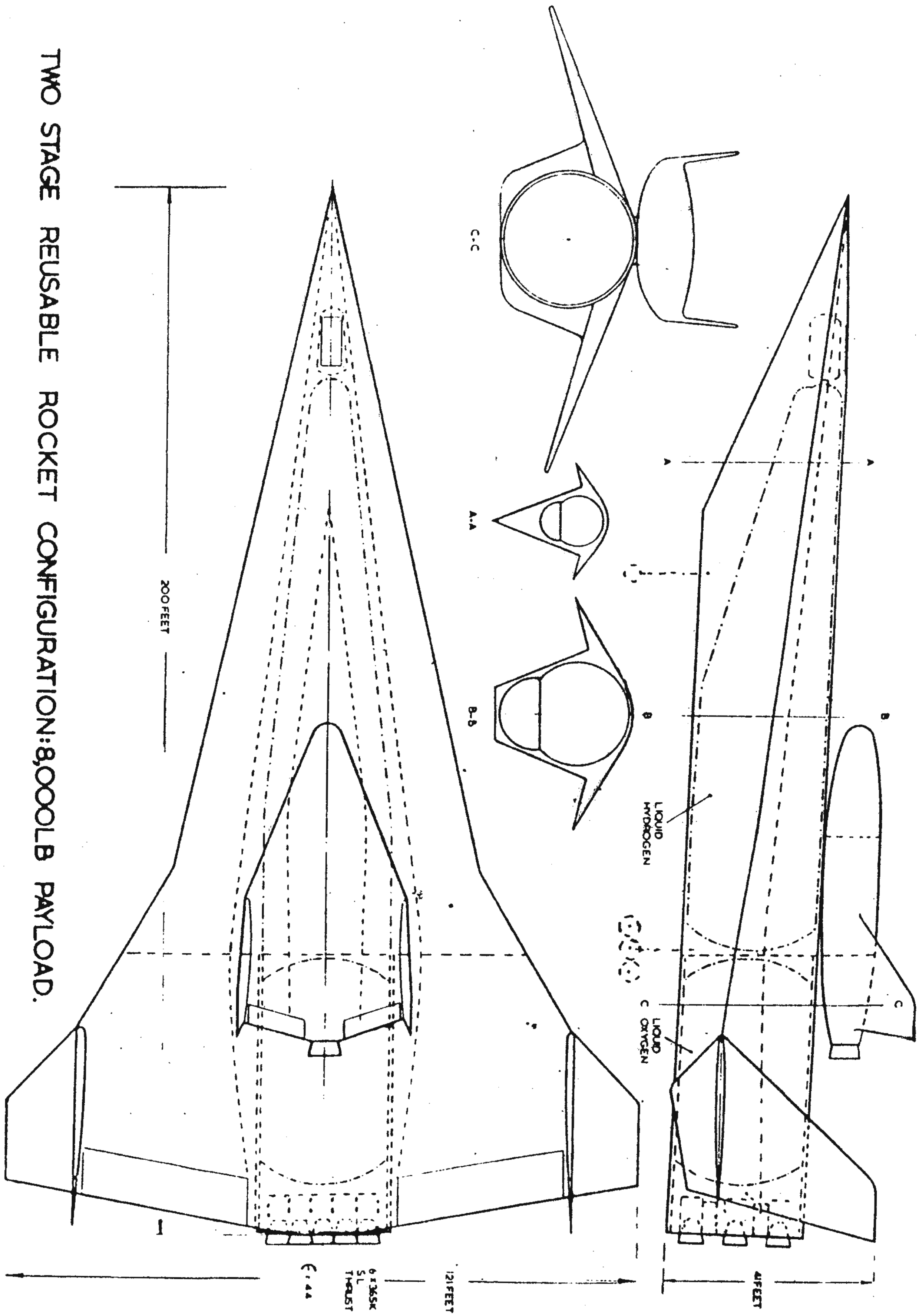
NORTHROP HL-10

MARTIN X-24A

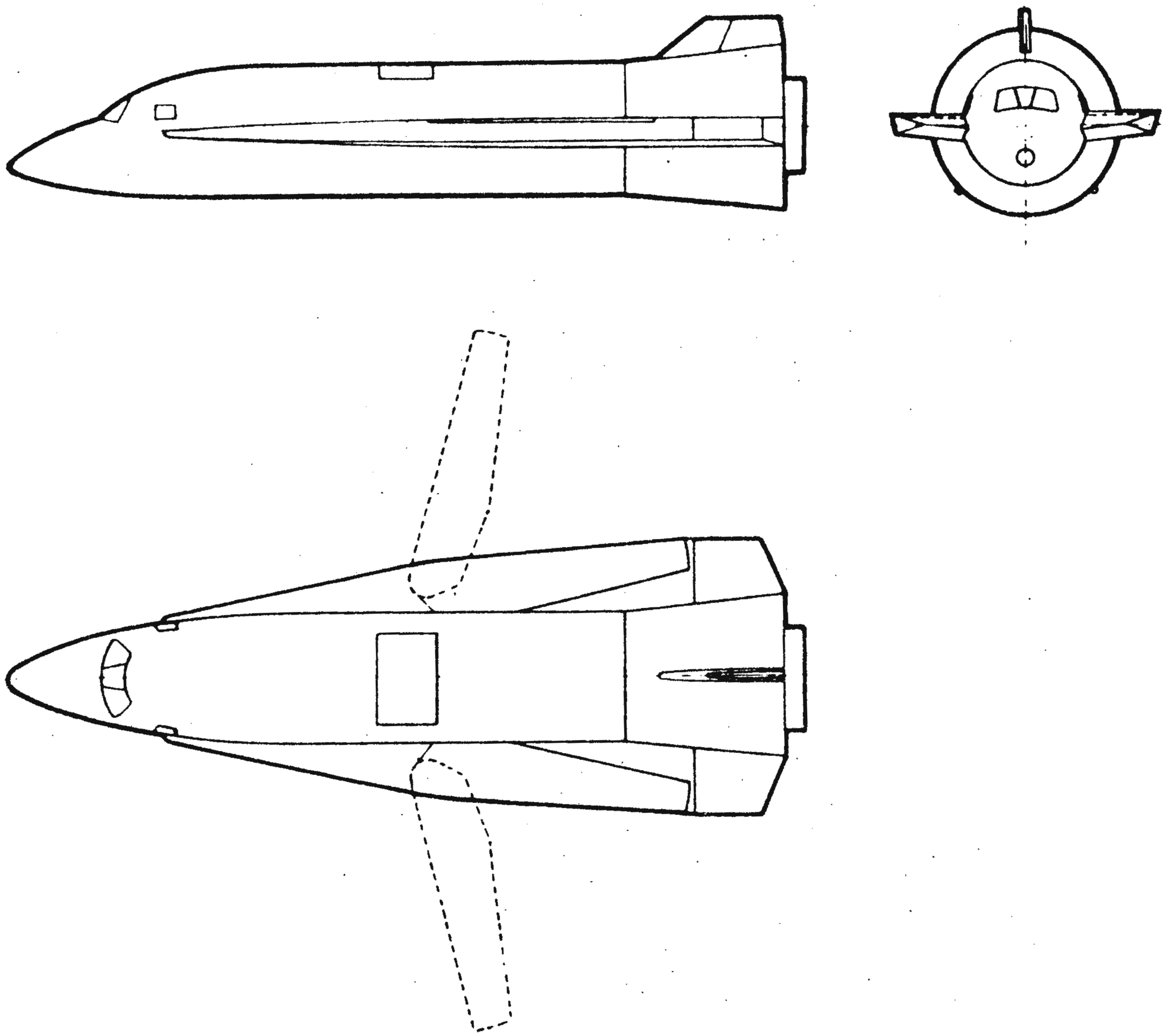
MARTIN X-24B



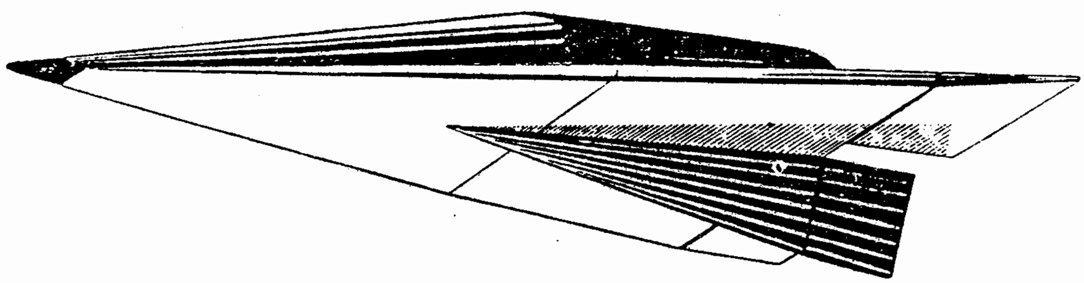
ALTERNATIVE HORIZONTAL TAKEOFF (HTO) AND VERTICAL TAKEOFF (VTO) CONCEPTS FOR A SHUTTLE EXAMINED BY THE BRITISH AIRCRAFT COMPANY IN THE MID TO LATE 1960's. MUSTARD, FAR RIGHT, EVENTUALLY EMERGED AS THE FAVORED CONCEPT BY 1971.



TWO-STAGE FULLY REUSABLE SHUTTLE POSTULATED BY HAWKER-SIDDELEY AVIATION LIMITED OF GREAT BRITAIN, 1971.

