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# Why the X-33 VentureStar Gave SSTO a Bad Name

Carl F. Ehrlich, Jr[1]
*Retired*

**The X-33/Venturestar program was initiated by NASA in 1995 to develop a technology maturity demonstrator that would give future entrepreneurs the confidence that the technologies required for a commercially-developed Single Stage To Orbit (SSTO) vehicle were sufficiently matured to permit successful development to start by about 2000. The X-33 prototype was to demonstrate these maturities through a brief series of flight demonstrations. The Lockheed X-33/Venturestar concept was selected to fulfill this role. Taking note that the "Prime Directive" for designing an SSTO vehicle is to "keep the weight out," the resulting X-33 design that consisted of side-by-side tanks (2 hydrogen and 2 oxygen) plus an aeroshell to form the external shape clearly violated this rule. The failure of this design approach has had the residual effect that SSTO concepts are not viable. How did this happen? We have to go back to the beginning to the mid-1960s and a prophetic conversation by the author with a Lockheed person in the early 1990s. Lockheed had embarked on a continuing series of studies featuring side-by-side and nestled tanks that were reported periodically during that same period. This design path evolved to the X-33/VentureStar vehicle concept with the inherent design deficiencies. Thus, the X-33/Venturestar concept was doomed to failure as an SSTO at the outset. The eventual tank manufacturing problems only rang the final bell.**

## I. Introduction

Phase I of the X-33 program was instigated by NASA in 1995 to develop a technology maturity demonstrator that would give future entrepreneurs the confidence that the critical technologies required for a commercially-developed Single Stage To Orbit (SSTO) vehicle were sufficiently matured to permit successful development to start by about CY 2000. The X-33 prototype was to demonstrate these maturities through a brief series of flight demonstrations in realistic operational environments. The goal was to lower the cost from $10,000 per pound of payload to low earth orbit to $1,000 per pound to low earth orbit.

The Lockheed Venturestar concept was selected in 1996 to conduct Phase II of the program. The Phase II technical objectives (as described by NASA in its Cooperative Agreement Notice) were to implement:

> "*Technology demonstrations (flight and ground) must be implemented to reduce the business and technical risks to produce the capability to have low development and operations costs which will enable privately financed development and operation of a [low cost] next generation space transportation system.*
>
> *The X-33 flight system, subsystems, and major components shall be designed and tested (in flight and ground) so as to ensure their traceability (technology and general design similarity) and scaleability (directly scaleable weights, margins, loads, design, fabrication methods, and testing approaches) to a full scale SSTO rocket system. Technical objectives include improved mass fraction for vehicle structures and improved thrust to weight for rocket propulsion systems.*
>
> *"The X-33 system must demonstrate key "aircraft like" operational attributes required for a cost effective SSTO rocket system. At a minimum, key demonstrations should include: operability (e.g., increased Thermal Protection System (TPS) robustness, weather, etc.), reusability, affordability, and safe abort…."*

Taking note that the "Prime Directive" for designing an SSTO vehicle is to maximize the propellant mass fraction (or, conversely, to minimize the structural mass fraction): i.e., "keep the weight out," Figure 1, and others like it, has been around for years. It portrays the basic design issue of SSTO concepts versus the more efficient two-stage systems. The latter can reach orbital conditions with most available materials technologies. Without sufficient attention to inert weight or the lack of advanced materials, SSTO weight growth becomes asymptotic and fails. Its only when advances in technologies permit significant weight reduction (or, more correctly, weight avoidance) that single stage systems can avoid immense weight penalties and become viable design concepts.

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[1] AIAA Associate Fellow

The three principal candidates that were proposed are illustrated in Fig. 2. The Rockwell candidate was designed as an elementary cone-head rocket with wings attached to enable a horizontal landing on a runway. In this approach, the wing loads were carried through the aft spar directly to the thrust structure, while the forward wing spar carried the loads into the intertank structure forward of the oxygen tank (the aft tank). This design was to make the propellant tanks to be the primary load-carrying structures while minimizing or eliminating the need for secondary structures throughout.

The McDonnell-Douglas concept was quite similar in that it was also basically a cone-head rocket but in this case carried additional propellants to enable a vertical landing at a prepared site, much like the earlier DC-X experimental vehicle. This extra propellant was most likely carried in additional tanks, separate from the main ascent propellant tanks. Thus, the weight assessed for the additional tanks and propellants essentially matched the wings of the Rockwell concept.

