3. Design Options and Issues

In this section we review design issues relating to future TAV development, including the advantages and disadvantages of alternative TAV launch and landing modes and those of multiple or single-stage TAV concepts. We also review the RLV and TAV presented at the RAND TAV workshop.

Launch and Landing Modes

Reusable launch vehicles or TAVs can be placed in three categories according to the modes of launch and recovery they employ. In contrast, traditional expendable space launch systems are vertical take-off systems, which by definition have no recovery modes.[1] The three categories are discussed below.

Vertical Take-off and Horizontal Landing (VTHL)

The Space Shuttle Transportation System (SSTS) is the archetypical example in this category. The SSTS first-stage elements—the solid rocket boosters and the external fuel tank—are expended about 100 seconds into launch after a vertical ascent from the launch pad. The shuttle itself continues on to orbit and after reentry lands horizontally like a airplane. Another example is the Rockwell X-33 concept, which will be discussed in more detail later in this section.

VTHL vehicles are typically aerodynamically stable in flight on their return descent trajectories, although they may, like the shuttle, have relatively low lift-to-drag ratios (L/D), which imply high landing speeds. These types of vehicles need have landing gear designed for only landing loads and not for the full vehicle Gross Lift-Off Weight (GLOW).

On the launch pad and during the early stages of ascent, the vehicle structure must be designed to take full gravity and main engine thrust loads in the vertical direction.

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[1]The solid rocket boosters of the Space Shuttle Transportation System are recovered from the ocean after splash down, and Boeing has worked for several years on a partially recoverable first-stage booster rocket system in which high-cost engines and turbomachinery would be recovered after splash down.

Vertical Take-off and Vertical Landing (VTVL)

To date, no operational reusable launch vehicles have been developed that fall into this category. However, the McDonnell Douglas X-33 concept and DC-X flight demonstration vehicles are VTVL designs. These vehicles have ballistic missile aerodynamic characteristics and no wing structures, providing an advantage during ascent because there are no parasitic drag losses due to wings. However, this type of vehicle design can result in high reentry speeds and high aeroshell heating rates during reentry. This may lead to the disadvantage of greater thermal protection requirements on reentry and increased vehicle mass for the vehicle thermal protection system (TPS).

Landing is accomplished by restarting and firing the main engines. This increases total mission propellant requirements, but results in reduced structural weight because wings and related structures are not needed. An increase of approximately 1000 ft/sec in ideal velocity is needed for vertical powered landing.[2] Studies have indicated that there is no overwhelming advantage or difference in overall vehicle weight (GLOW) between vehicles using horizontal and vertical landing modes. However, there are increased risks of mission failure with vertical landing systems because of requirements for main engine restart, the high thrust levels potentially needed, and precise thrust vector control needed at landing and after reentry and exposure to the space environment.

Horizontal Take-off and Horizontal Landing (HTHL)

There are no current examples of an HTHL system. The Pegasus winged booster rocket is a horizontal take-off vehicle that is released at altitude from a first-stage carrier aircraft. The system is composed of a B-52 or L-1011 carrier aircraft and a winged rocket vehicle with three stages. About 5 seconds after Pegasus is dropped from the carrier aircraft, the first-stage solid rocket motor ignites. The rocket accelerates and uses aerodynamic forces to change its trajectory and pitch upwards. One advantage of an HTHL system is that lift forces can be used to adjust the ascent trajectory as needed in the atmosphere and to counteract gravity losses.

At take-off, the HTHL vehicle must possess landing gear capable of handling the full gravity loads of a fully fueled vehicle. Thus, the landing gear can be quite heavy, which has led to HTHL designs in which the vehicle first stage is a rocket or jet powered sled containing the landing gear. Once take-off speed is

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[2]R.L. Chase, *A Comparison of Horizontal and Vertical Launch Modes for Earth-to-Orbit NASP-Derived Vehicles*, AIAA 91-2388, AIAA/SAE/ASME 27th Joint Propulsion Conference, June 24–26, 1991.

established, the second stage HTHL vehicle would separate from the supporting sled and take off like a conventional aircraft. Such HTHL systems may suffer from a significant operational disadvantage because they have to operate from air bases with extraordinarily long runways to accommodate sufficient stopping distance for the first-stage sled.

