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History of the Phoenix VTOL SSTO and Recent Developments in Single-Stage Launch Systems

Gary C. Hudson

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FOREWORD

Some aerospace authorities assert that single-stage-to-orbit vehicles are impossible, or are so challenging that they are the functional equivalent of impossible. This paper traces three decades of design work on SSTO concepts and the independent analyses that have judged these various SSTO designs to be entirely achievable. The paper also shows that lightweight structures are the most critical technology involved in SSTOs—which means the advanced composite materials of the 1990s have made the technical case for SSTO feasibility even stronger, compared to the metallic SSTO structures evaluated in the past.

In addition to this document, available separately, is a recent Arthur D. Little report that specifically examines the feasibility of the Roton SSTO design and the abilities of the Rotary Rocket management team.

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March 1999

History of the Phoenix VTOL SSTO and Recent Developments in Single-Stage Launch Systems†

Gary C. Hudson

Abstract

If the long-awaited exploitation of space is to occur in an economical and affordable fashion, inexpensive and reliable means to transport cargo and people to and from LEO will be required in the 21st century. The author has studied the vertical-takeoff-and-landing (VTOL) single-stage-to-orbit (SSTO) launch vehicle concept for use as a LEO transport for more than two decades. VTOL SSTO represents one feasible solution to the problem of low cost space transportation.

Building on work conducted in the 1960s by Bono and in the early 1970s by the Chrysler Corporation, Gomersall and others, the author conceived the Phoenix concept in 1972 as a means to provide inexpensive access to space. The basic concept survived into the 1980s and was refined to the degree that the vehicle could be built with existing technology and prove suitable for use by non-astronaut passengers.

This paper will review the history of the VTOL SSTO concept and the Phoenix designs. It will also discuss the role the Phoenix concept had in stimulating consideration of the single-stage-to-orbit approach by the U.S. Government in on-going SSTO concept studies. These studies are currently expected to lead to prototype hardware development aimed at demonstrating the SSTO approach by 1995-97 in the form of the McDonnell-Douglas DC-Y.

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INTRODUCTION

It has been humorously remarked that there are three stages to a good idea. In stage one critics comment "It will never work, don't waste my time." In stage two the idea progresses to the point where the same critics concede "Well, perhaps it would work, but why would you want to bother?" In stage three the previous critics come around to the view "I always said it was a good idea"... and occasionally try to claim the idea as their own. The thirty-year quest for a practical VTOL SSTO vehicle has now reached stage three.

This review paper is an attempt to place recent activity on SSTO in historical perspective. To do that, we must first consider the primary motivation behind single-stage approaches to space vehicle design.

BACKGROUND

The motivation to build an SSTO can be traced to the desire for a space transport vehicle which replicates the ease of operation of a jet transport, thus yielding low costs to place cargo and passengers into earth orbit. To accomplish this in a single stage

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is a technical challenge that can be met only by the intelligent combination of lightweight structures, altitude-compensating rocket engines and an "intact abort" philosophy of operation [Ref. 1]. In addition, the operational philosophy of commercial jet aircraft must be embraced by the rocket designer; it is intolerable to burden an advanced SSTO with the cumbersome and unnecessary army of technicians and managers which have been built up by national space bureaucracies in the United States and other countries.

SSTO has been shown to be achievable by three separate approaches. The subject of this paper, VTOL, was the first concept to demonstrate the benefits of an SSTO. Recent analysis by U.S. aerospace contractors has confirmed that both VTHL and HTHL systems would also be practical. Previous analysis has already confirmed that a variation of HTHL, "air-launching", would be feasible. It is, therefore, not the author's purpose to extol the virtues of VTOL, but rather to provide a technical history showing how early concepts led directly to the re-birth of interest in all forms of single stage vehicles.

Why has it taken so long for the SSTO concept to reach widespread acceptance within the aerospace technical community in the United States? The answer is complex, but can be traced, first and foremost, to the peculiar relationship which exists in the U.S. between the government, until recently the sole customer for launch systems, and the suppliers of the actual launch hardware, the airframe contractors or "primes". The customer specifies, usually in great detail, the bounds of a solution for a particular engineering problem. Contractors ignore such boundaries at their extreme risk. This stimulus/response conditioning of the contractors effectively suppresses any desire to "stand out from the crowd", except in the most trivial of ways.

Thus we must rephrase the question and ask why haven't government officials specified SSTO in past projects? Here the answer is relatively straightforward. Governments are by nature conservative entities. It usually does not pay to propose risky endeavors, when safer, albeit more expensive or less optimal, paths may be traveled. The paymasters of government agencies are not technically learned, so they cannot exert effective oversight. Further, until recently there have been only two places within the U.S. government where launch vehicle developments have been undertaken. One has been the USAF (United States Air Force), and the other NASA (National Aeronautics and Space Administration).

The USAF has depended on derivatives of former IRBMs or ICBMs for the past thirty years. The USAF waged a long battle to free itself from a previous government policy of total reliance on the (former) STS or Space Transportation System/Space Shuttle in favor of the Delta II, the MLV (Medium Launch Vehicle) and the Titan IV. This preference for conventional expendable launch vehicles is rooted in the extraordinary resistance of most military men towards change—a natural result of the environment in which they are forced to exercise their craft. Lower costs or increased performance are of little value in conflict when compared with familiarity, routine and reliability of results.

NASA is another matter. With a charter to seek out new technology, it is natural to suppose that all new ideas would receive fair and objective hearings from NASA analysts. As most anyone who has ever suggested a new idea to a NASA center can attest however, such is rarely the case. It is in NASA's interest to take very small steps toward an ill-defined goal since such a policy can sustain the agency indefinitely. It must be remembered that NASA opposed Kennedy's plan to go to the moon on a crash basis [Ref. 2].

Furthermore, it is easy to find justifications for resistance to change on technical grounds, especially in expensive and risky projects such as launch vehicle development. Any junior engineer can show that it is "easier" to build a two-stage vehicle than a single-stage. In the face of clear incentives not to take risks building a vehicle which offers future payoffs which might not be desirable anyway[1], it is easy to see that SSTO, along with many other examples of high risk/high payoff technologies, was not likely to be fostered at NASA.

As proof of this thesis, the U.S. government agency, which is today actually funding an SSTO hardware development effort, is neither the USAF nor NASA, but a relatively new, aggressive, goal-oriented organization: the SDIO (Strategic Defense Initiative Organization). SDIO actually has a task to perform—strategic defense. They require inexpensive

[1] For example, reducing the manpower associated with launches may conflict with the goal of providing high levels of employment in key congressional districts.