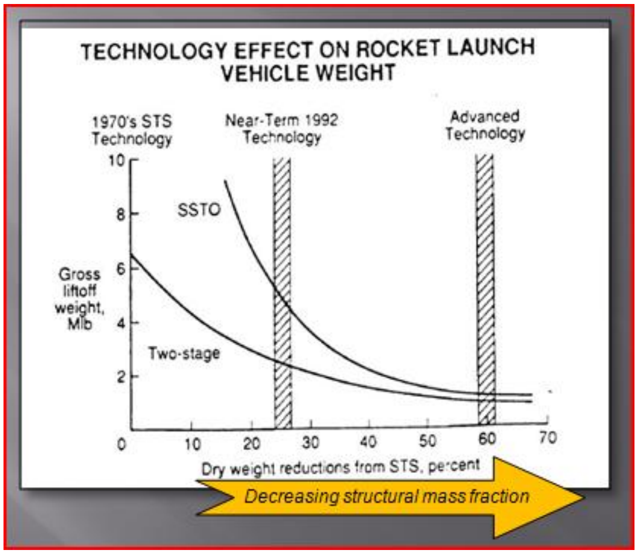

**Figure 1. Decreasing mass fraction through technology advances increases the likelihood that the design and development of SSTO concepts can succeed.**

On the other hand, the Lockheed-Martin Venturestar/X-33 concept employed two cone-head rockets to do the job of a single set of tanks in the other concepts, as can be seem in the left illustration in Fig. 3. Note that the two forward tanks are fused together. Finally, an aerodynamic shell was required to provide a clean aerodynamic shape and to mount the Thermal Protection System (TPS), as can be seen in the right illustration in Fig. 3.

**Figure 2. The three major competitors for the X-33 program were concepts from Rockwell, McDonnell-Douglas, and Lockheed-Martin, International (later Boeing).**

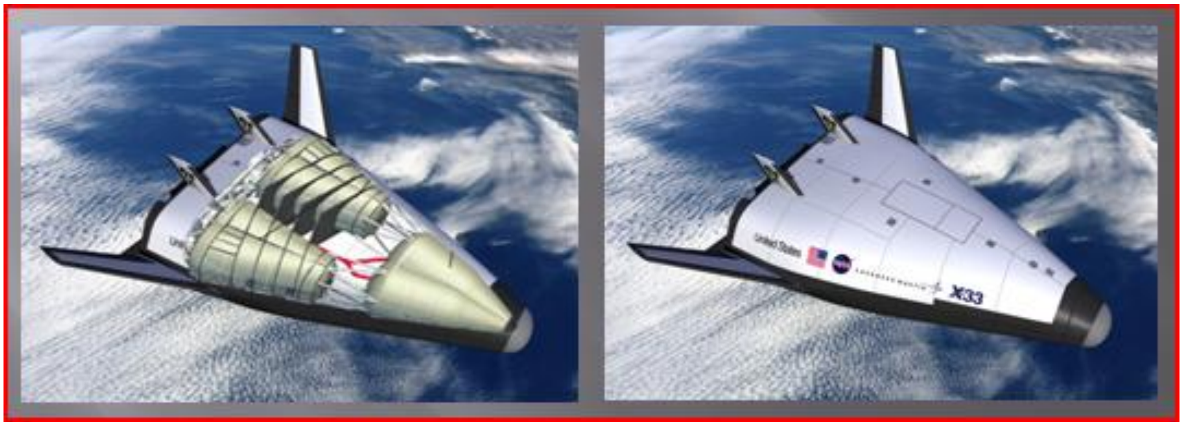

**Figure 3. The design concept broke the “Prime Directive” for SSTO design by incorporating two sets of tanks plus extensive secondary structure to support the required aeroshell.**

## II. Venturestar/X-33 Design Approach

The “Prime Directive” of SSTO design focuses the approach on minimizing the primary structure while the complexities of lifting body design require that the configuration aerodynamic development regard the total 360 degree flow field right from the start of design. The Venturestar/X-33 development departed from these ideals.

### A. Structural Concept.

The “twined tank” approach set up the rest of the design and development process for built-in and unavoidable weight penalties. This all followed directly from the two cone-head rockets doing the job of one: they had mor surface area, had to be tied together laterally, load also had to be sheared laterally, and, finally, an aeroshell had to beaded to cover all this up and support the TPS. Thus, the structural mass fraction was severely compromised.