Vehicle Staging

To date all operational space launch vehicles have been multistage systems in which booster rockets separate from the launch vehicle at some point in the ascent trajectory. Because heavy first-stage rocket engines and tanks are expended during ascent, the mass of upper stages can be reduced considerably relative to the payload carried. The ratio of payload to total stage mass is considerably higher for an upper stage. In other words, vehicle staging can significantly reduce the delta-V required for the final upper stage to reach orbit. Vehicle staging may be accomplished by using a launch platform, by in-flight propellant transfer to the orbital vehicle, or by use of conventional upper stages.[3]

The launch platform can be either an aircraft or a sled, and the aircraft launch platform could carry and release the orbital vehicle in a variety of configurations. It could carry the orbital vehicle underneath its fuselage and release the vehicle in an air-drop maneuver. The orbital vehicle could be mounted on top of its fuselage and be released when in a dive or pitch-up maneuver. Or it could tow the orbital vehicle to the release altitude and launch it by releasing the tow line.

Adding stages to a launch system increases performance and the payload delivered to orbit, but vehicle complexity is increased. Each stage requires its own separate propulsion system and tankage. Stages have to be programmed or commanded to separate at appropriate times during ascent, which may require independent avionics systems for each stage, communications relays between stages, and explosive bolts or other mechanisms to ensure proper separation.

Single Stage To Orbit Systems

An SSTO vehicle would be a single integrated vehicle that would not expend components during its ascent to orbit. Such a vehicle would also reenter and land either horizontally or vertically for subsequent launch and reuse.

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[3]Gregory, Bawles, and Ardeura, *Two Stage to Orbit Airbreathing and Rocket System for Low Risk, Affordable Access to Space*, NASA, April 1994; and U. Mehta, *Air-Breathing Aerospace Plane Development Essentials: Hypersonic Propulsion Flight Tests*, NASA TM-108857, November 1994.

Developing and demonstrating an SSTO system will be a difficult challenge because of the delta-V and vehicle mass fraction required. However, these daunting challenges may possibly be met by using advanced lightweight composite materials to reduce vehicle empty weight, high specific impulse propulsion systems to increase performance, or air-breathing engines to reduce the amount of oxidizer (and thus GLOW) required to achieve orbit. [4]

Various SSTO programs have been embarked upon in the recent past, perhaps the most notable being the NASP program, which was based on a complex air-breathing propulsion concept. The technology challenges associated with air-breathing propulsion systems and other aspects of this design approach proved so difficult that no prototype vehicle was ever built.

More recently, NASA has initiated the X-33 program, whose goal is to demonstrate key SSTO technologies by the year 2000, leading the way for an eventual operational vehicle that could replace the space shuttle and existing expendable rocket boosters. The competing X-33 designs and the winning system are described in more detail later in this section.

Operability may be one advantage of an SSTO system over multiple-stage vehicles. The latter may require additional support infrastructure because of the complexity of multiple-stage systems. On the other hand, an SSTO system may be inherently more complex than a staged system because of the additional performance demanded of the propulsion system and because of other technologies necessary to gain the performance levels needed to reach orbit.

The supporting infrastructure for an SSTO system may be smaller and less expensive than for a multiple-stage system, but this will probably be sensitive to whether a horizontal or vertical take-off mode is adopted, as this difference can distinguish between aircraft-like operations and the need for specialized space launch complex support.

Two Stage to Orbit (TSTO) Systems

The simplest multistage space launch system would have only two stages. For a reusable TSTO system, both stages would be reusable. If one imagines what a reusable TSTO system could look like, the original German Sanger HTHL concept immediately comes to mind. The first stage would use air-breathing

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[4]F. S. Billig, "Design and Development of Single Stage to Orbit Vehicle*s*," *Johns Hopkins APL Technical Digest*, Vol. II, Nos. 3 and 4, July-December 1990.

propulsion and operate much like an aircraft. The second stage would be a rocket-powered orbital vehicle.

TSTO Air-Launched Concepts. The German Sanger concept is but one example of a TSTO air-launched system. In the original Sanger proposal, the orbital vehicle was carried on top of a specially designed first-stage supersonic Mach 6 aircraft that had no central rear tail structure, making vehicle release relatively straightforward.