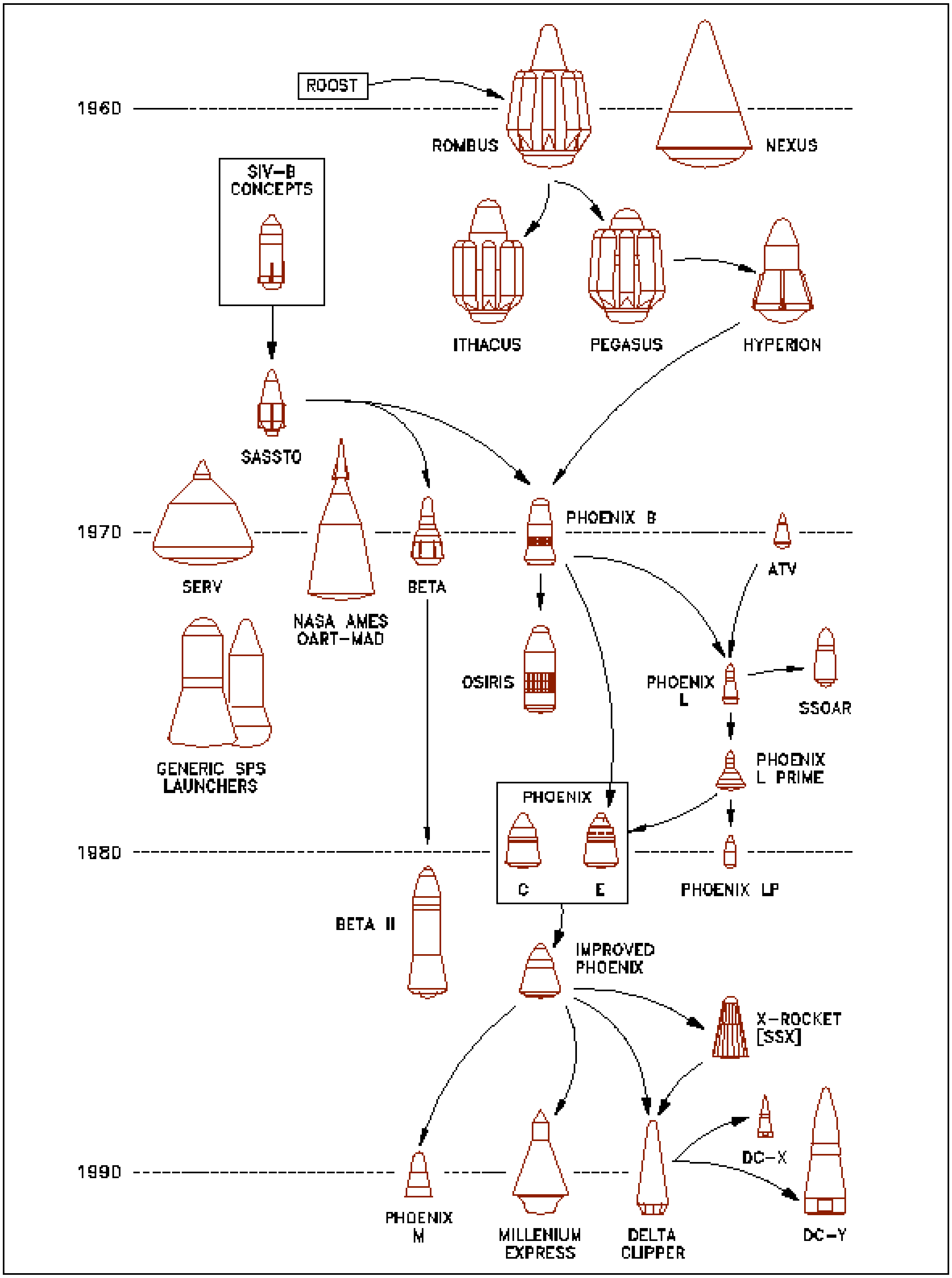

Figure 1 - The Evolutionary Tree of VTOL SSTO Concepts

and routine access to space in order to accomplish this task. It is no surprise that SSTO languished until such a patron could be found. If SSTO vehicles are built within U.S. government-sponsored programs, it will be because SDIO was not burdened by obsolete, parochial thinking when it came to space transportation; they had a different paradigm. Once this customer[2] (SDIO) communicated to the contractors that they wanted an SSTO, it quickly became "feasible" to build one.

THE WORLD-CIRCLING SPACESHIP: A FALSE START

SSTO vehicles may be expendable or reusable. This paper will focus on reusables, since expendables would not achieve anything like the cost reduction that might be expected from a well-designed reusable. From a matter of historical perspective, however, it should be pointed out that the first proposals for a serious SSTO "world-circling spaceship", made in 1946 [Ref. 3], were for an expendable. It is relevant to this discussion for two reasons. One, the proposal was made early in the history of rocketry, and thus might be seen as a naive ab initio expression of a highly desirable end, that is, single-stage-to-orbit. Second, it was technically far advanced over the art of the day in scope and execution, but lacked staying power in the development and funding cycle. It is interesting to note that several companies endorsed the notion of a single-stage spaceship, but a "scientific analysis" of propellant density and rocket engine performance, while mathematically correct, failed to support the engineering assessment that single-stage was practical. Emphasis changed from finding a low structural weight solution (to contain the relatively low-density lox-hydrogen propellant) to finding high-density rocket propellants, which would yield longer ranges, even with the poor structural weights achievable at that time. This analysis effectively dampened enthusiasm for single-stage vehicles for years.

SSTO vehicles, in any version, languished for the next decade and a half. It is still widely believed, even today, that the difficulty of SSTO is tied to poor propulsion systems, and that modern propulsion engines are inadequate to the task, let alone those of the 1950s. (For example, there were no operational lox-hydrogen rocket engines until the end of that decade, when the Pratt & Whitney RL10 first appeared.)

In fact, the difficulty of SSTO is tied much more to propellant mass fraction (l') than propulsion performance. The exception is the need for altitude compensation in the nozzle of the SSTO rocket engine, which may be achieved by any of several techniques discussed later in this paper. A thought experiment, written in 1987 and published here as an appendix, discusses the conversion of existing, off-the-shelf hardware components (for example the Saturn S-IVB stage or Shuttle External Tank and the Space Shuttle Main Engine) into practical SSTO expendable vehicles.

Another early SSTO proposal is worthy of a brief mention here, mainly since it was the first to employ altitude-compensating rocket engines. Proposed in 1963 by General Electric, this concept [Ref. 4] was never given a name, but was intended to place in orbit an integral, fully assembled, rotating space station as a single element. The "payload" would have been the propellant tanks of the vehicle, configured into a beaded torus and with internal outfitting for future inhabitants. Propulsion was from a plug nozzle, which later evolved into the Rocketdyne "aerospike". Most notable, this concept did not rely on pump-fed rocket engines, but instead was pressure-fed.

THE TRUE BEGINNINGS OF VTOL/SSTO: THE BONO SSTOS

While this paper concentrates upon reusable, chemically-powered SSTO vehicles, it is important to note that the first person to conceive of a reusable VTOL/SSTO vehicle began with an expendable concept, called the One-stage Orbital Space Truck, or OOST. Converted to quasi-reusability by the addition of a ballute/balloon that was inflated by residual hydrogen and surrounded the conventionally-shaped OOST, it was renamed ROOST, the "R" designating reusability. The ROOST concept [Ref. 5], developed by the father of VTOL/SSTO, Phil Bono of Douglas Space and Missiles Company, was to be recovered by a helicopter and towed, under aerostatic lift, to a refurbishment site. The vehicle used conventional rocket engines, and it is important to note the specific impulse (Isp) of these engines was only 410

[2] Critics, including those who have opposed SSTO for decades, would say "naive customer".

seconds in vacuum compared with the higher performance RL10 (444 sec) or the SSME (452 sec). In the spirit of the day, ROOST could orbit a payload of 1,000,000 pounds.

Bono published his SSTO ideas in a imaginative little book written with K. Gatland in 1969 [Ref. 6]. This popular work still is a useful reference for those interested in the historical background of the VTOL/SSTO concept. The book does not discuss ROOST, but begins with Bono's ROMBUS vehicle, which was operable either as a SSTO, or as a stage-and-a-half vehicle, dropping unneeded hydrogen propellant tanks during ascent to orbit. Bono was the first to suggest that ROMBUS vehicles might be used to re-fuel a separate vehicle in orbit, which had boosted with tanks attached (at a payload penalty). This vehicle would then proceed to the moon or Mars with a massive payload. Bono also suggested that the used hydrogen fuel tanks could be used as habitats for lunar settlers or explorers. As with ROOST, ROMBUS had a large payload capability, measured in the million pound range [Ref. 7, 8].