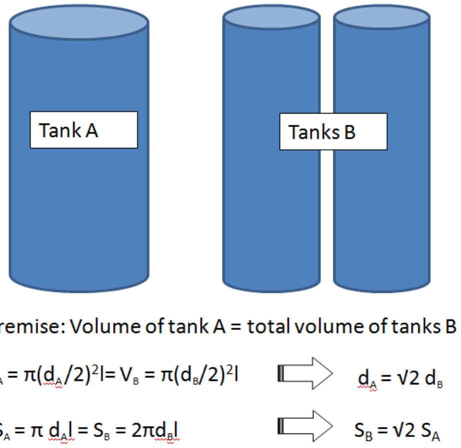

**Figure 4. Twin cylindrical tanks holding equal volume_as a single tank have about 40% more lateral surface area than a single tank.**

Twin cylindrical tanks holding the same volume as a single tank have a total (lateral) surface area of ~1.414 (sqrt 2) times the area of a single tank, Fig. 4. Therefore, the total tank weight had to increase because it is well established that tank weight is concentrated in its shell surface.

Then these tanks had to be tied together laterally in several places both for relative positioning and to resist in-flight bending and torsion. Again the installed weight had to increase.

The engine thrust had be sheared laterally to each tank set, adding thrust structure, and again the installed weight had to increase.

The aerodynamic shell which supported the TPS required significant secondary structure for support, Fig. 5. Therefore, the system weight again had to increase.

The metallic TPS, which was one of vehicle’s the paramount design features, required multiple clips for attachment, Figs.6 to 8. Therefore, the TPS installed weight had to increase.

All of these weight increases required by the basic design approach, therefore, individually and collectively violated the Prime Directive of SSTO design:

**“Keep the weight out.”**

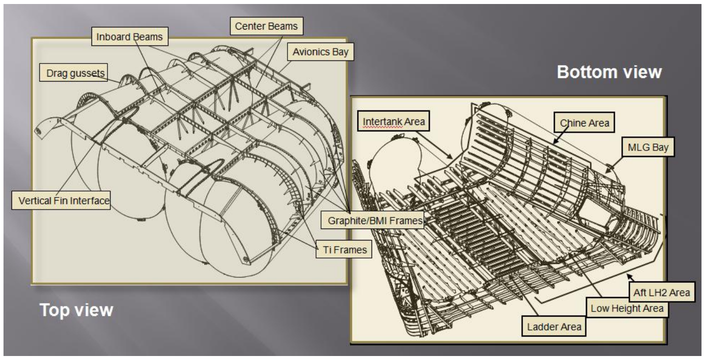

**Figure 5. The secondary structure needed to support the aeroshell was very complex.**

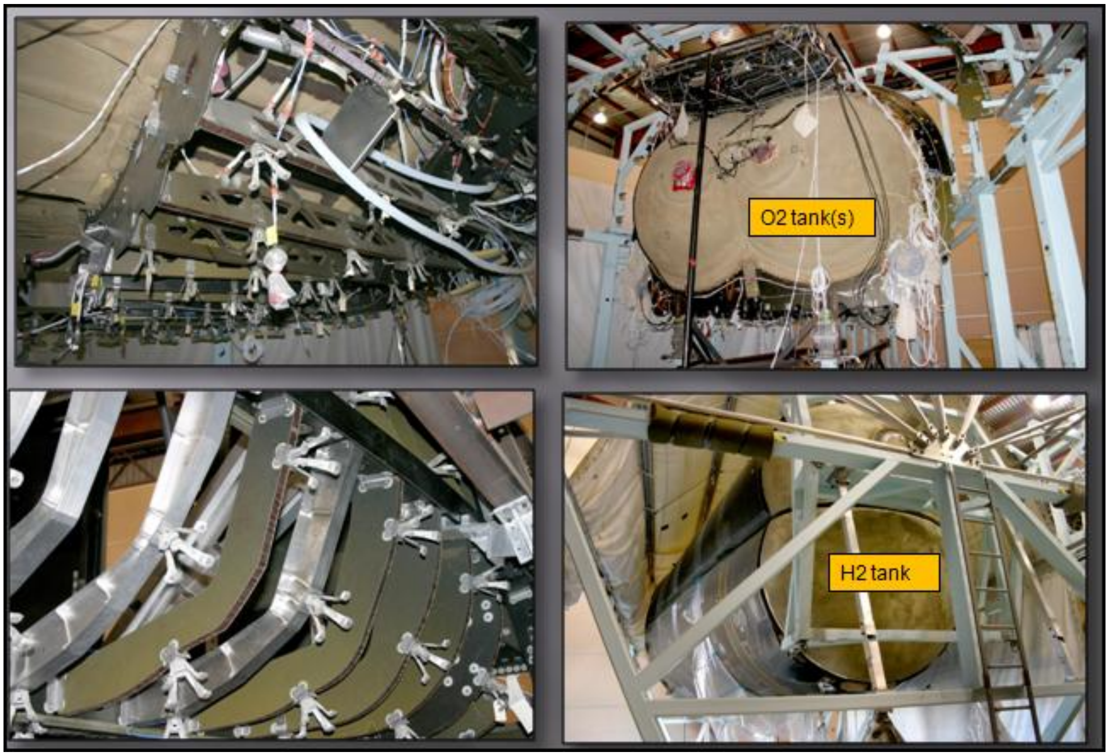

**Figure 6. Structural details - general views of the complex secondary structure.**

**Figure 7-1. The secondary structure had to be dense to support the TPS attachments.**

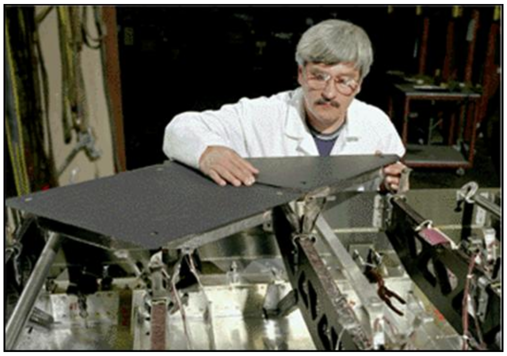

**Figure 7-2 Careful fitting was required for TPS installation.**

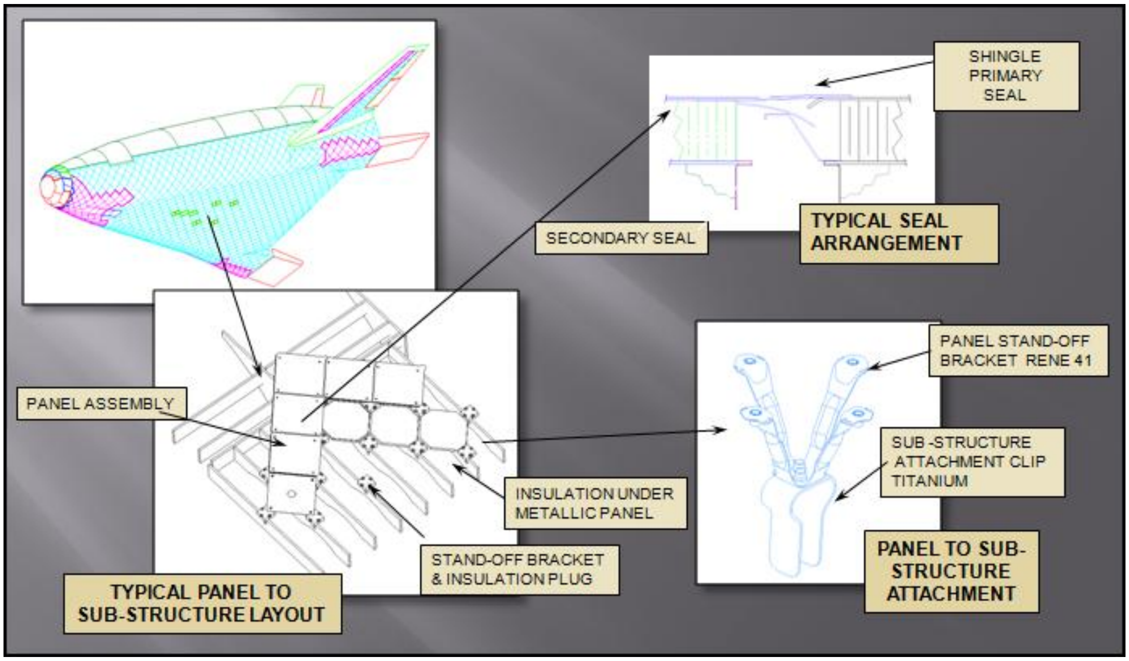

**Figure 8. Metallic TPS panel array integration was very complex.**

### B. Aerodynamic Considerations.

Lifting body entry vehicles, in particular, have unique design considerations that are fundamental. For instance, when considering longitudinal stability characteristics, one must understand that the natural location of the aerodynamic center at subsonic speeds is somewhere near 55% of the overall length without making allowances for the body contours and fins/wings. At the higher speeds encountered on entering the atmosphere, Newtonian flow takes precedence. Then the center of pressure is at about 2/3 (66%) of the overall length, which is the centroid of the planform area. It will vary from this location again depending on the influence of the body contours and fins. But these are all good and reliable first order rule of thumb estimates.