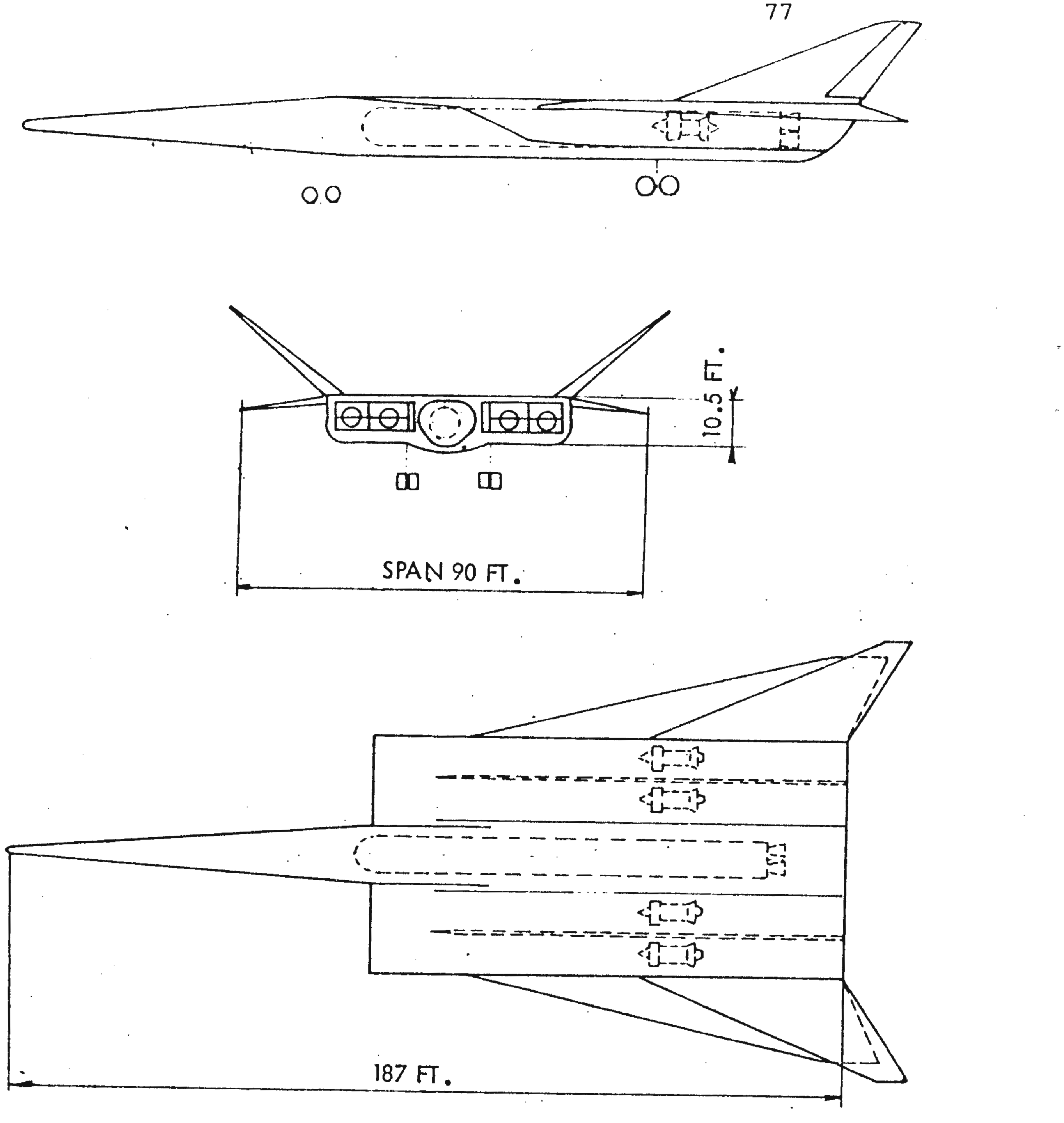


FRENCH "SPACE TAXI" PROPOSAL BY THE CENTRE NATIONAL D'ETUDES SPATEALES. THIS CRAFT, CAPABLE OF CARRYING UP TO THREE OR FOUR TONS INTO EARTH ORBIT, WOULD BE LAUNCHED FROM A HORIZONTAL TAKEOFF-TYPE WINGED AIRCRAFT POWERED BY TURBO-RAMJET PROPULSION. AFTER COMPLETING A LIFTING REENTRY, IT WOULD DEPLOY A VARIABLE-GEOMETRY WING FOR ITS FINAL GLIDE TO EARTH. APPROX. 1963-1971.



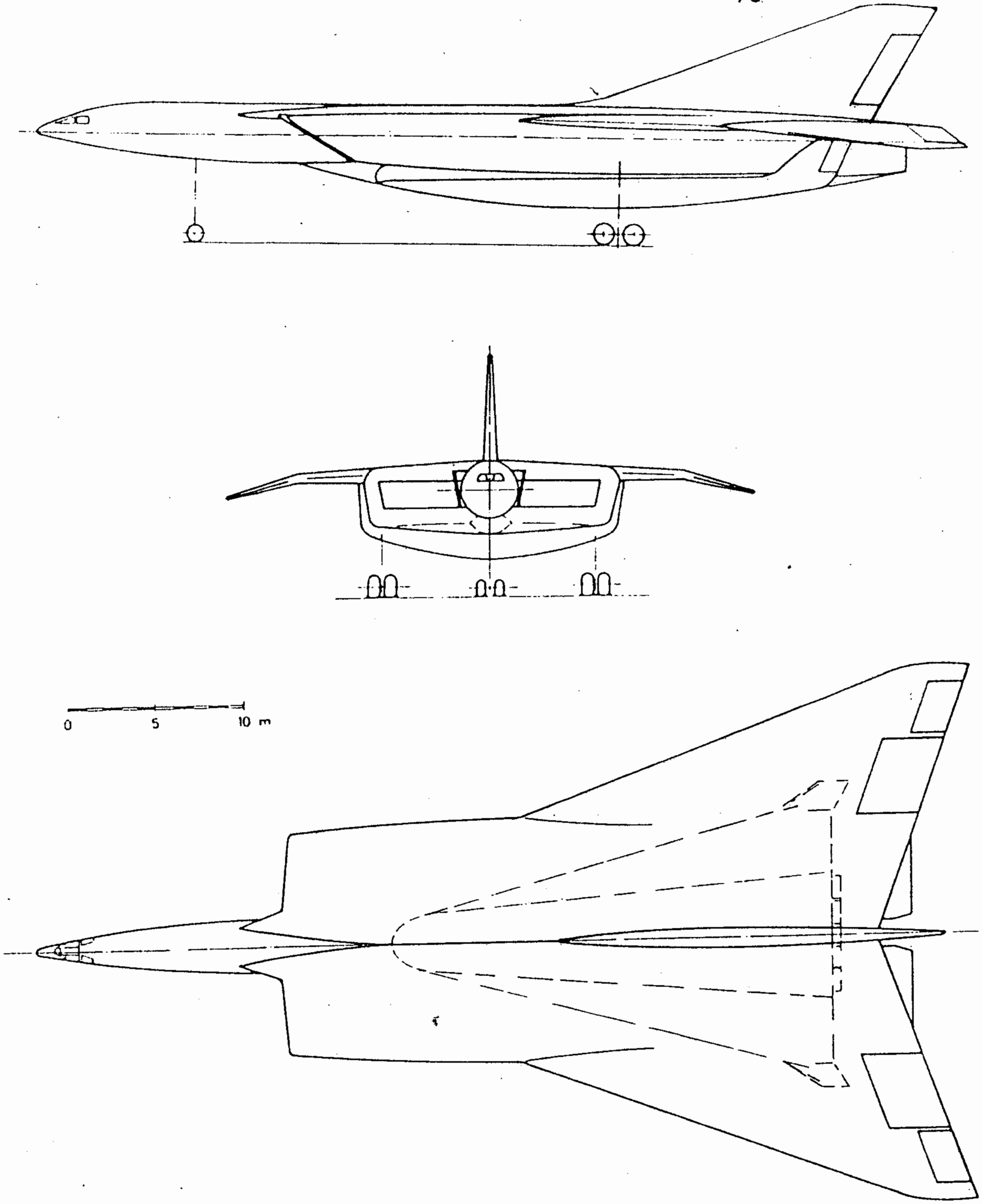
VERAS

FRENCH HYPERSONIC RESEARCH AIRCRAFT PROPOSAL. THIS PROJECT, KNOWN AS VERAS (FOR VEHICLE FOR RESEARCH IN AEROTHERMODYNAMICS AND STRUCTURES) CONSISTED OF A HIGHLY SWEPT ARROW WING HAVING A COMBINED CYLINDRO-CONICAL FUSELAGE AND, UNCHARACTERISTIC OF SUCH DESIGNS, A VENTRAL FIN. IT WOULD HAVE A MAXIMUM WEIGHT OF 3,000 LBS., AND BE CAPABLE OF A 500 SECOND DURATION MACH 10 CRUISE AT 150,000 FEET. THE VERAS CONCEPT PROVED A USEFUL TECHNOLOGICAL EXERCISE, MUCH AS THE AMERICAN X-20A PROGRAM HAD. APPROX. 1964-1971.

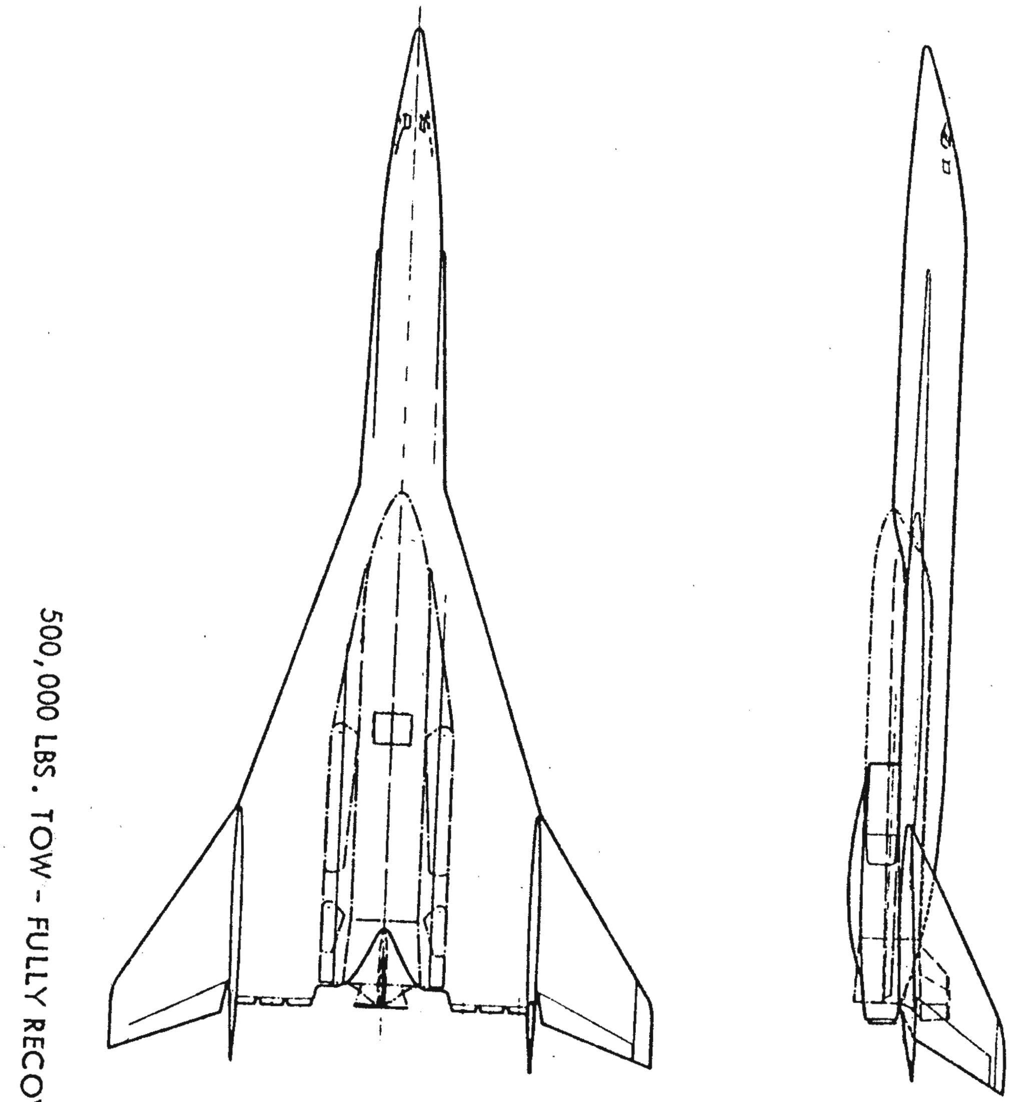


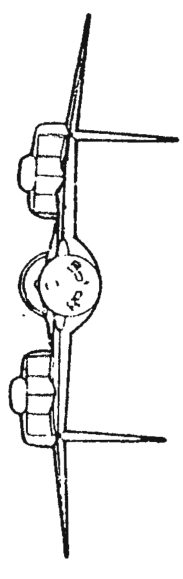
TURBOFAN-RAMJET AEROSPACE LAUNCHER
PLT/SUD-AVIATION CONCEPT

JOINT STUDY BETWEEN THE FRENCH MINISTRY OF DEFENSE AND THE SUD-AVIATION FIRM FOR A HYPERSONIC LAUNCH AIRCRAFT CAPABLE OF ACTING AS A LAUNCH PLATFORM FOR INTERNALLY HOUSED EXPENDABLE BOOSTERS. NOTE THAT THIS IS NOT A TRUE SHUTTLE CONCEPT. 1965-1971