Bono then refined the ROMBUS vehicle into the Pegasus (and a military troop transport version, ITHACUS). Pegasus was envisioned as a smaller version of ROMBUS, with a market focused on cargo to orbit and passenger transport to antipodal destinations. To offset the sensitivity of all SSTOs to reduction in engine performance and/or increases in dry weight, Bono's next vehicle, Hyperion [Ref. 9], incorporated a launching sled. Operationally, it would have restricted Hyperion to only a few geographically optimal sites, but the concept would later be revived in the HTHL Boeing RASV.

A significant part of Bono's work focused on the Saturn upper stage, the SIVB, manufactured by his employer, McDonnell-Douglas (MDAC). He first considered reuse of the SIVB in its Saturn configuration [Ref. 10], but finally refined the idea into a small VTOL SSTO named SASSTO (Saturn Application Single-Stage-To-Orbit) [Ref 11]. SASSTO would have provided spectacular increases in performance to the Saturn IB and Saturn V workhorses of the American space program. Operating as an SSTO, it could have carried the two-person Gemini capsule to orbit. He suggested that SASSTO could also be used as a lifeboat or rescue vehicle, an idea which presages similar suggestions made by contractors during the SDIO Phase I study effort.

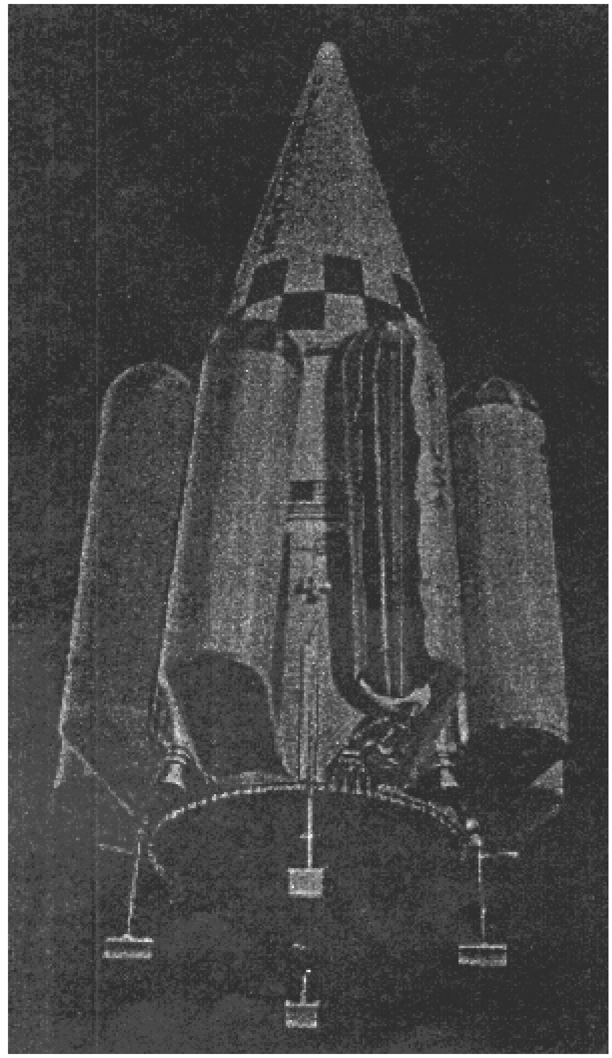

Figure 2 - ROOST

Bono was making his claims of single-stage reusability in an era when reusable vehicles of any type were considered to be expensive, difficult and probably not worth the effort. In light of the arguments against his integrated solution—against reuse, against perceived optimistic engine performance estimates, and against mass fraction—it is not surprising that he gave up the struggle about the time the Space Shuttle program was approved by NASA. What is remarkable was that he was able to persist in this vision for as long as he did.

Bono was the first designer to combine an altitude-compensating propulsion system into a single-stage, which was reusable. This was his most significant contribution to the campaign for SSTO concept acceptance. He was also the first to suggest the use of active cooling to protect the heat shield of the

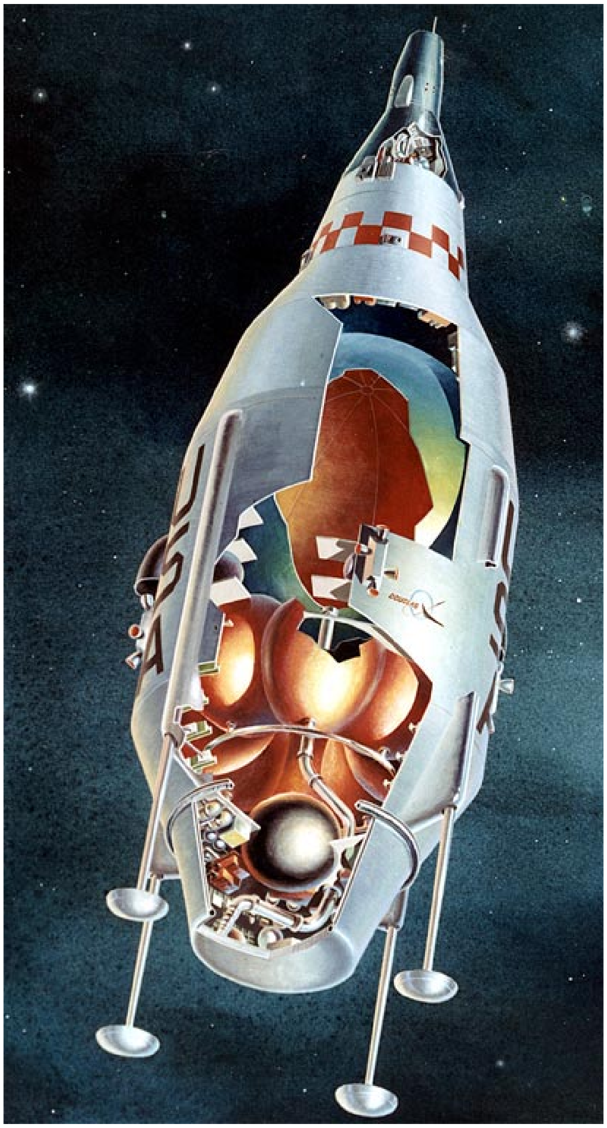

Figure 3 - SASSTO

vehicle during reentry, an approach later adopted by both the Boeing SPS launcher and the Phoenix[3].

BETA I & II

In 1969, MBB (Messerschmitt-Bolkow-Blohm) designer D. Koelle used the SASSTO vehicle as his baseline to begin evaluation of the VTOL SSTO concept called BETA (Ballistisches Enistufiges Traeger-Aggregat). He finally derived a heavier vehicle, more conservatively designed, and thus more in keeping with European launch vehicle technology of the day, capable of a few tons of payload to LEO [Ref. 12,13].

[3] Bono expected to use hydrogen for cooling; the other vehicles mentioned would have employed water.

The analysis of BETA was carefully done, and should have been convincing to analysts who retained their objectivity. Regrettably, there were few who would fall into that category: the emotional investment in the position that SSTO was not possible was too strong, even in the face of evidence to the contrary.