If both the first- and second-stage vehicles were designed specifically for a TSTO system, they could be integrated into a combined vehicle configuration in a number of ways. The staging maneuver could potentially be performed at subsonic or supersonic speeds. An air-drop stage separation maneuver is relatively easy at subsonic speeds, as illustrated today by Pegasus. Air launch of the orbital vehicle from on top of the carrier aircraft may be a more difficult maneuver to accomplish if the carrier aircraft is not specially designed for such a maneuver. However, it is important to note that the shuttle was successfully air launched from on top of a specially modified B-747 ferry vehicle during landing tests. The carrier vehicle used in those tests is the current Shuttle Carrier Aircraft (SCA), a modified B-747-100 with an augmented vertical tail for increased stability when mated to the shuttle. The SCA can ferry vehicles that weigh up to 236,000 lb.

Supersonic vehicle separation is also feasible and was demonstrated several decades ago in operations in which the SR-71 air-launched a ramjet-powered drone at Mach 3 speeds. The cause of the one vehicle separation failure during these SR-71 drone operations was later discovered, and it was determined that the SR-71 air-launch maneuver could be safely executed at Mach 3.[5]

An important issue for all proposed space launch systems is development cost. In the case of an SSTO system, cost may not be minimized significantly by using existing vehicle systems or subsystems. However, it may be possible to use existing aircraft for the first stage of an air-launched HTHL system. The overall acquisition cost for a TSTO system would be significantly reduced if a commercial jumbo jet were modified for this purpose (development of a new jumbo jet can cost as much as $5B, or as much as a new launch vehicle). In contrast, if jumbo jet aircraft were bought off of a commercial production line, the unit cost would probably be less than $200M.

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[5]Private communication from Bruno Augenstein of RAND.

Potential carrier aircraft include the current SCA, the B-747-100, the commercially available B-747-400, the potential future commercial variant of this four-engine jumbo jet (the B-747-600X), and the Russian AN-224 large transport aircraft. The maximum take-off weights of these aircraft are given in Table 3.1. From the table it is apparent that planned future aircraft could provide 30 percent or more lift capacity than the current SCA.

Air-launch platform designs offer other potential advantages, such as not having to use fixed launch pads, and they could enable a dramatic departure from complex vertical vehicle integration and launch facilities. First-stage launch aircraft could operate above cloud level, which would permit bad weather to be avoided, increasing launch availability and permitting operation at altitudes where dynamic pressures during launch would be significantly reduced.

Nevertheless, special facilities at launch sites may be needed for TSTO HTHL systems, such as cranes, gantries, and support structures.

Aircraft lift performance must satisfy required system launch conditions for speed and altitude. One drawback of TSTO air-launched systems is that the size of the orbital vehicle is limited by the lift capability of the carrier aircraft. This in turn ultimately limits the scalability of these designs, and prohibits evolution to very large designs and payload capabilities.

However, by using an aircraft as the first stage one potentially gains the greatly increased reliability and operability associated with commercial aircraft. In addition, many existing and potential military TAV missions may be accomplished without needing large or even medium-sized payloads, and could conceivably be carried out by an air-launched TAV.

A possible issue regarding military TAVs is whether military missions could be performed responsively using a TSTO vehicle. The additional complexity of integrating the orbital vehicle with the carrier aircraft results in time delays.

Aerial Propellant Transfer Concepts. In aerial propellant transfer concepts, the carrier aircraft is replaced by an entirely separate tanker aircraft. In this way, the orbital vehicle or TAV can take off from the ground horizontally with its

Table 3.1

Maximum Take-Off Weights of Potential Carrier Aircraft

Version	SCA	B-747-100	B-747-400	B-747-600X	An-224
Maximum take-off weight (lb)	710,000	735,000	875,000	1,000,000+	1,250,000+

SOURCES: Robert Ropelewski, "Boeing seeks to extend jumbo monopoly," *Interavia*, April 1996.

propellant tanks largely empty. It then approaches and hooks up to the tanker and fills its tanks. Upon completion of the refueling operation, it disengages, throttles its rocket engines to maximum thrust, and ascends to orbit.

Because the TAV would be rocket powered, additional rocket engines may have to be ignited during the aerial refueling operation, and because rocket engines typically cannot operate at low throttle settings, the refueling operation would be quite challenging and could probably not be performed by an auto-pilot or remote control system. For these reasons, this type of TAV would have to be manned.

The alignment of the refueling aircraft and TAV and the degree of engine throttleability required during aerial refueling are significant safety issues for this type of design.