Likewise, the center of gravity will be somewhere aft of 68% due to the weight of the installed propulsion system. One needs to recognize that the propellant tanks will be empty during entry and the payload may or may not be on board (failure to deploy, etc.). This means that the vehicle center of gravity will be somewhat variable and must be accommodated by the aerodynamic control system.

Now clearly, lifting surfaces must be provided aft to compensate for the expected variations in the center of gravity, the entry center of pressure, and the subsonic aerodynamic center and yet provide adequate margins for longitudinal stability

Visual inspection of the Venturestar/X-33, Fig. 9, suggests that the initial outboard fin arrangement appears to be inadequate for this purpose, as they are more vertical fin-like than wing-like. Following this line of reasoning, one would suspect that the outboard fins would have to become more efficient lifting surfaces at least low speeds in order to “pull” the subsonic aerodynamic center more in line with expected the center of gravity. This infers, then, that there would have to be a considerable effort expended to “balance” these diverse requirements, plus all of the intermediate speeds.

Thus, the initial Venturestar/X-33 outer fins had to become more like wings. Therefore, the installed weight had to increase.

Additionally, the central fins are clearly operating in the uncontrolled upwash from the large nose cap and the probably separated flow over the upper body. They also appear to be inadequate in the initial design and would have to become much larger, and heavier, to be effective for yaw stability.

Collectively, these considerations directly imply that more weight would have to be added aft, further compounding the stability margin considerations.

### C. Collected Findings.

Since the X-33 represented the Venturestar/RLV design concept, it was clear that the full scale RLV would have significantly broken the “Prime Directive” of SSTO design.

**Figure 9. Initial fin arrangements were incompatible for aerodynamic stability.**

- Twinned tanks increased tank surface area
- The tanks had to be tied laterally to maintain their structural integrity
- Engine thrust had to be sheared laterally to the tanks
- The aeroshell required secondary structure for support and to mount the TPS
- The metallic TPS required multiple clips for attachment
- Longitudinal and lateral aerodynamic stability required larger center and outer panels

These complexities all would have resulted in increased weight. Thus, the structural mass fraction had to have increased significantly at the expense of propellant mass fraction. Thus, the basic concept appeared to be fatally flawed as an SSTO design approach. To find out how this happened, we must review that historical background of the Venturestar concept.

## III. Origins Of The Design

How did all this happen? Well, we have to go back to the beginning in the mid-1960s and to a later prophetic conversation between the author and a Lockheed person in the early 1990s.

### A. Early Entry Vehicle Design Features.

Some of the earliest concepts for reusable entry vehicles were well under way by the mid-1060s. From these early developments, the well-known Air Force’s X-24A, NASA’s HL-10, and M2F2 flight test articles were developed. The Air Force’s Flight Dymanic Laboratory (forerunner of the present Air Force Research Laboratory), was separately undertaking research in the hypersonic flight regime. These developments were originally conceived as hypersonic research vehicles with performance goals of : L/D=3 at Mach=20, and 200,000 ft. altitude One of these developments was the FDL-5A lifting body vehicle, Fig. 10. It featured a long slender nose, now typical of hypersonic flight vehicles, very sharp (for that era) leading edges, a single vertical fin, and side panels to provide directional stability and dihedral effect. These surfaces originated the “compression-sharing” concept which characterized the shared aerodynamic loads of the lateral and upper aft surfaces – at least at low angles of attack – eliminating the need for fins at entry angles of attack.

This configuration was tested extensively at all Mach numbers. One of the more significant tests were vapor screen flow visualizations conducted the Arnold Engineering and Development Center (AEDC) in the mid-1060s. These were conducted over a range of Mach numbers to visualize the flow field surrounding the vehicles and to better understand its aerodynamic and aero-thermodynamic characteristics. Some of the results at Mach = 3.5 are shown in Fig. 11.

**Figure 10. FDL-5A high hypersonic L/D research vehicle ca. 1967.**

In these tests, a narrow sheet of light was projected across the test section after the flow had been cooled slightly to liquefy a portion of the air to create a cloud. The dark areas in the illuminated area depict regions where the flow had been re-vaporized by the local vortex flow field energy. The left image of Fig. 11 shows the leading edge vortex at about the mid-length of the body plus a group of separation vortices along the upper centerline. The right image shows that these vortices had all combined into an energetic flow field.