Nearly twenty years later in 1987, Koelle revisited the SSTO idea with BETA II [Ref.14], which had a larger payload, but thanks to a more sophisticated trajectory analysis, actually required a lower total delta-v to reach orbit. Koelle went on to become a major promoter of the two-stage winged Sänger project, which is presently vying for European Space Agency support as a follow-on to Ariane 5.

The Phoenix Series 1969-1980

In the late 1960s, Bono's SIVB SSTO and its successor, SASSTO (with a measure of the configuration approach of Hyperion) were a principal influence on the early design philosophy of a new SSTO vehicle series named after the mythical bird that rose from the ashes: Phoenix[4].

Early Phoenix designs were based on the conclusion that propulsion performance was less important than lightweight airframes and engines, and also that it would be necessary to provide a means for intact abort of the complete vehicle.

Phoenix was meant to be developed, tested, and operated commercially with private funds. For this to be practical, it was necessary to limit development costs by building on the existing technology base. Propulsion systems and structures were as conventional as the design requirements would permit them to be. Early Phoenix vehicles used RL10 chambers and pumps, later graduating to J-2 engine hardware. With a few exceptions, most of the structures were aluminum or steel.

Several key improvements and innovations were needed to achieve the desired payload goals. These improvements came in the next generation of Phoenix designs in the early 1980s.

[4] The ashes were the ashes of Project Apollo, and the spirit of the early days of the American space effort, which, by the beginning of the 1970s, were thought to have died.

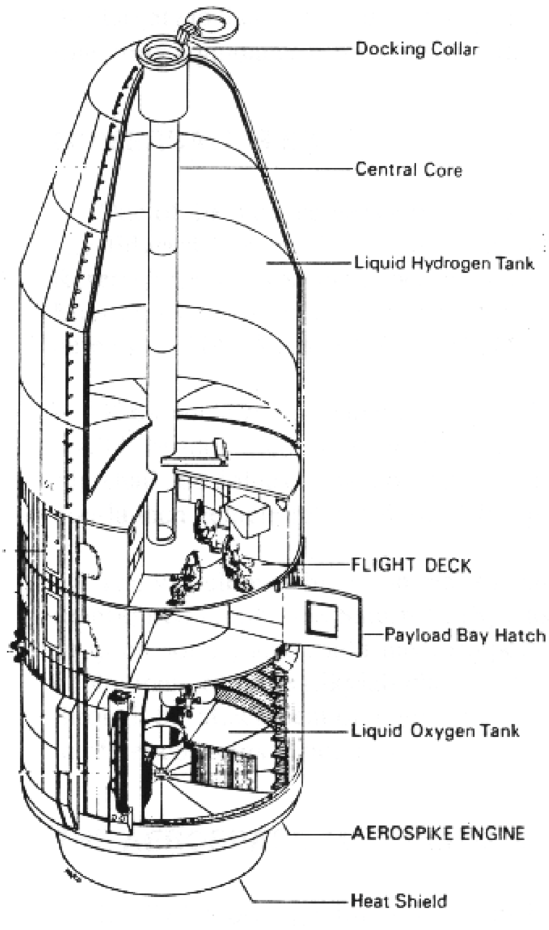

Figure 4 - OSIRIS, A Growth Phoenix B

CHRYSLER SERV

Without question, the most detailed design study ever performed on a VTOL SSTO was conducted by the Chrysler Corporation's Space Division in Michoud, Louisiana during 1970-71. The team, led by Charles Tharratt, produced a detailed, six-volume plan for a large SSTO, called SERV (Single-Stage Earth-Orbital Reusable Vehicle), which could carry Shuttle-class payloads to LEO [Ref 15]. Like Gomersall (see below), the Chrysler team used a winged spacecraft mounted on the nose of the SERV, to provide for passenger flights.

The vehicle proved that a fully reusable VTOL SSTO could be built, but since it did not fit the NASA plan of the period for a two-stage flyback booster/orbiter combination space shuttle, it was shelved.

SERV used a metal honeycomb structural technique, which would later resurface in the Boeing RASV HTHL vehicle. It was also noted for its unusual solution to the landing propulsion problem faced by all VTOLs. SERV used a large number of vertical-lift jet engines to cancel terminal velocity and to provide for hover time. This proved to be necessary due largely to their self-imposed requirement that they land the vehicle on a small pad, while tolerating a guidance error typical of the worst case performance of the Apollo spacecraft.

GOMERSALL'S SSTO

One of the most conservatively designed SSTOs, an unnamed concept authored by the late Edward Gomersall, was documented only in an unpublished internal NASA Ames Research Center working paper in 1970. The paper was prepared under the auspices of the Mission Analysis Division of the Office of Advanced Research & Technology, referred to here as the NASA Ames OART-MAD vehicle [Ref.16].

The vehicle was promoted as a Space Shuttle, and because of the strong opposition within NASA headquarters and the two other principal NASA manned Spaceflight Centers, Marshall and Johnson, the concept was quickly suppressed and Gomersall was assigned to non-launch vehicle-related duties [Ref. personal communication].

The vehicle was based on realistic structural technology and conventional propulsion (configured around the Saturn J-2[S] class powerhead). It could be uprated by the use of strap-on solids, and could have supported a continuing lunar exploration campaign, the deployment of large (Skylab-class) space station components, or the launch of passengers through the attachment of a winged crew spacecraft. The winged spacecraft was designed to offset concerns about crossrange[5]

[5] Crossrange has been the bane of most VTOL SSTO concepts. Since all of the concepts discussed in this paper are base entry vehicles, with the notable exception of Delta Clipper, the L/D ration of any of these vehicles is bound to be low, typically under 0.5. This guarantees that a crossrange beyond a few hundred miles will be unobtainable. While it has been shown that crossrange is not necessary for a successful VTOL SSTO, most recently by R. Jurmain of General Dynamics Space systems

THE AEROSPACE TEST VEHICLE (ATV)

In 1972, working with only minimal support from within the agency, NASA Marshall Space Flight Center engineer George Detko put together a design for a small VTOL SSTO [Ref. 17] which was notable for two reasons. First, the vehicle had a GLOW of less than 50,000 lbs, far less than accepted wisdom said could ever be feasible for a single-stage. Second, the vehicle was configured to carry a two-person crew, and was shown to be capable of both orbital flights and antipodal "priority cargo" delivery.

This vehicle had a significant impact on concurrent Phoenix design efforts. A major goal of the Phoenix program was development of a VTOL SSTO without government funding support. A smaller vehicle could be built more easily and was therefore attractive. A detailed redesign of the ATV, performed by the author and Tom A. Brosz and renamed the "Aerospike Test Vehicle", led directly to the small Phoenix series, including the Phoenix L (for light) and Phoenix L Prime.

THE MID-1970S SPS AND MIXED MODE CONCEPTS

In response to U.S. government energy policies, large SSTOs were proposed in the mid-1970s by several groups working on ways to launch the components of massive SPS platforms (Satellite Solar Power). In 1977 Boeing produced a vehicle design for a 500,000-pound payload version which would launch from the edge of a water-filled man-made lagoon and recover in the lagoon [Ref. 18]. The vehicle was notable for its use of a water-cooled heat shield, a characteristic that was later adopted by the Phoenix vehicles.