Another safety issue for this design is the selection of the propellant to be used in the aerial refueling operation. In one design approach, hydrogen peroxide (90 percent concentration) and kerosene have been considered; the peroxide would be the propellant transferred from the tanker aircraft to the TAV. However, if peroxide is contaminated, it can become unstable and explode. Propellant contamination during refueling would be a significant safety issue and may make such operations very hazardous.

It has also been proposed that liquid oxygen (LOX) be transferred to the TAV in an aerial refueling operation. However, the transfer of cryogenic propellants introduces other complexities and potential hazards that require careful examination. This is a potentially high-payoff technology and should be investigated more thoroughly.

Propellant must be consumed at a significant rate during the transfer process, because a rocket engine is not as efficient as an air-breather. The transfer rate is a critical design consideration for these concepts. Refueling time must be minimized and propellant transfer rate maximized.

The NASP Program

The NASP program was conceived to develop an experimental aircraft, the X-30, to explore the entire hypersonic velocity flight range. The original program goal, to insert a manned air-breathing SSTO vehicle into low earth orbit, was never

realized, although more than \$1.73B was spent in this effort.[6]   In 1987, the Air Force asked RAND to review the status of this program. At that time, RAND concluded that many vital technology development issues remained unresolved, even after several years of intensive research.[7] The major technology risk areas identified were computational fluid dynamics (CFD) and the integrated combined cycle propulsion system that contained air-breathing and rocket components.

The Defense Science Board (DSB) Task Force also reviewed the program in 1988 and found six critical technology areas: aerodynamics, supersonic mixing and fuel-air combustion, high temperature materials, actively cooled structures, control systems, and CFD. The DSB concluded that the development schedule for all these critical technologies was unrealistic.

At that time, both RAND and the DSB concluded that the CFD state-of-the-art could not serve as the primary NASP design tool and that this state of affairs would continue to exist for a decade or more. Integrated testing of the airframe and propulsion system also could not be performed with existing ground facilities because the upper velocity limit was Mach 10 or less. Resolution of fundamental design uncertainties for such an air-breathing system would require flight tests (the largest aerodynamic uncertainty were considered to be the transition point from laminar to turbulent flow, whose location affects engine performance, structural heating, and drag). Experimental flight data was considered essential to calibrate unvalidated CFD codes.

The NASP ascent trajectory had to be depressed in the atmosphere to ensure that its engines injected enough oxygen. This led to high aeroshell temperatures during supersonic flight, which in turn necessitated the use of advanced TPS materials and active cooling of leading edges and other surfaces. The working fluid in the NASP design would have been hydrogen, so hydrogen embrittlement was a potential problem for the active cooling channels in some of the vehicle structures that would have to operate in high temperature and pressure regimes.

The NASP combined cycle propulsion system was also risky. The engine design would have had to smoothly transition from a slow speed mode to ramjet mode, and then to a scramjet mode of operation. Major uncertainties regarding the mixing of hydrogen and air at high Mach numbers remain to be resolved and could have a significant impact on the design of such a propulsion system.

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[6]Lt Gen Thomas S. Moorman, Jr., *DoD Space Launch Modernization Plan*, Briefing to the National Security Industrial Association (NSIA), 8 June 1994.

[7]Bruno Augenstein and Elwyn Harris, *The National Aerospace Plane (NASP): Development Issues for the Follow-On Vehicle, Executive Summary*, RAND, R-3878/1-AF, 1993, and related references.

Finally, uncertainty in subsystem characteristics and in hypersonic flight conditions meant that sophisticated new control systems would have had to be developed in parallel with the propulsion and airframe and integrated with them, adding to the complexity and technical risk in the NASP air-breathing propulsion concept.

In contrast, most of the TAVs considered at the RAND workshop were rocket-powered vehicles. Such vehicles do not suffer the severe heat loads NASP would have had to endure during ascent. None of the X-33 designs presented at the workshop required actively cooled vehicle structures or surfaces. At the RAND TAV workshop, skepticism was expressed about relying on CFD codes, except in well-understood, relatively low Mach number regimes. Fortunately, the rocket-powered TAV proposals considered at the workshop are generally in the low Mach number regime during atmospheric transit, and therefore are less subject to hypersonic design uncertainties than was NASP. And because there are no air inlets for air-breathing engines in purely rocket-powered TAVs, the hypersonics of these vehicles are generally easier to understand and predict.