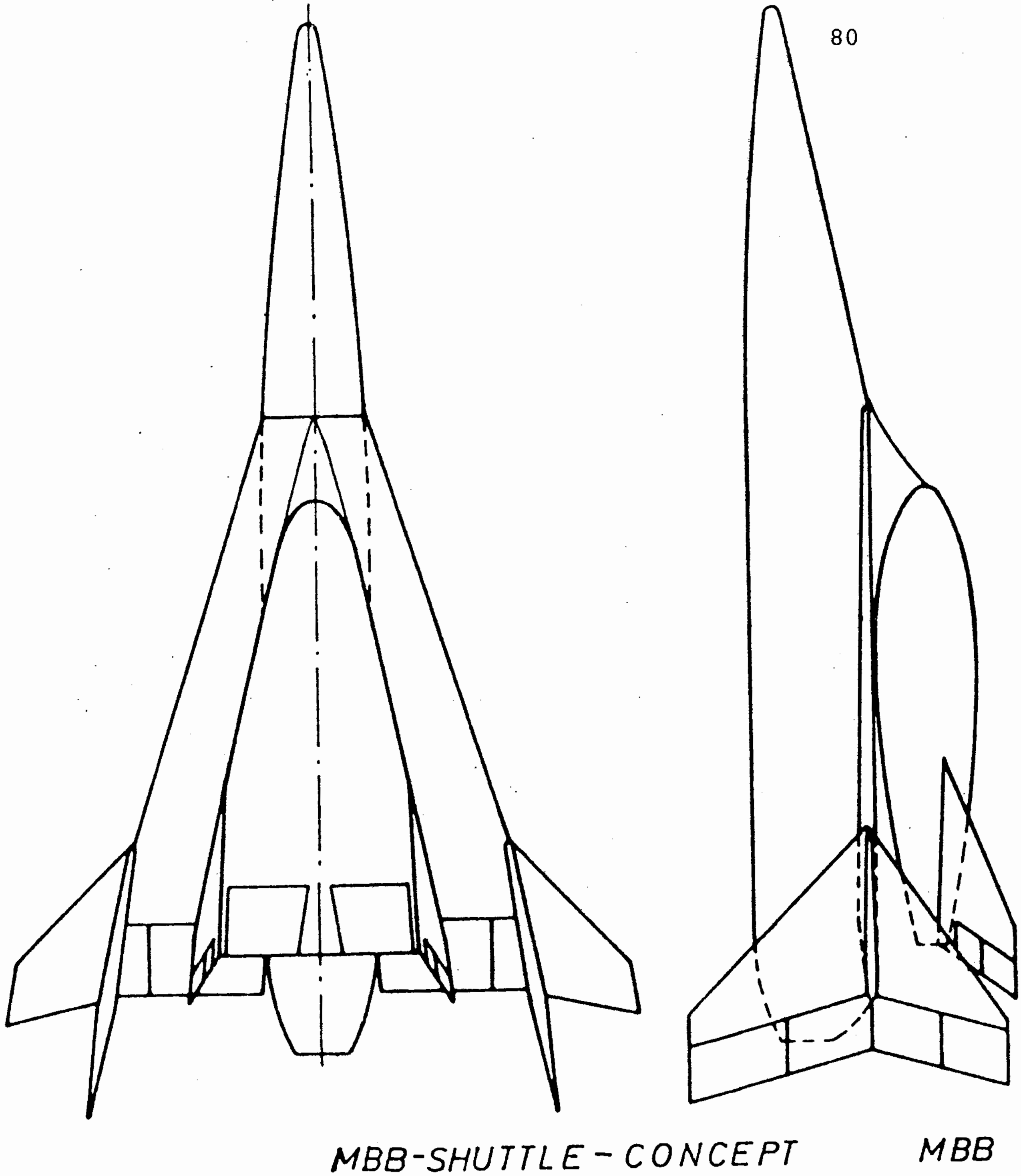


JOINT FRANCO-GERMAN COOPERATIVE SHUTTLE DESIGN STUDY BY NORD, SNECMA, AND ENTWICKLUNGSRING NORD (ERNO) FOR AN "AEROSPACE TRANSPORTER" KNOWN AS THE MISTRAL, CONSISTING OF A WINGED JET-PROPELLED LAUNCH AIRCRAFT AND A LIFTING BODY ORBITER NESTLED BENEATH IT. LATER VERSIONS OF THE MISTRAL WERE LESS ELEGANT IN APPEARANCE, AND CONFIGURED TO LAUNCH CONVENTIONAL UNMANNED UPPER STAGES. APPROX. 1965-1971

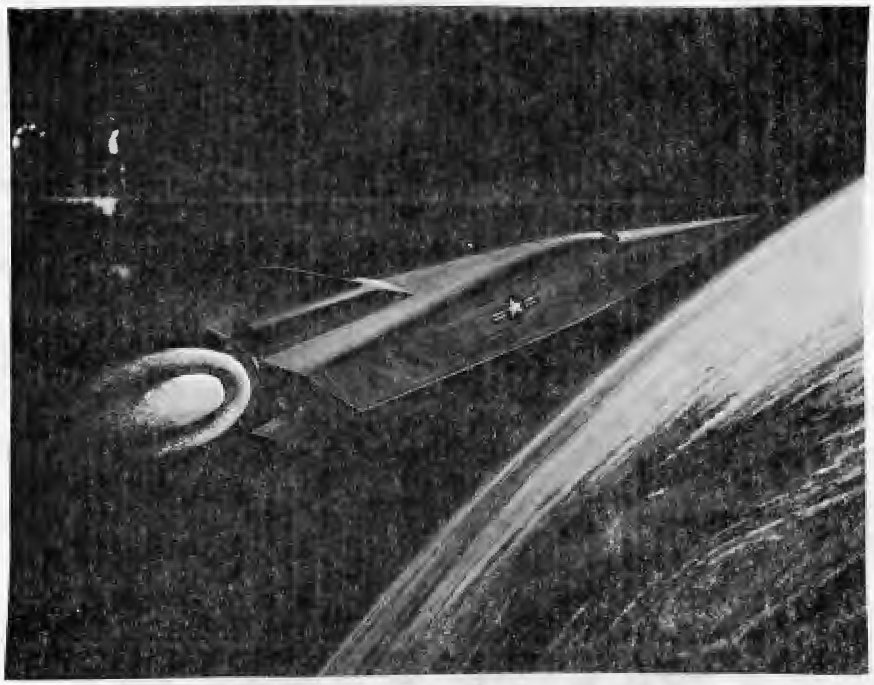




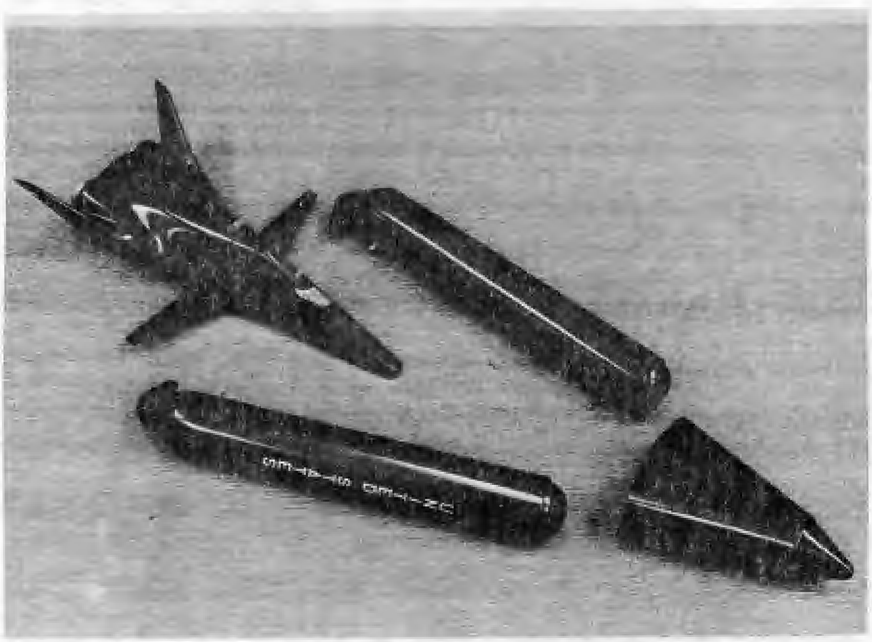
A FRENCH SHUTTLE CONCEPT BY AVIONS MARCEL DASSAULT FOR A SIX-ENGINE TURBOJET LAUNCH AIRCRAFT AND A RECOVERABLE "SPACE TAXI" REENTRY VEHICLE HAVING A 2,000 LB. PAYLOAD CAPABILITY. 1963-1971



FEDERAL REPUBLIC OF GERMANY STUDY FOR A TWO-STAGE-TO-ORBIT FULLY REUSABLE SHUTTLE BY MESSERSCHMITT-BÖLKOW-BLOHM GmbH, LATE 1960's.



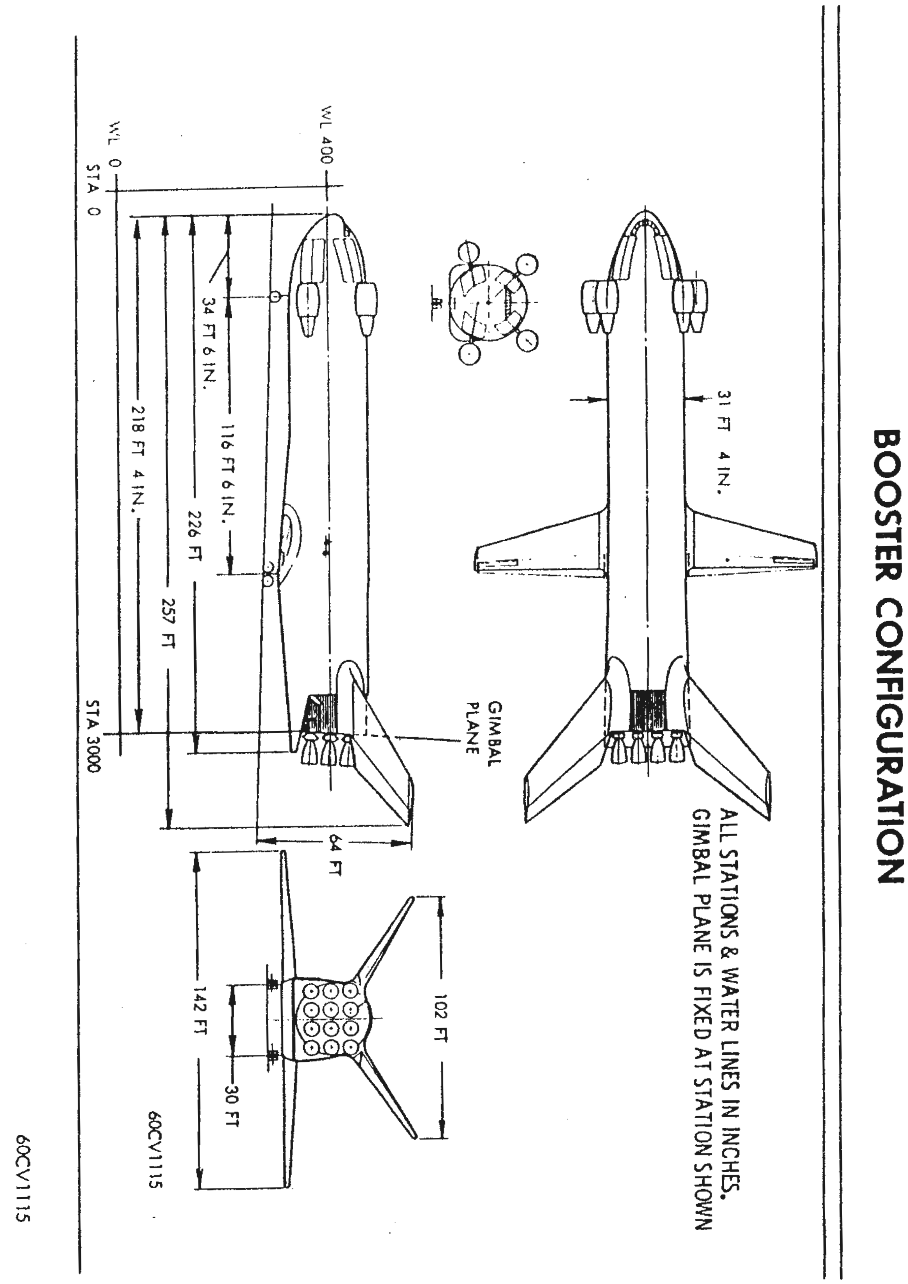
LOCKHEED-USAF FLIGHT DYNAMICS LABORATORY
MANEUVERABLE ENTRY VEHICLE PROPOSAL, 1967