Several other investigators considered very large VTOL SSTOs, since it was generally believed that larger vehicles would be easier to make work than smaller ones. One variation on this approach was the application of dual fuel propulsion systems to the VTOL SSTO concept, which reduced tank mass in direct proportion to the achieved reduction of propellant volume which is characteristic of these

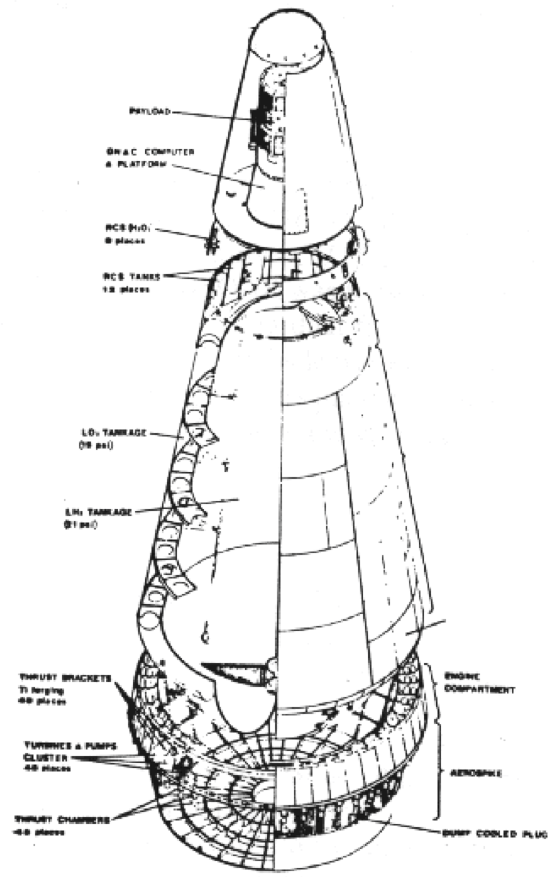

Figure 5 - Aerospike Test Vehicle

types of propulsion systems. A modification of this approach was used on the 1982 Phoenix C and E vehicles. Instead of employing dual fuels (hydrogen and kerosene) in combination with liquid oxygen, the Phoenix was designed to burn a single fuel (hydrogen) at a variable mixture ratio. This achieved most of the benefits of dual fuel propulsion without the need for a second fuel pump and the attendant combustor complexities [Ref. 19].

SSOAR

The SSOAR (for Single Stage to Orbit And Return) was proposed by Earth/Space, Inc. an entrepreneurial venture established in California in 1976. The founder of this venture, P. Seigler, had been convinced of the viability and utility of VTOL SSTO from analysis of Phoenix studies [Ref. personal communication]. SSOAR was to be a lox-hydrogen vehicle employing an aerospike, though a second version using dual fuel was also mentioned in company literature. No technical paper describing the vehicle was ever published. Data and the

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Division through the use of site-synchronous orbits [Ref. personal communication], the desire persists. The Delta Clipper, a wingless cone, is now claiming a 1640 nautical miles crossrange, more than twice that achieved by the winged Space Shuttle.

illustration used in this paper were taken from a business plan published by the company in 1976 [Ref. 20]. The firm disappeared from the scene a few years later.

THE PHOENIX SERIES 1982-1991

In 1982, Pacific American Launch Systems was founded to develop VTOL SSTOs for the commercial marketplace. Starting with a "clean sheet" a family of vehicles was configured which boasted several innovations from Phoenix designs of the early to mid-1970s.

Shown in Figure 6, this family was comprised of two large vehicles (400K lb GLOW) and two small vehicles (under 70K lbs GLOW). The large vehicles were the Phoenix C (for cargo) and the Phoenix E (for excursion). The former would fly unmanned, while the name of the latter suggests its purpose to serve as a lunar or Mars lander, in addition to planned duties as a LEO passenger transporter. The smaller vehicle, called Phoenix LP, also came in a cargo or crewed version. In retrospect, these look very similar to the DC-Y SDIO vehicle configuration. Nose entry was investigated for the smaller vehicle, but rejected due to thermal and stability concerns.

The innovations in this vehicle family included the employment of mixed-mode dual-fuel propulsion to achieve higher propellant mass fractions, a more compact vehicle and the use of individual bell nozzle rocket engines for propulsion. Twenty-four engines were chosen to permit "several-engine-out" intact abort, while at the same time reducing the cost to develop the propulsion system (smaller engines being easier to handle and test than larger ones).

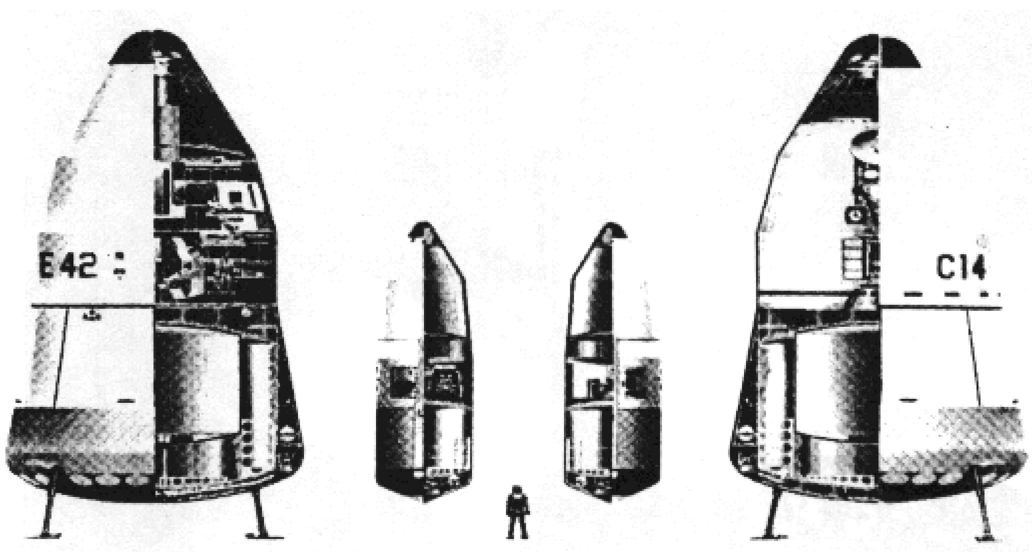

Figure 6 - 1982 Phoenix Mixed-Mode Vehicle Family

Propellant choices for the dual fuel system included hydrogen plus either methane, propane or kerosene. Propane was finally chosen for density, cost and the fact that it could be stored at close to the lox boiling point, unlike kerosene. Propane is also a relatively clean-burning hydrocarbon, which reduced engine development and maintenance problems.

During the design process, it became clear that the dual-fuel system would add complexity to the development of the Phoenix, and that most of the gains of dual-fuel could be achieved by changing the mixture ratio of a lox-hydrogen rocket engine during ascent. This was an idea which had already been considered by Chase and Cormier [Ref. 21]. In the next iteration of the design [Ref. 22,23], this change was incorporated, along with changes in structural layout and materials selection. For example, the thermal protection changed from passive to active, employing water-cooling of bare aluminum skins.

The propulsion system also changed with the improved Phoenix. The pendulum had swung back to the aerospike, renamed "aeroplug". The aeroplug differed from the earlier aerospike in that only a few percent of the plug surface remained, in order to give a smooth base for reentry. This meant an unavoidable loss of performance. However, in SSTO design, performance is of less importance than lightweight structures. Eliminating nearly all of the engine nozzle dramatically increased the engine thrust/weight ratio, essentially making up for the lost performance.

This aeroplug engine used J-2S turbomachinery and could operate at 1200 psia combustion pressure. It would have had a modest area ratio of about 200:1, reducing the in-flight Mach number effect that ultra-high area ratio engines suffer from. Steering would be by differential throttling.