SSTO Versus TSTO Designs

A central debate concerning the design and development of future launch vehicles is whether the focus of effort should be on an SSTO or a TSTO system. Traditionally, SSTO designs were considered more technically challenging because of the mass fractions required. They were also more performance sensitive and subject to substantial GLOW growth if mass fraction or specific impulse (Isp) design goals could not be met. However, many of these assessments were made assuming the use of 1960s or 1970s technologies. With the development of modern composite materials and lightweight metal alloys and TPS, the overall weight of launch vehicle structures can be reduced, perhaps by up to 35 percent.[8] In principle, modern SSTO vehicle dry weights should be substantially less than earlier designs that relied on aluminum airframes and first-generation TPS materials. Indeed, it has been claimed that 1990s technologies will reduce SSTO dry weights by a factor of two from their 1960s predecessors.[9] Thus, it has been argued that it is now possible to build an SSTO vehicle using 1990s technologies and that the technical risks and performance

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[8]Jay P. Penn, *SSTO vs. TSTO Design Considerations—An Assessment of the Overall Performance, Design Considerations, Technologies, Costs, and Sensitivities of SSTO and TSTO Designs Using Modern Technologies*, The Aerospace Corp., Space Technology & Applications International Forum (STAIF-96), January 7-11, 1996, Albuquerque, NM.

[9]Ibid.

sensitivities of such modern designs would be much less than those of earlier designs.

However, it should be noted that the same advances in materials and TPS would also benefit the mass fraction and performance characteristics of TSTO designs. It has been estimated by Dr. Karasopoulos of Wright Labs (WL/LI) that the delta-V advantage of air-launching an orbital vehicle or TAV is somewhere between 1800-2400 fps over a ground-launched SSTO system designed to carry the same size payload. If the dry weight of an air-launched TAV can be reduced, the delta-V advantage for this type of system would be enhanced in two ways. The carrier aircraft could potentially release the TAV at a higher altitude because of its reduced weight, and the TAV would require less propellant or lower Isp to deliver the same size payload to orbit because of its improved mass fraction.

The quantitative advantages of using new materials in SSTO and TSTO designs have been estimated using vehicle sizing and performance prediction codes. These codes have been used to predict that SSTO systems will benefit much more from the use of new materials than TSTO systems.[10] However, it is not clear that these predictive codes apply with equal accuracy to SSTO and TSTO systems. In the last few decades, ground-launched SSTO designs have received a great deal more attention than air-launched TSTO systems, partly because of the focus of the NASP program.

Others have argued that ground-launched SSTOs are superior to air-launched TSTOs because (1) the technology readiness levels are higher for SSTOs; (2) air-launched TSTOs are more sensitive to performance losses; (3) ground-launched systems can be scaled up in size if necessary, while air-launched systems cannot; and (4) the design fidelity of air-launched TSTOs is generally lower than current SSTO designs.[11]

The last point is certainly true. Relatively little design work has been spent in looking at air-launched TSTO concepts. It is also true that unless completely new very large carrier aircraft are developed, air-launched TSTOs may not be able to be scaled up in size to meet less-than-predicted engine performance or unanticipated growth in vehicle dry weight. However, while it is true that some air-launched concepts may be more sensitive to performance losses, it is by no means clear that all air-launched concepts are. The air-launched TSTO concept chosen for the above referenced comparison to an SSTO design was Black Horse, which is an aerial-refueled concept and strictly speaking not an air-launched

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[10]Ibid.

[11]Lt Col Jess Sponable, *Ground Launched SSTO TAV versus Air Launched TAV*, Phillips Laboratory, PL/VTX, 2 May 1995.

design. The above analysis was also performed using a launch vehicle sizing code that may not treat SSTO and TSTO concepts with equal accuracy and that assumed certain TSTO vehicle characteristics that may not be applicable to all air-launched TSTO designs.

If air-launched TSTO concepts do have an Achilles heel, it is their lack of scalability when existing carrier aircraft are used the first stage of the system. The lift capacity of commercial and military transport aircraft is limited and transport aircraft designs themselves are not easily scalable without incurring significant new development costs. Furthermore, it would cost several billion dollars to develop a new very large transport aircraft designed from scratch to act as the first stage for a TSTO system. On the other hand, if an air-launched TSTO system employed a TAV designed for launch from a modified commercial jumbo jet, the total development cost for the entire TSTO system could be reduced because the first stage would essentially be based on a commercial off-the-shelf product.