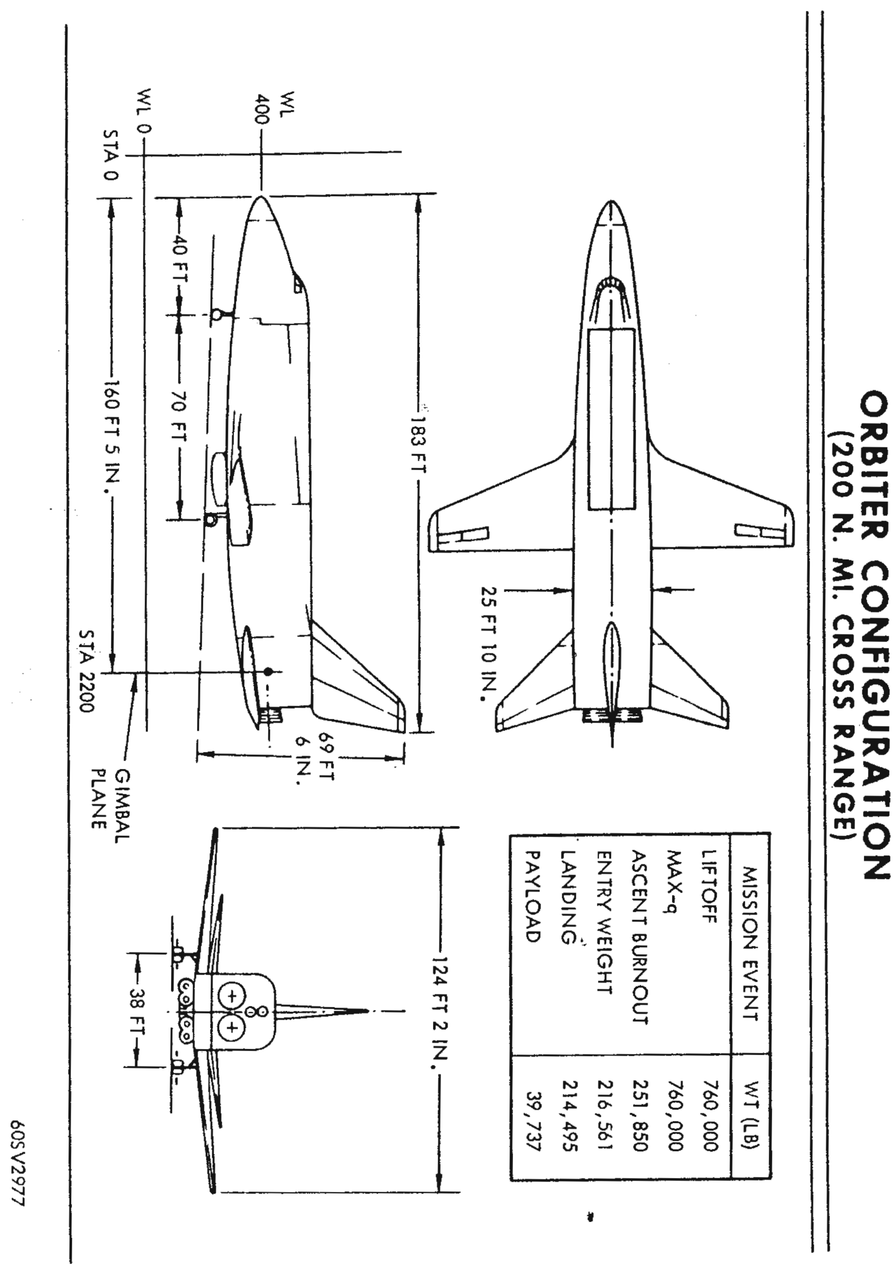
LOCKHEED "STAGE-AND-A-HALF" SHUTTLE CONCEPT, UTILIZING A VARIABLE-GEOMETRY LIFTING BODY ORBITER WITH FLANKING EXTERNAL FUEL TANKS AND NOSECAP, 1969

NASA FAGET STRAIGHT-WING BOOSTER AND ORBITER.
BOOSTER IS SIZE OF C-5A TRANSPORT. 1969

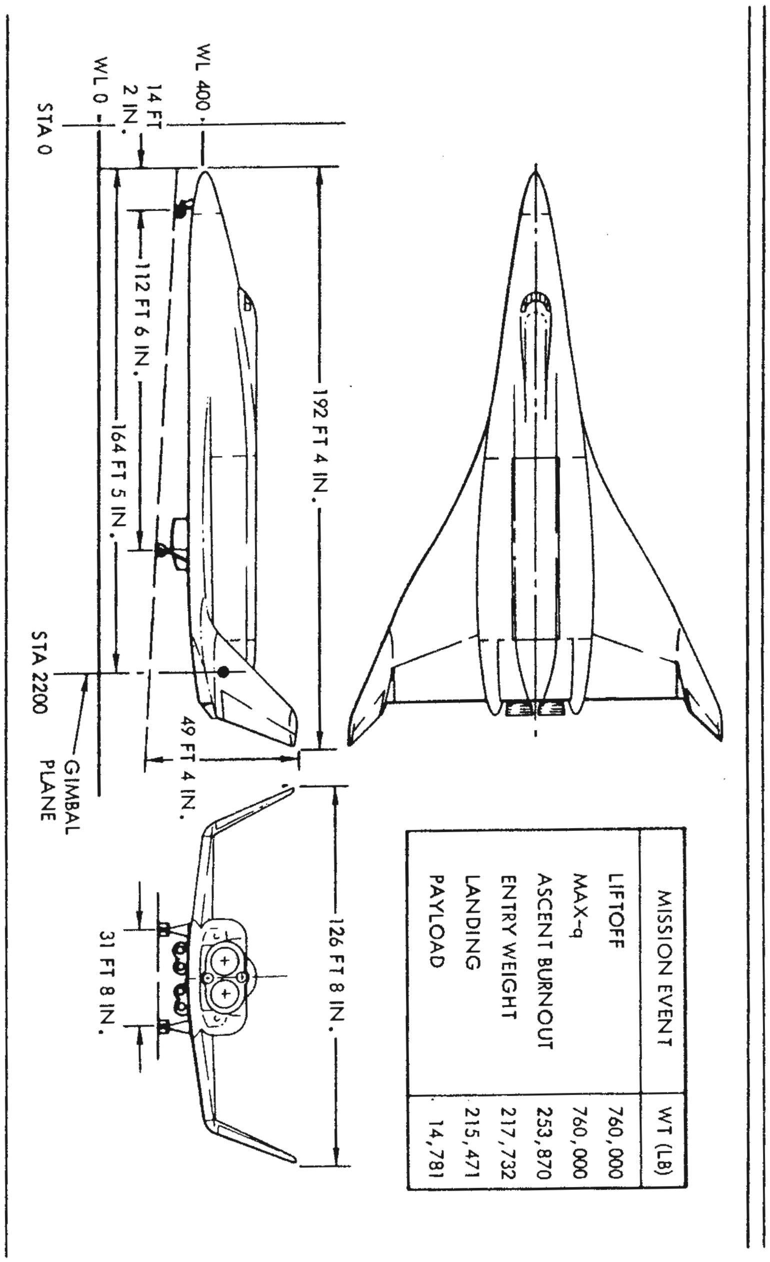
INTERMEDIATE ROCKWELL SHUTTLE DESIGN FOR FULLY
REUSABLE BLENDED WING-BODY SHUTTLE PLUS STRAIGHT
WING FAGET-STYLE BOOSTER, 1969



THIS 1970 BOOSTER CONFIGURATION PRESENTED AT A NASA MSC SHUTTLE PROGRAM TECHNICAL BASELINE BRIEFING ILLUSTRATES THE GARGANTUAN NATURE OF THE FULLY REUSABLE STUDIES. THIS BOOSTER, DESIGNED TO CARRY THE LOW OR HIGH L/D SHUTTLE CONCEPTS PRESENTED IN THE FOLLOWING TWO DRAWINGS, IS 257 FEET LONG, WITH NO LESS THAN TWELVE ROCKET ENGINES, AS WELL AS FOUR "POP OUT" TURBOFANS FOR LANDING.



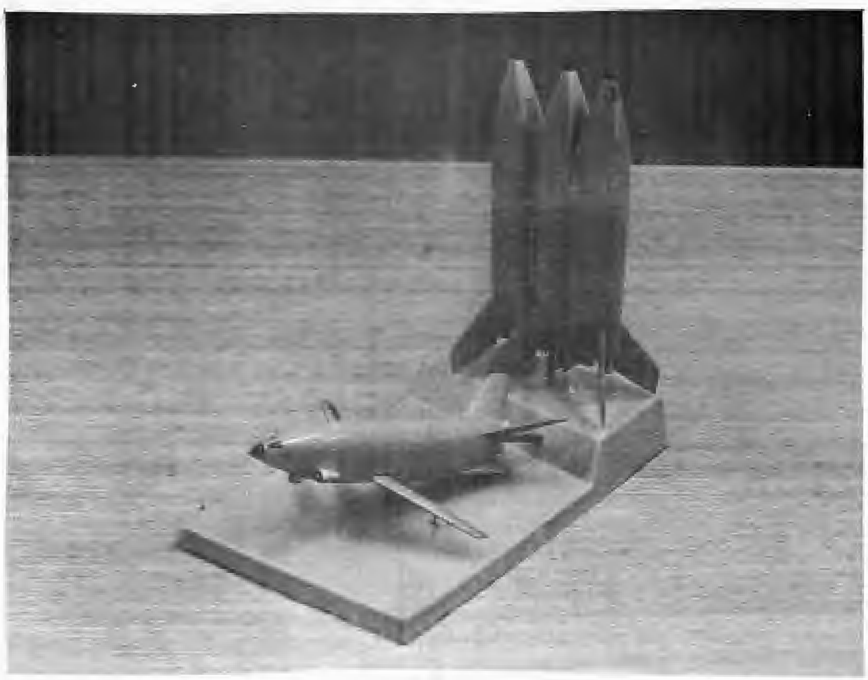
AT THE 1970 NASA MSC SHUTTLE BASELINE BRIEFING, ATTENDEES STUDIED THIS REFINED FAGET ORBITER, TO BE AIRLAUNCHED FROM THE BOOSTER ON THE PREVIOUS DRAWING. NOTE THE SMALL PAYLOAD TO ORBIT, AS WELL AS FOUR LANDING ENGINES DEPLOYED BELOW THE MID-FUSELAGE. THE 200 MILE CROSS RANGE WAS TOTALLY UNACCEPTABLE TO THE DEPARTMENT OF DEFENSE, AS WAS THE SMALL PAYLOAD TO ORBIT.