A number of smaller versions of the vehicle were also considered. These are represented in Figure 1 by the icon labeled Phoenix M, for medium. All of these small vehicles used individual altitude-compensating bell nozzles rather than the aeroplug. Composites would be used in the aeroshell and, possibly, in the propellant tankage.

In the final analysis, these modern Phoenix designs were feasible using technology and materials in common service during the 1980s. This fact would be finally accepted at the beginning of the next decade.

Figure 7 - 1985 Phoenix Design, Mixed-Mode, Single-Fuel Version

X-ROCKET AND SSX

In the late 1980s Maxwell W. Hunter, attempted to bring the VTOL SSTO to mainstream acceptance by the aerospace establishment in the United States with the X-Rocket (sometimes also called X-OP, for experimental-operational). After several fruitless years attempting to interest private investors in the Phoenix vehicles, Hunter, then an employee of Lockheed Missiles and Space Company, used his position to force consideration of the concept by the AD (Advanced Development) Division of the company. Even after the Shuttle Challenger debacle, it was not possible to obtain private funds of the necessary magnitude to begin Phoenix development. Hunter then conceived of the X-Rocket plan as a way to win establishment support. [Ref. 24, 25]

AD undertook a study of a conical, 500,000 lb gross weight vehicle powered by a cluster of uprated RL10 rocket engines. After a design study that confirmed the basic concept, Hunter began to promote the concept to government officials. This prompted LMSC to order an independent review of the X-Rocket by another division within the company, the MSD (Missile Systems Division). MSD's sole line of business at LMSC is the design and manufacture of the Trident series of submarine-launched ballistic missiles. As might be expected under these circumstances, the MSD review was not favorable. Using parametric analysis, which was more suited for solid-propellant ICBMs, MSD engineers concluded that the vehicle would have zero payload. This is significant in view of the perhaps unintentional, bias that would have been inherently present in the minds of the engineers performing the review. An analogy might be to ask the designers of a Porsche to have their work reviewed by the builders of railroad tank cars. A further brief review conducted by the USAF Aerospace Corporation also was less than favorable.

LMSC dropped further consideration of the X-Rocket after these reviews, and Hunter retired shortly thereafter. As an independent consultant, he renamed the vehicle concept SSX (for Spaceship Experimental), and began to refine the concept [Ref. 26]. In December 1988, Hunter and the author briefed the ad hoc Citizen's Advisory Council on

National Space Policy[6]. The general concept was endorsed by the Council and by the High Frontier, Inc. organization, a Washington-based lobby for the Strategic Defense Initiative (SDI) program. Working together, Hunter and High Frontier convinced SDI and other national officials that a study should be initiated to determine the feasibility, once and for all, of SSTO.

The Aerospace Corporation Report

Several analyses of VTOL SSTOs were performed by the Aerospace Corporation, a civilian analysis arm of the USAF, during the 1980s. With a single exception, these "analyses" amounted to superficial repetitions of the difficulty in achieving the required mass fraction, and the reiteration that staged rockets were preferable. No opportunity for rebuttal on the part of VTOL SSTO proponents was provided.

However, after high level interest was generated in Washington, in the spring of 1989 a much more detailed report was prepared on the concept [Ref. 27]. Interestingly, the title of the report refers to the "Phoenix:SSX" vehicle, and the analysis is a blend of work performed by Lockheed on the X-Rocket, and Phoenix briefing documents of 1986; the same work that had been dismissed out of hand by earlier Aerospace Corporation reports.

This report was quite a bit different from ones previous. It concluded that the basic idea was feasible, with a few disagreements over technical approaches. In fact, the earlier version of the report [19 July 89] was highly positive, while the final version [15 August 89] was somewhat more restrained. It is instructive to note that a senior Aerospace executive authored two of the earlier reports that ridiculed both Phoenix and X-Rocket. Since nothing had changed technically, the positive tone of the 19 July version was an embarrassment and the more muted endorsement of the 15 August version was necessary to obtain his release signature [Ref. personal communication]. In any case, the fact that Aerospace had essentially endorsed the concept paved the way for the initiation of the SDIO SSTO program[7].

The SDIO Program

The SDIO (Strategic Defense Initiative Organization) funded four of six respondents to a request for proposals in August, 1990. (The two unlucky proposers were Grumman and Third Millennium, Inc., both of which favored HTHL air-launched concepts.) Companies funded included McDonnell-Douglas, Rockwell, General Dynamics and Boeing. While it was widely understood in the community that the program managers at SDIO favored the VTOL concepts typified by the SSX, pressure from at least one of the potential contractors forced SDIO to open the competition to all types of SSTOs [Ref. personal communication].

Both MDAC and GD rapidly settled on VTOL approaches. Boeing proposed an improved version of its HTHL sled- or rail-launched RASV (Reusable Aerodynamic Space Vehicle) powered by uprated SSMEs (Shuttle Main Engines), while Rockwell fixed upon a VTHL, similar in many respects to the Space Shuttle Orbiter, but with an aerospike engine. About $12 million was spent on this Phase I design effort, which lasted from August 89 to June 90.

Though it is fiercely denied by the government participants, the view is widely held throughout the aerospace community that SDIO was only interested in a VTOL approach. Contractors that did not respond favorably to this approach were effectively excluded from consideration for Phase II of the program: the design of a prototype or "Y" vehicle, and the fabrication of an "X" subscale demonstrator. MDAC, widely considered to be the favored SDIO contractor from the beginning of the competition, was awarded the Phase II contract for approximately $60 million. This opinion, rightly or wrongly held, is reinforced by the fact that, while final reports have been completed, they have not been released to the aerospace community or the public.

The designated demonstrator vehicle, called the DC-X, is scheduled for flight in the spring/early summer of 1993. It has been designed to validate the nose

[6] The reception to a previous pair of briefings to this Council by the author in 1981 and 1983, were mostly negative due to the strong opposition of established aerospace contractors. Technically, little changed between these earlier presentations and the one in 1988; the Challenger disaster was largely responsible for the changed response on the part of Council members.

[7] This endorsement was actually quite significant. In the entire thirty-year history of the organization, this may well be the first report approved for release, which endorsed a major new idea proposed from outside of the Aerospace Corporation itself.

entry (as distinct from base entry) approach of MDAC as well as to demonstrate landing function. Interestingly, it will not demonstrate the most critical issue for practical SSTO: structural mass fraction[8]. The DC-Y prototype of the orbital operational vehicle is scheduled for its first suborbital flight in 1995, and a first orbital mission in 1997.

The Millennium Express

General Dynamics Space Systems Division proposed a VTOL SSTO named the Millennium Express as their answer to the requirements posed in the SDIO solicitation for Phase II. The final vehicle was a 15-degree cone with a 20%-length Rocketdyne aerospike engine. Payload was specified as 10K lbs into polar LEO. The Express had an ejectable crew cabin.

The Delta Clipper (DC-X and DC-Y)

McDonnell-Douglas Space Systems Division proposed a VTOL SSTO called the Delta Clipper as their answer to the requirements posed in the SDIO solicitation for Phase II. The principal difference between Delta Clipper and previous VTOL SSTO concepts is that the Clipper will reenter nose, rather than base, first. This decision was made to improve the limited crossrange available to base-entry vehicles. It remains to be seen whether the crossrange will be worth the price paid in additional thermal protection required for the lifting entry, as well as the forced acceptance of a less efficient structural concept (in contrast to a simpler base-first vehicle).