The probability that such a TSTO system could be developed successfully is a function of the maximum payload size intended for the vehicle (or, put another way, the TAV design margins used and the lift capacity of the carrier aircraft in the overall design). Realistic air-launched TAV designs that are based on existing technologies and commercial aircraft capabilities should contain adequate design margins for TAV engine performance and structural weights, and therefore may not be able to handle the MLV size payloads envisioned for SSTO systems. Nevertheless, development of an air-launched TSTO system that is designed for small to medium sized payloads, say up to 5000 lb to a polar orbit, may be feasible and could cost substantially less than SSTO vehicles designed to lift MLV size payloads into orbit.

Current Concepts

Table 3.2 lists most of the RLV and TAV design concepts discussed at the RAND TAV workshop. Several of these concepts are based on detailed technology and design studies, while others reflect promising but newer and less thoroughly explored concepts.

In addition to the X-33 and X-34 programs being sponsored by NASA, several TAV concepts discussed at the workshop have been under active investigation in the DoD laboratory community. Among these are the Black Horse in-flight aerial propellant transfer concept and a set of air-launched TAVs being studied at various Air Force laboratories. In addition to these, an air-launched TAV design

Table 3.2

RLV and TAV Design Concepts

Vehicle	Contractor/Lab	Staging	Payload	Propulsion	Comments	
X-33	Lockheed Martin	SSTO	Heavy	LOX-LH2	Lifting body, VTHL, aerospike engine	■
X-33	Rockwell	SSTO	Heavy	LOX-LH2	VTHL	▧
X-33	McDonnell	SSTO	Heavy	LOX-LH2	VTVL	▧
X-34	OSC	Air-drop	Small	LOX-storable	HTHL, L-1011	■
REFLY	Rockwell	Air-drop Pegasus	Very small	Noncryogenic	L-1011, B-52, reusable upper stage	□
NG TAV	Northrop-Grumman	Air-launched	Small	LOX-LH2	Boeing 747	√
Black Horse	Phillips Lab	Aerial-refueled	Small	H_2O_2-Kerosene	KC-135Q tanker	X
Neptune	Phillips Lab	Air-drop	Small	LOX-LH2	B-1B	
TAV	AMC HQ (Snead)	Air-launched	Medium	LOX-LH2	Boeing 777	

■ Under development (NASA) ▧ Design proposed □ Concept proposed

√ Concept performance verified X Concept performance problem identified

derived from a potential X-34 proposal by Northrop Grumman was also presented at the workshop. All are discussed below.

NASA X-33 Program

The purpose of the X-33 program is to prove the technological feasibility of an SSTO vehicle. Initially, a subscale demonstration vehicle will be developed that will serve as a technology testbed and a proof of principle for a full-scale RLV capable of achieving orbit with medium or perhaps even heavy payloads (those exceeding 20,000 lb).

As part of this effort, the following core technologies will be needed:

- Lightweight reusable cryogenic tanks
- Composite primary load bearing structures
- Advanced thermal protection systems
- Advanced propulsion
- Advanced avionics.

The X-33 is intended to demonstrate technology traceability and scalability from the subscale vehicle to a full-scale SSTO rocket. Critical design characteristics include a streamlined and efficient operations concept, flight stability and control, and demonstration of SSTO vehicle mass fraction. The NASA X-33 program may also lay the ground work for a future follow-on to the NASA space shuttle. NASA representative Bill Claybaugh, who presented an overview of NASA RLV programs at the RAND TAV workshop, stated that the intent of the NASA RLV program was not to develop a shuttle II (i.e., a replacement for the current space shuttle). Furthermore, there is no specific payload requirement for the X-33 program. The X-33 industrial partners were free to determine the payload capabilities of their experimental and follow-on RLV designs. In fact, as indicated below, all the X-33 competitors sized their full-scale RLVs for the commercial satellite launch market.

The three competing X-33 are illustrated in Figure 3.1. The vehicles are shown to scale. From left to right are the Lockheed Martin, McDonnell Douglas, and the Rockwell X-33 designs. It is apparent that the Rockwell design is the largest of the three. All three X-33 designs are based on cyrogenic LOX/LH2 rocket propulsion systems.