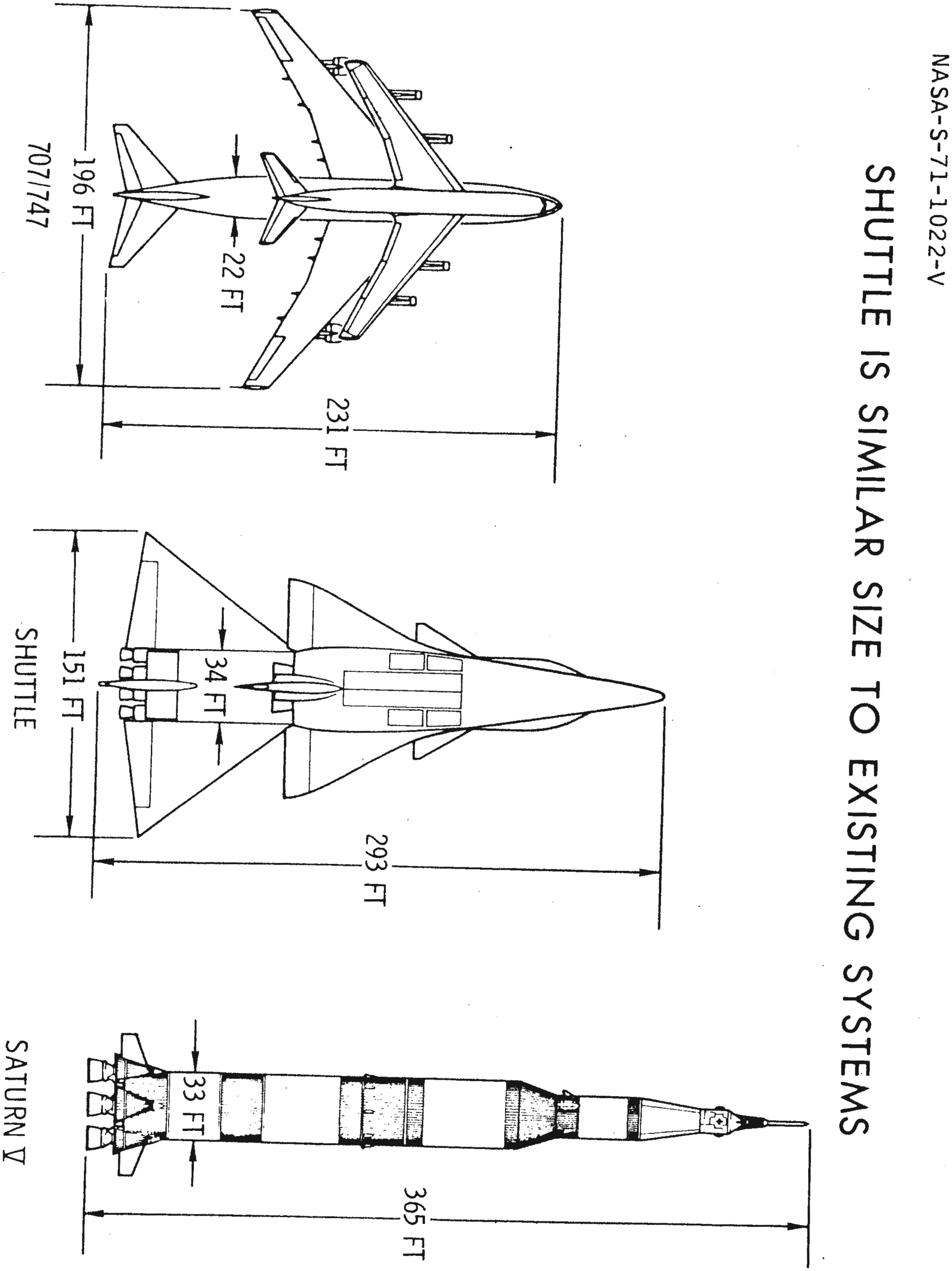
MISSION EVENT	WT (LB)
LIFTOFF	760,000
MAX-q	760,000
ASCENT BURNOUT	253,870
ENTRY WEIGHT	217,732
LANDING	215,471
PAYLOAD	14,781

THIS HIGH L/D AIR-LAUNCHED ORBITER WAS MUCH MORE ACCEPTABLE TO THE DEPARTMENT OF DEFENSE BECAUSE OF ITS CROSS RANGE CAPABILITY. HOWEVER, THE PAYLOAD WAS FAR TOO SMALL TO JUSTIFY THE DEVELOPMENT OF SUCH A COMPLEX SYSTEM. SUCH ORBITERS WERE ESSENTIALLY HUGE FLYING FUEL TANKS. WHEN SEMI-EXPENDABLE CONCEPTS WERE FIRST EXAMINED, THE ADVANTAGES OF REVERTING TO THE SPACE GLIDER CONCEPT WAS READILY APPARENT.

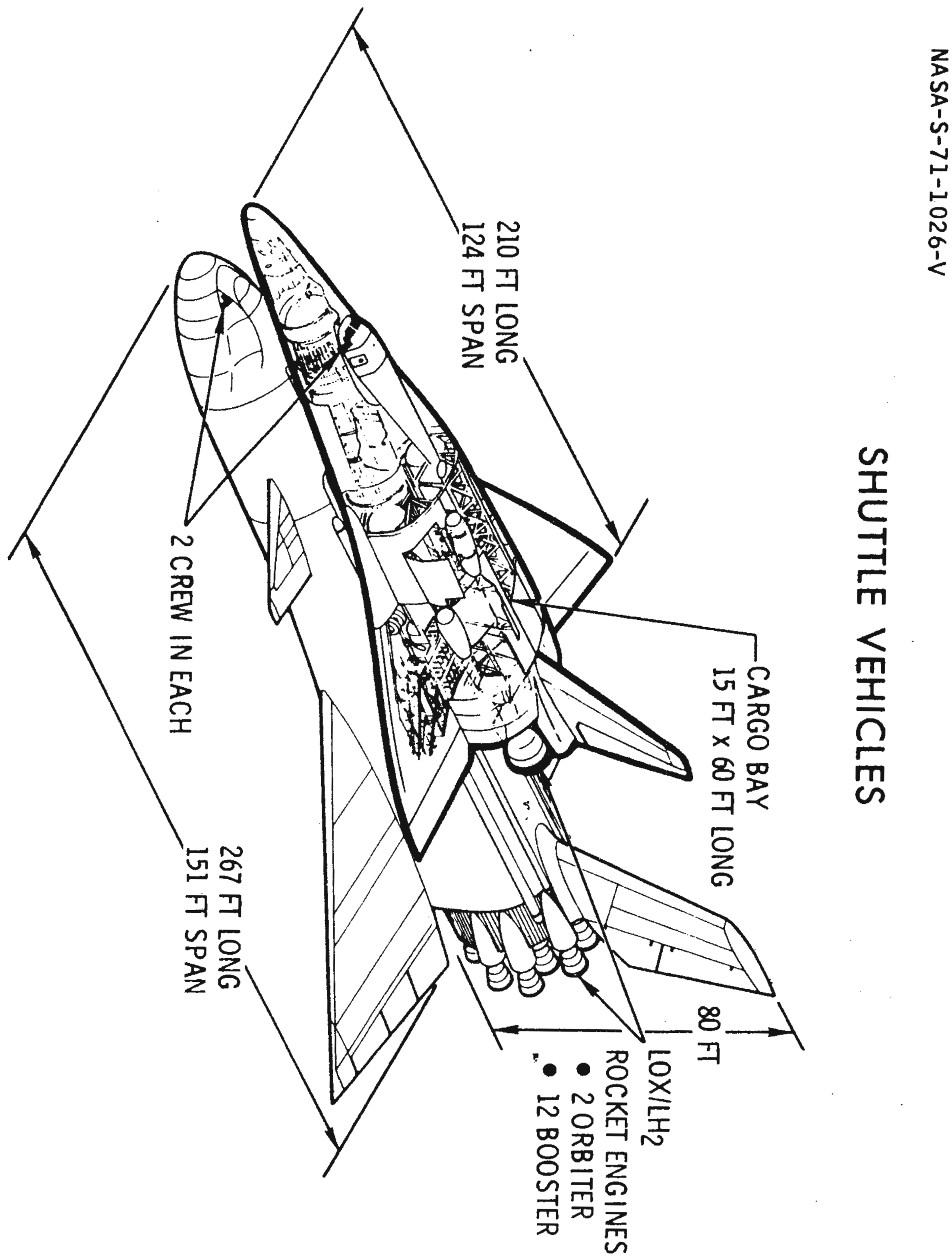
MARTIN TWO-BODY BOOSTER WITH "NESTLED" ORBITER; BOOSTER IS PILOTED AND RETURNS TO LAUNCH SITE. 1971



GENERAL DYNAMICS CONVAIR DIVISION FR-3A TRIAMESE SHUTTLE, WITH VARIABLE-GEOMETRY ORBITER. NOTE "POP OUT" LANDING ENGINES. 1971

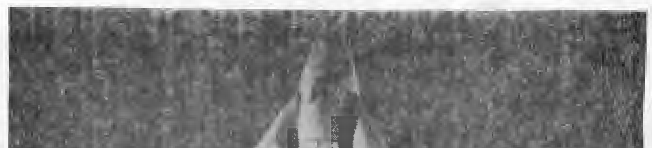


THIS 1971 NASA DRAWING GIVES EVEN MORE OF AN INDICATION OF THE IMMENSE RELATIVE SIZE OF THE FULLY REUSABLE SHUTTLE CONCEPTS

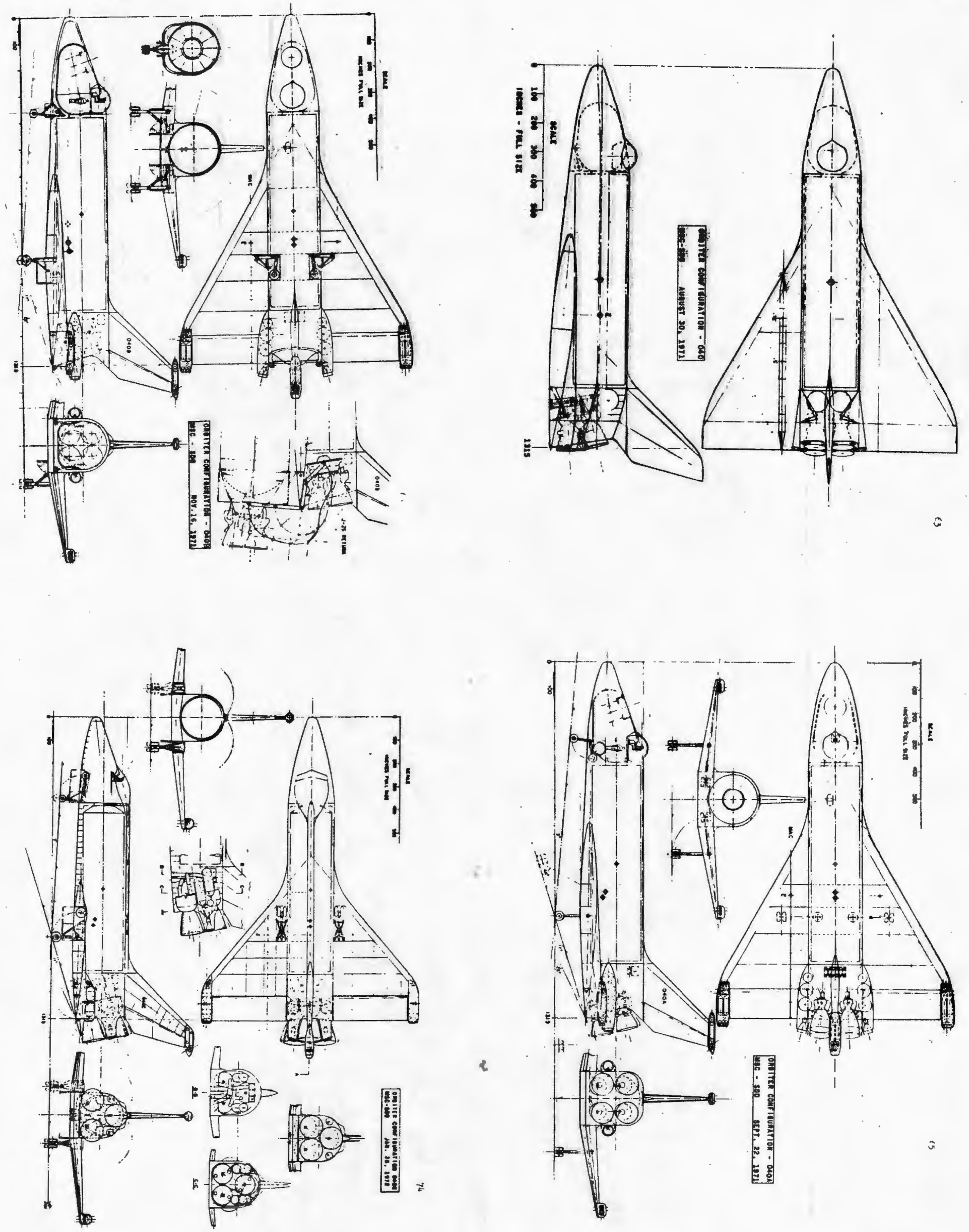


AGAIN, THIS 1971 DRAWING ILLUSTRATES THE SIZE AND COMPLEXITY CONTEMPLATED IN THE DESIGN OF THE FULLY REUSABLE SHUTTLE. AFTER THIS "LAST LOOK," SHUTTLE SUPPORTERS STUDIED SMALLER, SEMI-EXPENDABLE ORBITERS SIZED AROUND THEIR PAYLOAD BAY