SDIO and the contractor have, as of this writing, been less than forthcoming about the details of the Delta Clipper. Since the program is not classified, all information associated with it should be freely available, at least to U.S. citizens. Unfortunately this

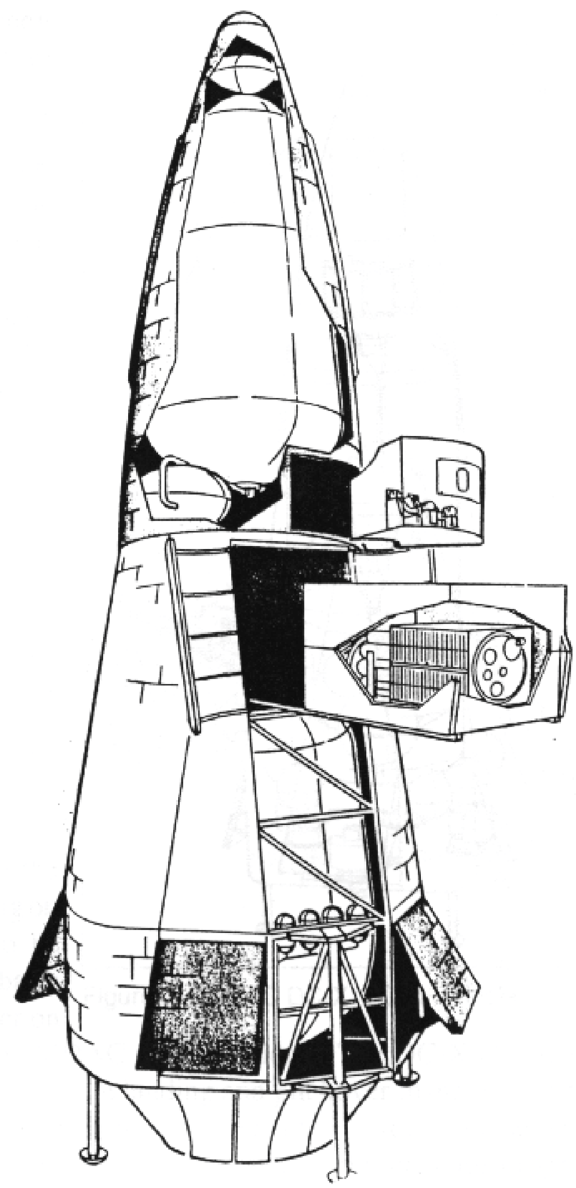

Figure 8 - MDAC DC-Y SDIO Vehicle

has not been the case to date. In fact, no information has been officially released about the vehicle dimensions, gross or empty weight, or mass fraction. Accordingly, it is impossible to assess the Delta Clipper design, or its prospects for achieving the goal of an operational VTOL SSTO before the end of the decade. We do know that there has been a major design change subsequent to the award of the development contract to MDAC. The aerospike

[8] It has often been said that SSTO is a problem of engine performance, thus the emphasis upon high Isp propulsion solutions, such as the United States National AeroSpace Plane (NASP). But in fact, as has been mentioned earlier in this paper, the problem is much more one of propellant mass fraction. In other words, lightweight structures. This has let many opponents of the SSTO concept to salve their consciences by claiming that SSTO is now possible only because of the advent of NASP materials, including advanced forms of metal matrix materials, new titanium alloys, and carbon-carbon heat shields. This explanation conveniently ignores the facts. None of the VTOLs proposed during the course of the Phase I SDIO study effort used any NASP materials, and the selected configuration - the Delta Clipper - also will not use any NASP materials (carbon-carbon was a proven technology long before NASP).

has apparently been replaced by 8 new, high-pressure bell nozzle rocket engines.

Based on analysis, however, certain observations can be made about the design. It would appear that a principal motivation for the vehicle configuration is to obtain high crossrange for the maneuverability required to perform military missions, rather than commercial flights. A September 1991 SDIO briefing document [Ref. 28] labels one chart "Global Reach...Global Power: Continental US to the World in Less Than One Hour". On the other had, nose-first entry does reduce the loads experienced by the crew and passengers to fewer than 2G, compared with 3G for base first lifting entries.

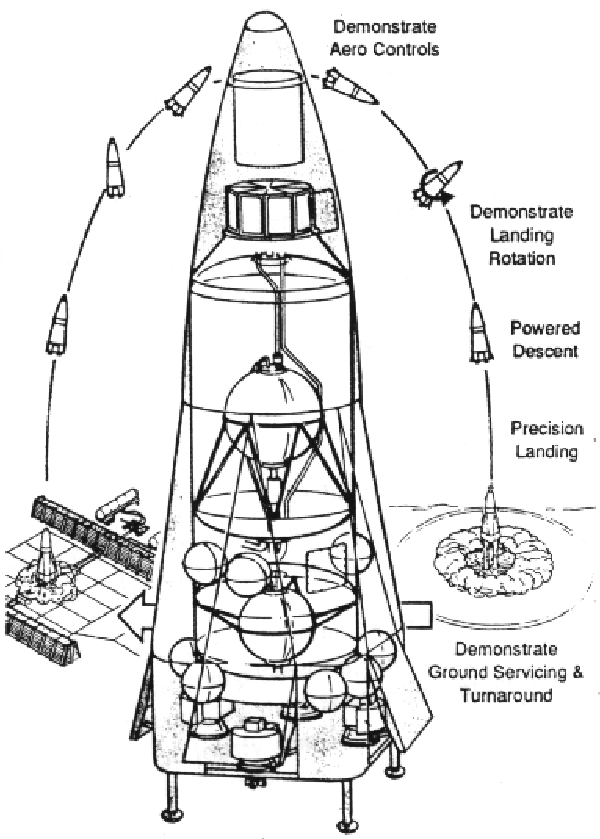

Figure 9 - MDAC DC-X SDIO Vehicle

Another observation is that the test program seems to be focusing on issues, which do not appear to be, critical for validation of the basic VTOL SSTO concept, but rather on uncertainties associated with the MDAC configuration. The DC-X effort, as mentioned earlier, seems to be concentrating on the landing and pitchover maneuver, to the exclusion of adequate focus on lightweight structure development. However, any assessment at this time is necessarily burdened by the purposeful fog, which obscures this program.

Common Issues for All VTOL SSTOs

All VTOL SSTOs must contend with several basic concerns, which can make or break any individual concept. More than any expendable rocket, and more in line with advanced commercial jet transports, a well-designed, practical SSTO must incorporate exactly the right combination of technologies necessary to achieve the goal of inexpensive, routine operation.

Without question, the issues of structural mass fraction, propulsion reliability and safety dominate this calculus. Anything which compromises either of these areas will likely result in a non-functional vehicle. A good analogy here is the well-known SR71 hypersonic aircraft. Justly lauded as a phenomenal achievement, it was nonetheless difficult to fly and maintain, and very labor and cost intensive. It will be all too easy to produce an SSTO which has the same characteristics, and which will fail the test of history.

All SSTOs require some form of altitude-compensating nozzle. It is a matter of the designer's taste and configuration choice that dictates which type, plug/aerospike or bell nozzle, best suits the design. If aerospike-like nozzles are used, they must be carefully analyzed to mitigate subtle performance losses, and to reduce excessive physical nozzle mass. The choice of turbomachinery also needs attention. By far the best choice would be an expander or hydrogen-bleed engine cycle, which is optimal for its tractability. Another consideration is NPSH (Net Positive Suction Head). While low NPSH pumps are difficult to develop, such a pump will pay for itself many times over by reducing tank weight and pressurization system mass. Most analysis of SSTOs have been performed by engineers used to the relatively high tank pressures associated with expendables; simply cutting tank pressure in half (from day 50 to 25 psia) will result in a nearly proportional mass reduction. Since tank mass is a major part of vehicle empty weight, such reductions are not insignificant. Similarly, reductions in engine mass through application of lightweight materials such as composites will have noticeable impact on dry weight.