The local energy of this flow explained the effectiveness of the centerline vertical fin that we had seen in earlier tests, even though the fin was obscured at higher angles of attack by the body – at least in the Newtonian sense. We then rationalized that if this flow made the fin effective in yaw, then it could also have a similar effect in pitch, if the flow was suitably deflected. These thoughts gave rise to the upper body panels outlined in white in Fig. 12 next to the fin. This is exactly what turned out to be true – and at all Mach numbers, which was even better yet. As the elevons deflected into the body base flowfield, the upper body panels could be deployed to provide extended pitch control at higher angles of attack. Thus, we eliminated a very significant pitch control limitation above 12-14 deg. angle of attack and we were able to achieve pitch trim at all flight angles of attack at all speeds.

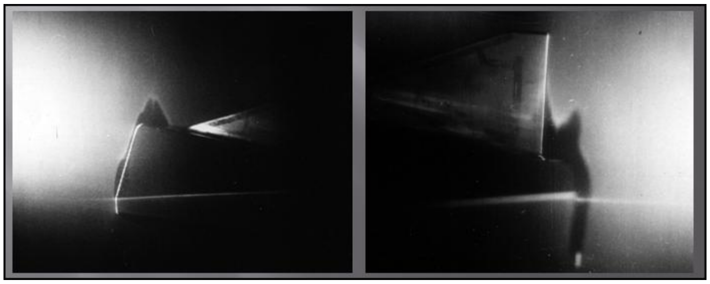

**Figure 11. Vapor screen tests revealed unexpected but profound design features of the leading edge vortex flow fields.**

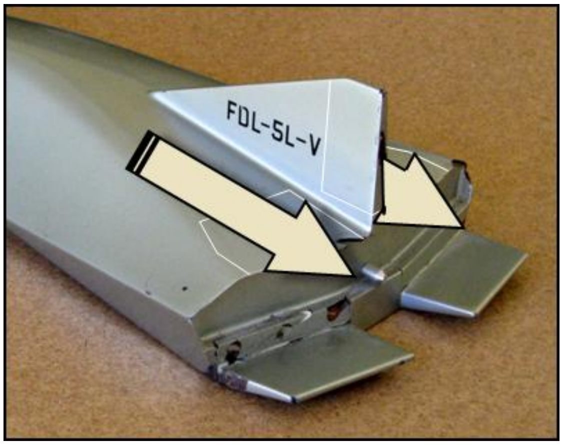

**Figure 12. Upper body vortex flow field enabled effective control in both pitch and yaw at higher angles of attack.**

The author looks back at these findings as a profound moment in his developing experience. When developing lifting bodies, or even body-dominated wing body concepts, one must consider the entire flowfield, windward and leeward, to fully and properly develop the vehicle. This implies that flow visualization data be obtained whenever possible.

Consideration of these vortex flow phenomena played a critical role in Lockheed's proposed Space Shuttle lifting body design efforts. Since the Space Shuttle reference design missions did not require the high hypersonic L/Ds of the earlier FDL-5A, the leading edges were allowed to increase somewhat. The target design $L/D_{max}$ was determined to about 1.2 to permit sufficient crossrange for a return to launch site at Vandenberg AFB following a polar launch azimuth. The configurations resulting from this design approach are shown in Fig. 13. The left image shows the vehicle as proposed and the right image shows the vehicle after more refinement during a follow-up contractual design effort. The latter vehicle achieved a