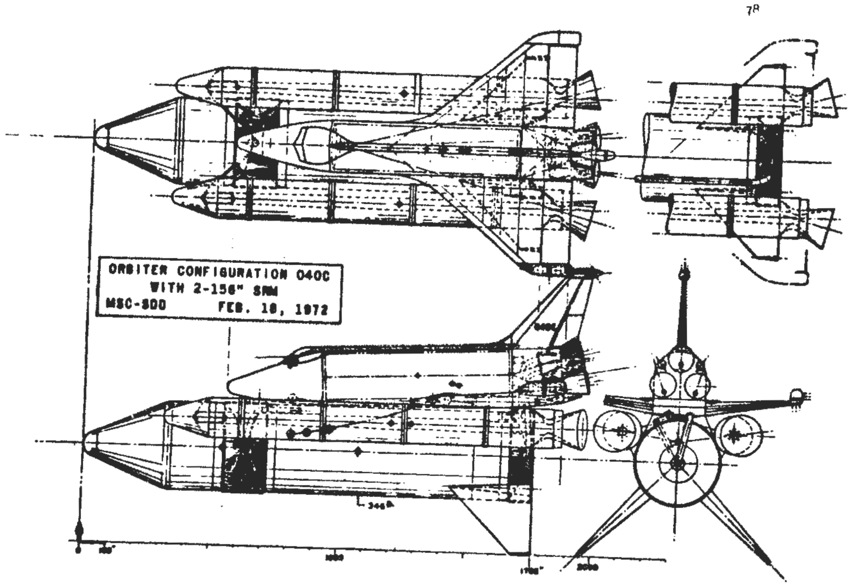
GRUMMAN-BOEING CONCEPT FOR PARTIALLY EXPENDABLE ORBITER AND FAGET-DERIVATIVE BOOSTER. TANKS FLANKING ORBITER ARE FOR LIQUID HYDROGEN. PAYLOAD CAPACITY 40,000 LBS. 1971



GRUMMAN-BOEING SHUTTLE CONCEPT USING EXPENDABLE MODIFIED SATURN S-1C BOOSTER AND JETTISONABLE HYDROGEN TANKS. 1971



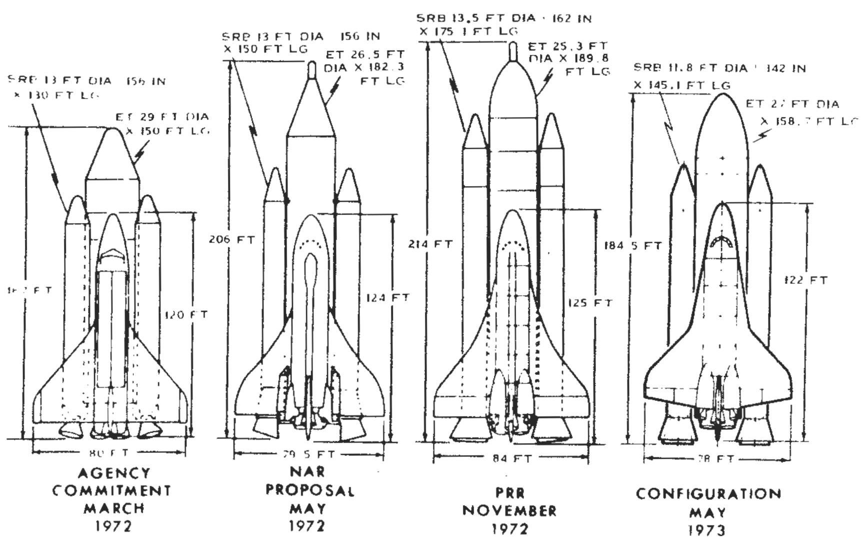
EVOLUTION OF THE NASA 040 ORBITER CONFIGURATION, 1971-1972
NOTE THE SHIFT FROM FOUR ENGINES TO THREE BY 040C (JANUARY 1972)



040C APPEARS WITH STRAP-ON SOLID FUEL BOOSTERS AND AN EXTERNAL PROPELLANT TANK, February 1972. NOTE THE FINS ON THE EXTERNAL TANK, AND THE RELATIVE POSITION OF THE STRAP-ON BOOSTERS.

SHUTTLE SYSTEMS DESIGN EVOLUTION

1972 - 1973



THE FINAL DESIGN REFINEMENT OF THE 040 ORBITER AND THE EXTERNAL TANK AND SOLID-FUEL BOOSTERS, 1972-1973. NOTE THE SMOOTHING OF SHUTTLE's EARLIER ANGULAR APPEARANCE.

THE SHUTTLE FLIES: THE ORBITER ENTERPRISE DURING THE SHUTTLE APPROACH AND LANDING TESTS, 1977

SOURCE NOTES

1. For Max Valier, see I. Essers, Max Valier: ein Vorkampfer der Weltraumfahrt, 1895-1930 (Düsseldorf: VDI-Verlag Gmbh, 1968), translated by the National Aeronautics and Space Administration as NASA TT F-664, Max Valier: A Pioneer of Space Travel (Washington, D.C.: NASA, 1976), pp. 81-97, 130-135, 248. See also Max Valier, Der Vorstoss in den Weltenraum: eine technische Möglichkeit (Munich: Verlag von R. Oldenbourg, 1924).

For the work of other pioneers mentioned, see A. A. Blagonravov, ed., K. E. Tsiolkovskiy: Sobraniye Sochineniy, Tom II Reaktivnyye Letatel'nyye Apparaty (Moscow: Izdatel'stvo Akademii Nauk SSSR, 1954), translated by the National Aeronautics and Space Administration as NASA TT F-237, Collected Works of K. E. Tsiolkovskiy, v. II Reactive Flying Machines (Washington, D.C.: NASA, 1965), pp. 528-530; Robert H. Goddard, "A Method of Reaching Extreme Altitudes," in Esther C. Goddard and G. Edward Pendray, eds., The Papers of Robert H. Goddard, v. I: 1898-1924 (New York: McGraw-Hill Book Company, 1970), pp. 337-406; Herman Oberth, Die Rakete zu den Planetenräumen (Munich: Verlag von R. Oldenbourg, 1923).

General introductions to early spacecraft conceptions can be found in Noel Deisch, "Navigation of Space in Early Speculation," Popular Astronomy (February 1930), pp. 73-88; W. R. Maxwell, "Some Aspects of the Origins and Early Development of Astronautics," British Interplanetary Society Journal (Sept.-Dec. 1962), pp. 415-425; and G. Edward Pendray, "Pioneer Rocket Development in the United States," in Eugene M. Emme, ed., The History of Rocket Technology: Essays on Research, Development, and Utility (Detroit: Wayne State University Press, 1964), pp. 19-20.

2. Werner Schulz, "Walter Hohmann's Contributions Towards Space Flight: An Appreciation on the Occasion of the Centenary of his Birthday," paper presented at the XXXth Congress, International Astronautical Federation, Munich, FRG, Sept. 21, 1979; Walter Hohmann, Die Erreichbarkeit der Himmelskörper (Munich: Verlag

von R. Oldenbourg, 1925); translated by the National Aeronautics and Space Administration as NASA TT F-44, The Attainability of Heavenly Bodies (Washington, D.C.: NASA, 1960).

3. Eugen Sänger, Raketenflugtechnik (Munich: Verlag von R. Oldenbourg, 1933), translated as NASA TT F-223, Rocket Flight Engineering (Washington, D.C.: NASA, 1965); Eugen Sänger, "Neuere Ergebnisse der Raketenflugtechnik," Flug: Zeitschrift für das gesamte Gebiet der Luftfahrt (December 1934), pp. 10-22; Irene Sänger-Bredt, "The Silver Bird Story: A Memoir," in R. Cargill Hall, ed., Essays of the History of Rocketry and Astronautics: Proceedings of the Third Through the Sixth History Symposia of the International Academy of Astronautics, v. I (Washington, D.C.: NASA, 1977), pp. 195-228.

4. Eugen Sänger and Irene Bredt (later Irene Sänger-Bredt), Über einen Raketenantrieb für Fernbomber, Deutsche Luftfahrtforschung UM 3538 (Ainring: DFS, Aug. 1944), translated by the Naval Technical Information Branch, Bureau of Aeronautics, United States Navy, as Translation CGD-32, A Rocket Drive for Long-Range Bombers (1952); Sänger-Bredt, "Silver Bird," pp. 209-212.

5. Wernher von Braun, "German Rocketry," in Arthur C. Clarke, ed., The Coming of the Space Age (New York: Meredith Press, 1967), pp. 54-55; Frederick I. Ordway and Mitchell R. Sharpe, The Rocket Team (New York: Thomas Y. Crowell Publishers, 1979), pp. 54-57; Walter Dornberger, V-2 (New York: The Viking Press, 1958), pp. 250-251; Rowland F. Pocock, German Guided Missiles of the Second World War (New York: Arco Publishing Company, 1967), pp. 98-99. See also Wasserbau-Versuchsanstalt Kochelsee Gmbh, Die Aerodynamische Entwicklung der Fernrakete A9 (A4b), Archiv Nr. 190 (Kochel: WVA, July 10, 1945).

6. See Walter C. Williams and Hubert M. Drake, "The Research Airplane: Past, Present, and Future," Aeronautical Engineering Review (January 1958), pp. 36-41; Kenneth S. Kleinknecht, "The Rocket Research Airplanes," in Eugene M. Emme, The History of

Rocket Technology, pp. 189-211; Richard P. Hallion, "American Rocket Aircraft: Precursors to Manned Flight Beyond the Atmosphere," paper presented at the XXVth Congress, International Astronautical Federation, Amsterdam, The Netherlands, Oct. 4, 1974; Richard P. Hallion, Supersonic Flight: Breaking the Sound Barrier and Beyond (New York: The Macmillan Company, 1972).

7. See, for example, Williams and Drake, "The Research Airplane," and Kleinknecht, "The Rocket Research Airplanes," passim.

8. John V. Becker, "The X-15 Program in Retrospect," Raumfahrtforschung (March-April 1969), p. 45. The "Sänger grab" attempt is briefly discussed in Sänger-Bredt, "Silver Bird," p. 215.

9. Hsue-shen Tsien, "Instruction and Research at the Daniel and Florence Guggenheim Jet Propulsion Center," Journal of the American Rocket Society (June 1950), p. 63.