The issue of dual-mode, single-fuel should also be readdressed. Reduction of tank volume will also have a proportional effect on empty mass, but one that might not pay in view of performance losses and increased engine mass for higher gross liftoff weights. Each vehicle design needs a careful, not cursory, analysis of this matter.

Thermal protection issues associated with VTOL SSTOs have not been resolved. A nose-entry vehicle such as DC-Y pays a heavy price for thermal protection; but due to the long heat pulse and higher integrated heating of the nose first reentry, there is little advantage to be had in active cooling. Base entry vehicles should seriously consider active cooling using transpiration, regenerative-dump, or water-wall/water-wick approaches.

Operability in all-weather is another feature which commercial launch systems should possess. (Active cooling is particularly suited to this requirement, due to the fragility of passive systems in precipitation.) But this issue also encompasses matters such as operation in winds aloft and near the ground during entry and landing. Very careful attention must be paid to this area if reasonable landing dispersions are to be achieved.

All in all, most of the problems that existed with earlier attempts to design reusable VTOL SSTOs can now be resolved. It remains a challenge to the designers to best integrate their options into a safe and inexpensive space transportation system.

CONCLUSIONS

The present SDIO SSTO program would not today exist if it were not for the efforts of pioneering designers such as Phil Bono and Edward Gomersall. During the long dry spell throughout the 1970s and 1980s, the effort was kept alive almost exclusively by the Phoenix effort, without any government-sponsored funding. Nearly all VTOL SSTO studies have been conducted outside the mainstream aerospace launch vehicle community, by talented amateurs, mavericks or outsiders, or by unconventional thinkers within government and industry who approached the problem of low cost space transportation from "first principles". That should send us a message.

A clear path to the proposed MDAC DC-X and DC-Y vehicles can be traced from SASSTO and Hyperion to Phoenix to X-Rocket/SSX. It remains to be seen whether VTOL SSTO will become part of the means to achieve inexpensive access to space, but if it does, the principal question future observers of the space transportation business will ask is: why did it take so long?

ACKNOWLEDGEMENTS

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Appendix - A Single-Stage-to-Orbit Thought Experiment

Since the first proposals for single-stage-to-orbit (SSTO) launch vehicles in the late 1940s, the chief criticism of the concept has remained the need for high mass fractions (ratio of propellant weight to loaded weight less payload) required for the concepts to be practical. Whether reusable or expendable, in many critics' minds the impossibility of SSTO remains tied to this issue. The purpose of this analysis is to dispel the concern over the issue of mass fraction. We propose to do this by means of a thought experiment.

Can any combination of existing or historical hardware, for which we know the precise weights and performance, be combined in a manner to yield a positive payload in low earth orbit in a single stage configuration?

The two systems, which we will review, are based upon two flown stages. The first concept employs the Saturn S-IVB stage, while the second uses the Shuttle's external tank (ET). In both cases we will baseline the Space Shuttle Main Engine (SSME) as the powerplant, even though higher performance could be achieved with a "clean-sheet" engine design.

S-IVB SSTO

The S-IVB was designed by the Douglas Aircraft Company in the early 1960s. At the time it was the largest LOX-hydrogen stage available, but it was soon overshadowed by the five-times larger S-II. The S-IVB was used for ten years, as both the second stage of the Saturn IB and the third stage of the Saturn V. In both applications the stage was subjected to far greater loads than it will see in our SSTO application. We should also note that the technology in this stage is now nearly thirty years old.

Table A shows the relative characteristics of both the S-IVB and the ET SSTOs. Reference [1] was used to compile S-IVB data and reference [2] was used for the ET.

Table A - Data for SSTO versions of the S-IVB and the Shuttle ET

	S-IVB	Shuttle ET
GLOW (lbs)	330,885	1,826,096
Number of SSME(s)	1	6
Isp (average)	425	425
Payload (lbs)[i]	10,360	59,064
Injected (lbs)	36,885	203,564
Propellant Weight (lbs) at 6:1	294,000	1,622,532
Propellant Volume (ft^3)	13,254	73,081
Average Prop. Density (lbs/ft^3)	22.2[ii]	22.2
T/W (at liftoff)[iii]	1.24	1.34
Lambda Prime	0.92	0.92
Delta V (fps)	30,000	30,000
Mass Ratio	8.971	8.971
Basic vehicle weight (lbs)	22,300	68,000
SSME(s)	+3,000	42,000
Thrust structure	--	30,000
Residuals (0.25% as achieved by S-IVB)	725	4,000
Avionics	500	500
Injected (less Payload)	26,525	144,500

[i] Any fairing weight and payload support provisions must be deleted from these numbers.
[ii] Assumes 5.5:1 mix ratio is changed to 6:1 without increasing tank volume, i.e. a floating bulkhead.
[iii] Assumes 109% SSME power level.

The S-IVB SSTO would be capable of placing about 10,000 pounds payload through a velocity increment of 30,000 feet per second. If the velocity requirement could be lowered to 29,300 fps (typical of a launch from the Cape), the increase in payload could be about 2,200 additional pounds. The weight of a payload fairing and support hardware must be subtracted from this number to obtain true capability.

Work by Bono (3) suggested that an S-IVB could be recovered at a penalty of 6,500 pounds. This would suggest that a primitive, but reusable SSTO could be built which would have a payload in the few thousand pound range, using twenty-year-old structural and propulsion technology.

Shuttle ET SSTO

A single-stage could also be made out of the Shuttle external tank by the addition of six SSMEs and a thrust structure to transfer the loads of the engines into the barrel of the tank. A generous 30,000 pounds was allotted to the thrust structure weight budget in Table A. No deletion of unnecessary hardware (such as the SRB load carry-thru structure, the orbiter attach bracketry, or the tank reinforcing beams) was postulated. (A weight savings of at least 10,000 pounds could be made here if desired.) Even so, a payload in the 60,000 pound class could be orbited in the expendable single-stage mode. Again, with a lower target for total velocity change, an additional 12,000 pounds of payload could be obtained.

Nearly 75% of the desired "heavy lift" NLS-class payload could be achieved without the expenditure of a dime on new technology. Wise use of newer high T/W engines, altitude compensating nozzles, high o/f mixture ratios or dual fuel, and modern structures would bring the payload to over 100,000 pounds at little risk, and in a phased developmental program. Recovery of the engines from orbit might reduce operating costs to an affordable level.

Conclusion

We have shown that off-the-shelf (or out-of-the-museum) flight-proven aerospace components can be combined to conclusively demonstrate the feasibility of SSTO. The addition of a dash of innovation, combined with remarkable advances in the state-of-the-art of materials, propulsion and avionics technology, which have occurred since the S-IVB, Shuttle ET and SSME were designed, would strongly suggest that a fully reusable, durable, and inexpensive SSTO could be fashioned without breakthroughs or further technology programs.

We do not propose that either of the conceptual vehicles discussed above actually be built. Rather, we suggest that a sensible and low risk program be initiated to explore the limits of present technology before spending vast sums on unproven or speculative programs. Such a program as we propose would have as its short-term goal the flight testing of a small SSTO, such as the Pacific American Phoenix or the Lockheed X-Rocket.

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