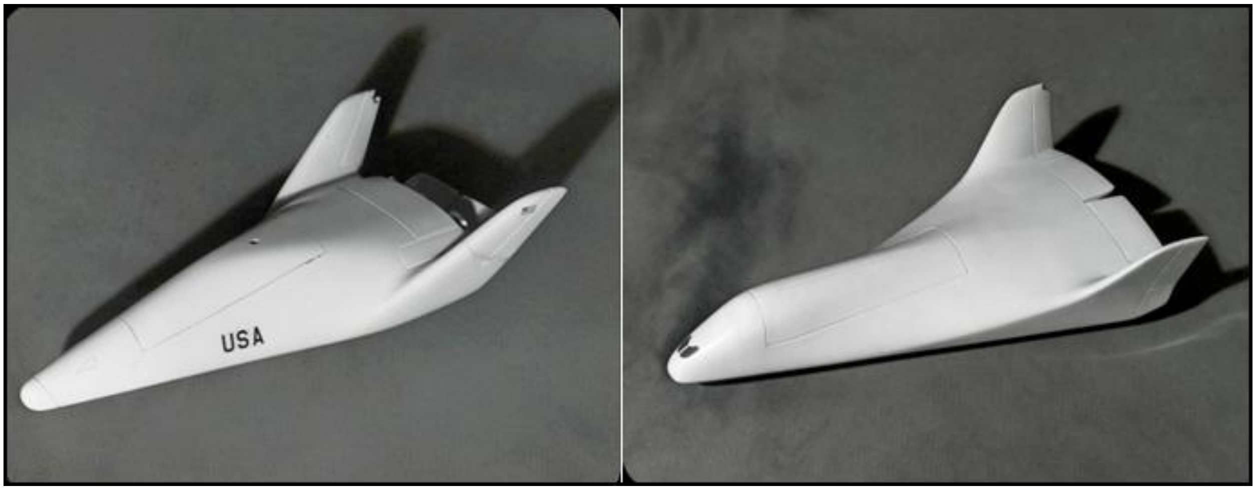

**Figure 13. Upper body flow field features controlled by the leading edges were critical to Lockheed's proposed Space Shuttle candidates, as reflected in early (left) and later (right) concepts.**

trimmed $L/D_{max}$ of 5.85 at landing. The fins on these vehicles were simply extensions of the side body panels of the FDL-5A that were needed as the vehicle CG moved considerably aft with the addition of ascent propulsion system. The outer fins then became, in part, end plates that served to increase the effective aspect ratio of the body, thus increasing the effective lift/drag ratio. Retention of the leading edge vortex flow fields to control the upper body flow fields at higher angles of attack was therefore crucial to these design efforts.

### B. Prophetic Conversation and Subsequent Events.

Fast forwarding to the early 1990s, the author had a chance conversation with a person who will be identified as "Joe," whom the author had known since our early days at Douglas Aircraft in Santa Monica, CA. We were wearing different corporate hats by then: I was Rockwell's Study Manager for the NASA/Personnel Launch System study and he had a significant role at Lockheed.

"Joe" noted that he wanted Lockheed to get back into the spacecraft business: His plan was to take the Lockheed Shuttle configuration and substantially increase the leading edge radii (LER) so as to decrease the LER heating and allow lower temperature TPS on those surfaces. The LER could then do double duty and become full body depth propellant tanks.

That planned leading edge treatment was a fatal error as "Joe" didn't understand the critical role that the leading edge vortices played in the design of Lockheed's Space Shuttle lifting bodies concepts. Since we were in a competitive environment at the time, the author didn't explain this pitfall that opened up for them as they took that design path.

Lockheed then embarked on a continuing series of studies featuring side-by-side and nestled tanks (Fig. 14) that were reported periodically in trade magazines later during that same period. The tanks had varying amounts of structural fairings. This approach eventually led to the development of an Aero-Ballistic Vehicle concept, Fig. 15.

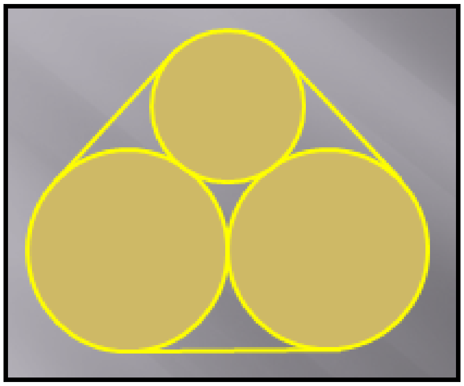

**Figure 14. Lockheed then embarked on a continuing series of studies featuring side-by-side and nestled tanks.**

This design path, in turn, led to the VentureStar vehicle. With this configuration incorporating the very large leading edge radii, the critical upper body flowfield was severely compromised. The body flowfield would be late in rolling up into vortices (if at all) with no benefit to the control of the upper surface flow field. The central fins would then operate in essentially the upwash from the blunt nose. The outer or side fins would provide little aft lift where it was clearly needed for low speed stability.

Hence, as shown in the near final Venturestar/X-33 configuration, Figure 16, the outer fins had become much larger and rolled down to provide the necessary aft lift for longitudinal stability. The central fins had become much larger to operate in a more organized flowfield. Therefore, more weight had been added aft which, in turn, added to the structural weight margin. For all practical purposes, then, the Venturestar/X-33 had become a wing-body vehicle with an oval cross-section,

**Figure 15. This design path led to the development of an Aero-ballistic vehicle concept.**

The proposed full scale Venturestar/RLV displayed even greater departures from the original sub-scale X-33, Fig.17. It now had an external payload bay, to provide additional internal propellant volume. However, this change must have incurred additional weight penalties due to the added structure and wetted area that required more TPS protection. The wings had a much greater span and the fins had been moved to the wing tips. Even with these departures from the original X-33, substantial traceability was claimed.