10. For general history of such studies in this time period, see NASA Langley Research Center staff report, "Conception and Research Background of the X-15 Project" (Hampton, VA: NASA LRC, June 1962), and NASA Langley Research Center staff report (draft document) "History of NACA-Proposed High-Mach Number, High-Altitude Research Airplane," (Hampton, VA: NASA LRC, n.d.), the latter hereafter referred to as NACA X-15 Origins, pp. 2-3. Both of these are in the files of the NASA History Office, Washington, D.C.

Woods' proposals are in the meeting minutes of the NACA Committee on Aerodynamics, Oct. 4, 1951, Jan. 30, 1952, and June 24, 1952, in Record Group 255, National Archives, Washington, D.C.

Hubert M. Drake and L. Robert Carman's "A Suggestion of Means for Flight Research at Hypersonic Velocities and High Altitudes" (Edwards, CA: NACA High-Speed Flight Research Station, n.d.), and "Suggested Program for High-Speed, High-Altitude Flight Research," (Edwards, CA: NACA HSFRS, August 1953), are in the NASA History Office archives, Washington, D.C.

For SAB interest, see Thomas A. Sturm, The USAF Scientific Advisory Board: Its First Twenty Years, 1944-1964 (Washington, D.C.: USAF Historical Division Liaison Office, Feb. 1, 1967), p. 59;

The ONR-Douglas project is detailed in Douglas Aircraft Company Summary Report for Contract Nonr 1266(00), "High Altitude and High-Speed Study," (El Segundo, CA: DAC, May 28, 1954), in the corporate files of the McDonnell-Douglas Corporation, Douglas Aircraft division, Long Beach, California. I also wish to acknowledge the assistance of Douglas engineer Edward H. Heinemann's letter to me of Feb. 10, 1972.

See also John V. Becker, "The X-15 Project," Astronautics & Aeronautics (February 1964), pp. 52-61.

11. NACA Research Airplane Projects Panel meeting minutes, Feb. 4-5, 1954, from the files of the NASA Langley Research Center; NACA X-15 Origins, pp. 4-45; Interview with John V. Becker, NASA Langley Research Center, Nov. 12, 1971; Hallion, "American Rocket Aircraft;" Robert S. Houston, Development of the X-15 Research Aircraft, 1954-1959, v. III of History of Wright Air Development Center, 1958 (Dayton, OH: Wright-Patterson AFB, Office of Information Services, June 1959), pp. 3-13; 17-21; 82-127; 184-185.

12. John V. Becker, "Principal Technology Contributions of X-15 Program," (NASA Langley Research Center, Oct. 8, 1968); Becker, "The X-15 Program in Retrospect."

13. An excellent summation of early X-15 research can be found in Wendell H. Stillwell's X-15 Research Results, NASA SP-60 (Washington, D.C.: NASA, 1965), and Joseph Weil's NASA Technical Note D-1278, Review of the X-15 Program (Washington, D.C.: NASA, June 1962). See also James E. Love, "X-15: Past and Future," paper presented at the Fort Wayne Section, Society of Automotive Engineers, Dec. 9, 1964; and Walter C. Williams, "The Role of the Pilot in the Mercury and X-15 Flights," Proceedings of the XIVth

AGARD General Assembly, NATO, Sept. 16-17, 1964, Lisbon, Portugal.

14. Richard P. Hallion, "X-15: Highest and Fastest of Them All," Flight International (Dec. 23, 1978), pp. 2256-2257, 2258, 2262. The X-15A-2 program is discussed in detail in Johnny G. Armstrong's Flight Planning and Conduct of the X-15A-2 Envelope Expansion Program, AFFTC-TD-69-4 (Edwards AFB: Air Force Flight Test Center, 1969), passim.

15. Becker, "X-15 Program in Retrospect;" Sänger-Bredt, "Silver Bird," pp. 223-224.

16. For Brown study group report, see C. E. Brown, et. al., "A Study of the Problems Relating to High-Speed High-Altitude Flight," (Hampton: NACA Langley Laboratory, June 25, 1953), in the files of the NASA Langley Research Center.

Von Braun's conceptual studies are detailed in Willy Ley and Chesley Bonestell's The Conquest of Space (New York: The Viking Press, 1956); Wernher von Braun "Prelude to Space Travel," in Cornelius Ryan, ed., Across the Space Frontier (New York: The Viking Press, 1953), pp. 12-70; Willy Ley and Wernher von Braun, The Exploration of Mars (New York: The Viking Press, 1956).

The Dornberger-Ehricke project is discussed in Willy Ley's Rockets, Missiles, and Men in Space (New York: The Viking Press, 1968), pp. 449-450.

A generally useful introduction to the lifting reentry work of the 1950's is E. P. Smith's "Space Shuttle in Perspective: History in the Making," presented at the XIth Annual Meeting of the American Institute of Aeronautics and Astronautics, Washington, D.C., Feb. 24-26, 1975.

17. For Dyna-Soar origins, see Clarence J. Geiger, *History of the X-20A Dyna-Soar*, v. I (Historical Division, Aeronautical Systems Division, Air Force Systems Command, Oct. 1963), pp. ix-x, 4-28; Kleinknecht, "The Rocket Research Airplanes," pp. 209-210; Eugene M. Emme, *Aeronautics and Astronautics: An American Chronology of Science and Technology in the Exploration of Space, 1915-1960* (Washington, D.C.: NASA, 1961), pp. 83, 85; the ballistic vs. lifting reentry approach and USAF-NACA relationships on the emerging Dyna-Soar effort is discussed in Loyd S. Swenson, James M. Grimwood, and Charles C. Alexander, *This New Ocean: A History of Project Mercury* (Washington, D.C.: NASA, 1966), pp. 71, 73-74. See also Robert R. Gilruth, "From Wallops Island to Project Mercury, 1945-1958: A Memoir," in R. Cargill Hall, ed., *Essays on the History of Rocketry and Astronautics: Proceedings of the Third Through the Sixth Symposia of the International Academy of Astronautics*, v. II (Washington, D.C.: NASA, 1977), pp. 463-465.

18. Geiger, *History of the X-20A Dyna-Soar*, pp. 29-49.

19. *Ibid.*, pp. 55-121. Details of the cancellation can be found in Geiger's subsequent *History of Aeronautical Systems Division, July-Dec. 1963*, v. III, *Termination of the X-20A Dyna-Soar* (Historical Division, Aeronautical Systems Division, Air Force Systems Command, Sept. 1964), *passim*. For Congressional and DoD criticism of the Dyna-Soar program and its impact upon AF planners, see Robert Frank Futrell, *Ideas, Concepts, Doctrine: A History of Basic Thinking in the United States Air Force, 1907-1964*, v. II (Maxwell AFB: Aerospace Studies Institute, Air University, June 1971), pp. 786, 792-795. The secretarial-level view of the Dyna-Soar cancellation can be found in a memo for the Secretary of Defense from Robert C. Seamans, Jr., and Harold Brown, signed Jan. 29-31, 1964, and in the files of the NASA Johnson Space Center History Office. Finally, Boeing report D2-23418, "Summary of Technical Advances: X-20 Program" (Seattle: The Boeing Company Aerospace Division, July 1964)

contains a comprehensive listing of X-20 technical accomplishments, as well as indications of what work remained to be done. I have also benefitted by discussing the cancellation with John V. Becker, chief of hypersonic research for the NASA Langley Research Center, and a major NASA "player" during the Dyna-Soar effort.

One interesting perspective on Dyna-Soar is that of the USAF Scientific Advisory Board; key SAB reports clearly indicate the growing disenchantment and uncertainty affecting the program. See, for example, SAB, "Report of the Aero and Space Vehicles Panel on Dyna Soar," (Jan. 1960), pp. 1-5; SAB, "Memorandum of the Scientific Advisory Board Aero & Space Vehicles Panel on Dyna Soar," (Dec. 1960), p. 1; SAB, "Report of the Scientific Advisory Board Aero and Space Vehicles Panel on Dyna Soar Phase Alpha Review," (Apr. 15, 1960), pp. 1-7; SAB, "Report of the Scientific Advisory Board Aerospace Vehicles Panel," (Nov. 1962), pp. 4-5. Copies of these SAB reports are in the files of the SAB, Hq. USAF, Washington, D.C.

20. SAB, "Memo-Report of the USAF Scientific Advisory Board Aerospace Vehicles/Propulsion Panels on Aerospaceplane, VTOL and Strategic Manned Aircraft," (Oct. 24, 1963), p. 1.

21. Ibid., p. 3; Aerospaceplane's saga of woe is clearly evident by tracing the SAB's growing exasperation over the program. See, for example, SAB, "Memorandum of the Scientific Advisory Board Ad Hoc Committee on Aerospace Plane," (Dec. 1960), pp. 1-10; SAB, "(U) Memorandum of the SAB Ad Hoc Committee on Aerospace Plane," (Aug. 7, 1961), pp. 1-7; SAB, "(U) Report of the Scientific Advisory Board Ad Hoc Committee on Aerospaceplane," (July 23-25, 1962), pp. 1-10. (Files of the SAB, Hq. USAF, Washington, D.C.).

22. For Ames' early work on blunt bodies and lifting reentry schemes, see Edwin P. Hartman, Adventures in Research: A History of the Ames Research Center, 1940-1965 (Washington, D.C.: NASA, 1970), pp. 215-218, 266-270, 294-298, 359-363, 451-452; and Clarence A. Syvertson, "Aircraft Without Wings," Science Journal (Dec. 1968), pp. 46-50. LUNEX is discussed in the Air Force Space Systems Division's Lunar Expedition Plan: LUNEX (Hq. SSD, Support Systems Plans Division, May 1961), copy in the files of the NASA JSC History Office, and in Courtney G. Brooks, James M. Grimwood, and Loyd S. Swenson, Chariots for Apollo: A History of Manned Lunar Spacecraft (Washington, D.C.: NASA, 1979), p. 62. For the lifting characteristics of American manned spacecraft, see E. P. Smith, "Space Shuttle in Perspective." I have also benefitted from a conversation with Clarence A. Syvertson on March 7, 1979 at the National Air and Space Museum.

23. For START, ASSET, and PRIME background, see U.S. House, Committee on Science and Astronautics, 1967 NASA Authorization, Pt. 2, 89th Congress, 2nd session, Feb.-Mar. 1966, pp. 1073-1077; and U.S. Congress, House, 1968 NASA Authorization, Pt. 2, 90th Congress, 1st session, April 1967, pp. 1011-1012. I wish to acknowledge the assistance of Col. C. L. Scoville, USAF (ret.), the former director of the START program. For details on the ASSET effort, see "McDonnell Corp. Making Space Research Craft," St. Louis Post-Despatch, Jan. 6, 1963; Frank G. McGuire, "First ASSET Launches Due in Summer," Missiles and Rockets (Jan. 14, 1963), p. 18; "Space Glider Lost at Sea After Suborbital Flight," The Washington Post, Feb. 24, 1965; USAF Air Force Systems Command news release 31.65; For PRIME and START, see "START and SV-5 Shuttle Gets Go-Ahead," Space Daily, March 4, 1965; "Decision on AF Manned Space Shuttle Nears," Space Daily, Sept. 20, 1965; William J. Normyle, "Manned Flight Tests to Seek Lifting-Body Technology," Aviation Week & Space Technology (May 16, 1966), pp. 64-75; "PRIME SV-5D-III Maneuvers and Recovered," Space Daily, April 21, 1967; James J. Haggerty, "USAF Finishes PRIME Project," Journal of the Armed Forces (June 3, 1967), p. 9.