Thus, the concept was doomed to failure at the outset as the structural mass fraction penalties inherent to this approach had to be far greater than allowed by "Prime Directive" of SSTO design. The eventual tank manufacturing problems only rang the final bell on the SSTO Venturestar/X-33 development effort.

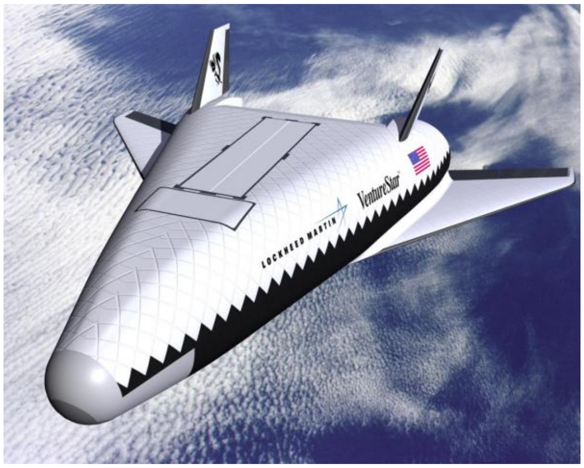

**Figure 16. Venturestar/X-33 aerodynamic changes included larger, more horizontal fins (wings) and larger vertical fins.**

**Figure 17. The full scale Venturestar/RLV appeared to be heading toward an external payload bay, possible to create more internal propellant volume.**

## IV. Closing Remarks

After the X-33 program was under way for several years, The Congressional Subcommittee on Space and Aeronautics of the Committee on Science, House of Representatives expressed concerns about technical difficulties encountered by the X-33 Program, the United States General Accounting Office (GAO) was requested to review the progress of the program. The GAO found, in part, that:

> *"problems encountered by Lockheed Martin while working toward the X-33 Program's technical requirements have caused cost increases, delay of the test vehicle's first flight, and revision of some performance objectives. The technical problems occurred during development and fabrication of the X-33vehicle's internal fuel tanks, rocket engines, and thermal protection system, the three key advanced technologies the program seeks to demonstrate."*

Among other design elements, the GAO report indicated that the vehicle's projected weight would exceed design requirements. Continuing, the report also said that:

> *"…Lockheed Martin and NASA program officials told us that weight reduction measures have already been incorporated into the preliminary design of the Venture Star RLV to meet the vehicle weight requirements.*
>
> *"The weight reduction measures are based on lessons learned designing and building the X-33 test vehicle. One of the weight-saving modifications is to attach the Venture Star vehicle's thermal protection system panels directly to the vehicle's interior structure and fuel tanks, eliminating the weight of the attachment structures used on the X-33 vehicle. Other weight-reducing modifications for the Venture Star RLVs include lighter weight composite and ceramic engine components and composite internal liquid oxygen tanks. Although the composite and ceramic components have not been demonstrated, NASA and Lockheed Martin plan to reduce the technical risks of providing these technologies for the Venture Star RLVs through ground-based demonstrations during the X-33 Program. "*

Nowhere does it say anything about changing the structural concept to resolve the critical and fundamental mass fraction problem for the Venturestar!

Thus, the Venturestar RLV as visualized by the X-33 was doomed to failure at the outset as an SSTO because: the original and fundamental aerodynamic concepts were abandoned; inefficient structural concepts were adopted, thus contributing to the structural mass fraction penalties; and finally the well-noted tank manufacturing problems only rang the final bell.

Since the end of the X-33 program, the broad category of Single Stage To Orbit system concepts have been left with a bad reputation. To be sure, a single stage concept can be a challenging venture, but, in spite of all this, a successful SSTO operational system can truly be achieved with an informed and proper design. By paying strict attention to the all-important structural and propellant mass properties (i.e., the "Prime Directive") while maintaining detailed oversight of the full aerodynamic flow field, a successful vehicle design can be developed and operated.

But maybe there is another aspect to a design that is struggling. Perhaps a willingness to partially or completely retreat to an alternate approach would be a valid attribute. The development of advanced concepts is really an act of discovery: once the basic definitions are made, the concept takes on a life of its own: it knows what it has to be to meet the requirements and it gives one clues through the data generated, Just like a good detective novel, one knows that the solution is there, but here one can't look at the last chapter to see it. Therefore, if the design is giving trouble it's saying the clues its giving out aren't being paid their due attention. Be prepared to back up a little bit or back up considerably, even to a new starting point. The right answer will show up as a nice neat package where everything "fits." Remember that 85% of the Life Cycle Cost is committed before 15% of the budget is spent!

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