24. The general background of the "heavyweight" lifting body program is discussed in Syvertson's "Aircraft Without Wings," and in "Lifting Bodies: Coming in on a Vanishing Wing," Northrop Technical Digest (June 1967), pp. 1-17. For the early state of the lifting body program, as well as Congressional concern over how it fit with the rest of America's space effort, see U.S. Senate, Committee on Aeronautical and Space Sciences, 1964 NASA Authorization, Pt. 1, 88th Congress, 1st session, April 1963, pp. 40, 608-634, and Pt. 2, 88th Congress, 1st session, June 1963, pp. 919-920. The actual early flight test program on the lifting bodies was extensively reported in the X-Press, the newspaper of the NASA Flight Research Center at Edwards AFB, California; file copies can be consulted at the Public Information Office, NASA Hugh L. Dryden Flight Research Facility, Edwards AFB, California. For early headquarters direction and comment, see letter, Raymond Bisplinghoff to NASA Center directors, Oct. 28, 1964, and letter, Alfred Eggers to Paul F. Bikle, Aug. 18, 1964, both in the files of the NASA History Office, Washington, D.C. See also flight reports for the M2-Fl lifting body, in the files of the NASA Dryden Flight Research Facility. I have benefitted from discussions from early lifting body program members including Paul Bikle, Victor Horton, Richard Klein, R. Dale Reed, and Milton Thompson.

25. Various M2-F2/M2-F3, HL-10, and X-24A flight reports, in the files of the NASA Dryden Flight Research Facility.

26. B. L. Schofield, D. F. Richardson, and P. C. Hoag, "Low L/D Instrument Approaches," (Sept. 1970), mss. copy, p. 6; R. G. Hoey, "A Flight Test Program to Evaluate Terminal Energy Management and Landing Characteristics of Lifting Reentry Vehicles," (March 1969); B. L. Schofield, D. F. Richardson, and P. C. Hoag, Terminal Area Energy Management, approach and Landing Investigation for Maneuvering Reentry Vehicles Using F-111A and NB-52B Aircraft, AFFTC Technology Document No. 70-2 (June 1970); in files of AFFTC History Office. Additionally, I have benefitted from discussions with Col. Peter C. Hoag, USAF; Robert G. Hoey; Jack Wesesky; and Johnny Armstrong.

27. John A. Manke and Michael V. Love, "X-24B Flight Test Program," paper presented at the annual meeting of The Society of Experimental Test Pilots, Los Angeles, California, Sept. 26, 1975. The program's origins, accomplishments, and significance is thoroughly examined in Johnny G. Armstrong's Flight Planning and Conduct of the X-24B Research Aircraft Flight Test Program, AFFTC TR-76-11 (Edwards AFB: AFFTC, 1977).

28. Smith, "Space Shuttle in Perspective."

29. Memorandum, Floyd L. Thompson to NASA Administrator James Webb, June 18, 1964, p. 2, and attached report by the NASA Special Ad Hoc Panel on Hypersonic Lifting Vehicles with Propulsion, Washington, D.C.: NASA Policy Planning Board Staff Paper, June 1964. Copy in the files of the NASA History Office, Washington, D.C.

30. Memo, Thompson-Webb, June 18, 1964, pp. 3-4.

31. A comprehensive collection of these studies has been assembled by the NASA Johnson Space Center's History Office. I wish to thank Mr. James M. Grimwood (the former JSC Historian) and the late Sally Gates, NASA archivist, for guiding my research in the collection that they assembled, as well as the current NASA JSC historian, Dr. Edward C. Ezell, for his assistance.

The following partial listing consists of abbreviated titles arranged in chronological order:

*Lockheed-NASA feasibility study of 10-ton orbital carrier (Aug. 16, 1962)

*Boeing lifting reentry logistics spacecraft (May 1963)

*Boeing Model 920-26 spacecraft (Feb. 3, 1964)

*Lockheed-AF preliminary study of two high L/D reentry vehicles (Sept. 10, 1964)

*McDonnell mission requirements for lifting systems (March 24, 1965)

*Boeing operational aspects of lifting systems (Aug. 1965)

*McDonnell mission requirements of lifting systems: final oral briefing (Aug. 18, 1965)

*Douglas parametric study of logistics entry vehicles (Sept. 1965)

*Martin-Marietta study of lifting bodies (May 1967)

*Convair studies of turbofan variable-geometry spacecraft (July 6, 1967)

*Convair study of propulsive lift descent and landing (Aug. 15, 1967)

*Convair variable-geometry spacecraft studies (July 12, 1968)

*North American-Rockwell deployable rotor reentry vehicles (Dec. 1968)

See also a report prepared by the NASA-Department of Defense Aeronautics and Astronautics Coordinating Board, Report of the Ad Hoc Subpanel on Reusable Launch Vehicle Technology (Washington, D.C.: NASA, Sept. 14, 1966). Copy in NASA JSC HO.

32. For early British work, see W. F. Hilton, Manned Satellites: Their Achievements and Potentialities (London: Hutchinson, 1965), pp. 88-89.

For later proposals, see R. F. Creasey and T. Smith, "Space Shuttle Remarks," and P. J. McKenzie, "Space Shuttle Techniques," in Selection of Papers Presented at the Space Shuttle Symposium, Smithsonian Museum of Natural History, Washington, D.C., October 16-19, 1969 (Washington, D.C.: NASA, 1969), pp. 259-289. Unfortunately, this document received only limited distribution; a copy is in the files of the NASA JSC HO.

33. See C. Bigot, "Space Shuttle Hypersonic Aircraft/Space-Taxi Studies;" Marcel Stoll, "A French Concept of the Space Shuttle;" Mme. Vinas-Espin, "French Contribution to the Design of a Satellite Launcher Aircraft;" R. Marguet, "Participation to the Study of Lifting Reentry;" and G. Leroy, "Veras Operation," all in Selection of Papers. . ., pp. 223-246, 613-638, and 671-684. I wish to acknowledge the assistance of Dr. Ing. Injas Widjaja of ERNO-Raumfahrttechnik GmBH and Professor Roger E. Bilstein of the University of Houston at Clear Lake City for furnishing

information on Veras and Mistral projects.

34. Dr. C. Reinhold, "On Aerospace Shuttle," in Selection of Papers. . ., p. 248.

35. Ibid., pp. 247-257; also F. Mysliwetz, "Aero-Thermodynamic Problems of Space Shuttles," pp. 443-469; and H. Tolle, "Thrust Staging on Space Shuttle Ascent Trajectories," both in the same report. For Sänger's later work, see Sänger-Bredt, "Silver Bird," pp. 224-225. There is an excellent 1:10 scale model of the Ju RT-8-01 (Inv.-Nr. 79184) on exhibit at the Deutsches Museum, Munich. I wish to acknowledge the assistance of Dr.-Ing. Walter Rathjen of the Deutsches Museum in facilitating some of my research on German shuttle concepts.

36. See Aviation Week and Space Technology, Nov. 6, 1978, p. 19; June 21, 1982, p. 16; and March 14, 1983, p. 255. See also Carl A. Forbrich, Jr., "The Soviet Space Shuttle Program," Air University Review (May-June 1980), pp. 55-61.

37. For example, see memo, Dale D. Myers to Robert R. Gilruth, Dec. 9, 1970, in the files of the NASA JSC HO. The current interest in European Shuttles--such as the French Hermes project, which draws heavily on the configuration of the present Space Shuttle--is proof that Shuttle enthusiasm is still to be found among the European community.

38. NASA-DoD AACB, Report of the Ad Hoc Subpanel on Reusable Launch Vehicle Technology, passim.

39. Space Shuttle Task Group, NASA Space Shuttle Summary Report (Washington, D.C.: NASA, rev. ed., July 31, 1969). See also NASA Office of Manned Space Flight, NASA's Manned Space Flight Program (Washington, D.C.: NASA, April 29, 1969), pp. 233-234.

40. John M. Logsdon, "The Space Shuttle Decision: Technology and Political Choice," Journal of Contemporary Business, VII, no. 3 (1978), pp. 13-30; J. C. D. Blaine, The End of an Era in Space Exploration (San Diego: American Astronautical Society, 1976), pp. 165-169.

41. Scott Pace, "Engineering Design and Political Choice: The Space Shuttle, 1969-1972," M.S. thesis, Massachusetts Institute of Technology, May 1982, pp. 2-3.

42. Science & Technology Division, U.S. Library of Congress, Aeronautics and Astronautics, 1970: Chronology on Science, Technology, and Policy (Washington, D.C.: NASA, 1971), p. 53.

43. Pace, "Engineering Design and Political Choice," pp. 103-104. There is an excellent discussion of NASA-DoD relationships on Shuttle in a report prepared by Barbara N. Luxenberg, Specialist in Aerospace Systems for the Congressional Research Service of the Library of Congress. This document appears as Chapter 7, "Space Transportation System" (pp. 445-637) in U.S. House, Subcommittee on Space Science and Applications of the Committee on Science and Technology, United States Civilian Space Programs, 1958-1978, v. I, 97th Congress, 1st session, January 1981. See especially pp. 565-576. I wish to acknowledge the contributions of Ms. Luxenberg to my research on the Shuttle.

44. Jerry Grey, Enterprise (New York: William Morrow and Company, Inc., 1979), pp. 67-68.

45. Pace, "Engineering Design and Political Choice," pp. 116, 135-149.

46. Ibid., p. 127. Documents useful in tracing NASA-AF relations over the roles and configuration of Shuttle include: NASA Marshall Space Flight Center release 70-102, May 26, 1970; letter, Dale Myers to Robert Gilruth, June 30, 1970; Space Shuttle Phase B Study Control Document NAS 9-10960, June 1970;

NASA Statement of Work for Space Transportation System, Sept. 2, 1969. These, plus other internal and external commentaries and correspondence, are in the files of the NASA JSC HO. See also Hans Mark, "The Impact of Our Enterprise in Space," *Technology in Society*, I, no. 1 (1979), pp. 43-53. I also benefitted from conversations with Maxime Faget, NASA JSC, on Shuttle's design evolution, and with James C. Fletcher, former NASA Administrator.

47. Memorandum for record, James C. Fletcher, George M. Low, and Richard C. McCurdy, "Selection of Contractor for Space Shuttle Program," Sept. 1972, in files of NASA JSC HO. See also Logsdon, "The Space Shuttle Decision," and Smith, "Space Shuttle in Perspective." An excellent summary of design proposals and configurations (including some extraordinary design planforms) is contained in a report issued by the Spacecraft Design Division of the NASA Manned Spacecraft Center (now the Lyndon B. Johnson Space Center), "Summary of MSC Shuttle Configurations (External H O Tanks)," (Houston: NASA MSC, rev. ed., June 30, 1972), in the files of the NASA JSC HO. A good survey of the Shuttle's final evolution from the Rockwell perspective can be found in Harry A. Scott's "Space Shuttle: A Case Study in Design," *Astronautics & Aeronautics* (June 1979), pp. 54-58.

48. NASA Langley Research Center scientists Paul Cooper and Paul F. Holloway prepared a definitive account of the evolution of the Shuttle's Thermal Protection System, including problems encountered and resolved, that appeared as "The Shuttle Tile Story," *Astronautics & Aeronautics* (January 1981), pp. 24-34, 36.

49. The advent of the Shuttle has been marked by a number of popular books on the possible impact of the Shuttle on the exploration and utilization of space. The best single summary on the present-day Shuttle and its capabilities and potential is still NASA SP-407, *Space Shuttle* (Washington, D.C.: NASA, 1976); incisive technical analyses of the Shuttle, potential

Shuttle uses, and possible Shuttle "spin-offs" are examined in Robert Salkeld, Donald W. Patterson, and Jerry Grey, Space Transportation Systems, v. I of the AIAA Aerospace Assessment Series (New York: American Institute of Aeronautics and Astronautics, 1978); the American Astronautical Society, Space Shuttles and Interplanetary Missions, v. XXVIII of Advances in the Astronautical Sciences (San Diego: AAS, 1970); the American Astronautical Society, Space Shuttle Missions of the '80's, v. XXXII of Advances in the Astronautical Sciences (San Diego: AAS, 1976); and in Gerard K. O'Neill's The High Frontier: Human Colonies in Space (New York: William Morrow and Company, Inc., 1977).

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