**Figure 3.1—Competing X-33 Vehicle Designs**

The X-33 contract was awarded to Lockheed Martin on July 4, 1996. First flight is scheduled for March 1999. Sometime after conclusion of the X-33 flight test program, NASA and the U.S. government will decide whether to proceed with development of a full-scale RLV. NASA has budgeted $941M for the program through 1999 in order to develop one demonstration vehicle. NASA will reportedly use $104M of this amount to support its own program infrastructure, while $837M will go to the contractors. Lockheed Martin, as a condition of the X-33 cooperative agreement and cost-sharing arrangement associated with the contract award, will invest $212M of its own corporate resources to develop the X-33. Lockheed Martin estimates that a fleet of two to three full-size RLVs will cost somewhere between $4.5–5 billion to build following the successful conclusion of the X-33 program.[12]

Below we review the X-33 designs proposed by the three contractors.

Lockheed Martin

The winning Lockheed Martin Skunkworks (LMSW) design is a lifting body VTHL SSTO vehicle with an integrated aerospike engine. The LMSW X-33 and full-scale RLV designs are shown in Figure 3.2. The LMSW X-33 will be a 53

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[12]S. Dornheim, "Follow-on Plan Key to X-33 Win," *Aviation Week & Space Technology*, July 8, 1996, p. 20.

SOURCE: NASA Marshall Space Flight Center, Internet Web
Address: http://rlv.msfc.nasa.gov
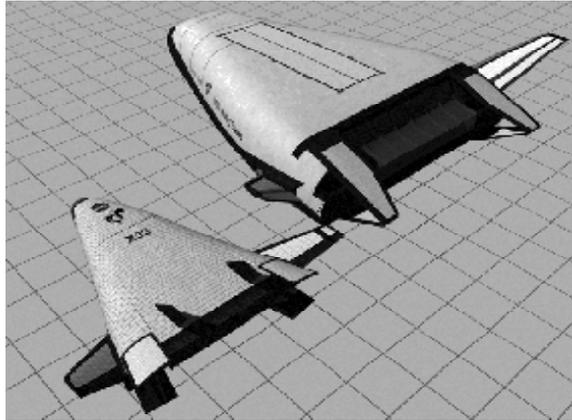
Figure 3.2—Comparison of LMSW X-33 and Full-Scale RLV Designs

percent subscale vehicle relative to a full-scale RLV and will not be capable of delivering payloads to orbit. Both vehicles will employ aerospike engine designs.

Key characteristics of the LMSW X-33 and full-scale RLV are shown in Table 3.3. From the table, it is evident that even though the X-33 will be a 53 percent subscale system in terms of linear dimension, it will be much smaller in terms of volume or dry weight. The X-33 will have 12 percent of the GLOW and 31 percent of the empty weight of the full-scale system.

There are significant technical risks associated with this design, and these were identified by Dr. David Urie, the LMSW program manager, at the RAND TAV workshop. These are vehicle integration, structures, propulsion, and thermal protection. To achieve an SSTO capability, LMSW will have to achieve specific design goals in the final integrated vehicle. These include specific mass density targets for TPS surface materials, internal load bearing structures, propellant tanks, and specific impulse goals for the propulsion system.

An innovative aspect of the LMSW X-33 design is the Rockwell Rocketdyne aerospike engines planned for the vehicle. The aerospike engines will be in a linear configuration of two rows divided by a central spike. The engines will be integrated into the vehicle frame as illustrated in Figure 3.3.

Aerospike engines could have several significant advantages. They may weigh less than conventional rocket engines and their performance efficiency should not degrade as much as that of conventional engines as the vehicle increases in

Table 3.3

Key LMSW X-33 Characteristics

System Characteristic	RLV	X-33
Length	127 ft.	67 ft.
Width	128 ft.	68 ft.
Gross liftoff weight	2,186,000 lb	273,000 lb.
Propellant	LH2/LOX	LH2/LOX
Propellant weight	1,929,000 lb.	211,000 lb.
Empty weight	197,000 lb.	63,000 lb.
Main propulsion	7 RS2200 linear aerospikes	2 J-2S linear aerospikes
Liftoff thrust	3,010,000 lb.	410,000 lb.
Maximum speed	Orbital	Mach 15+
Payload (100 nmi/28.5 deg orbit)	59,000 lb.	NA
Payload bay size	15 x 45 ft.	5 x 10 ft.

SOURCE: S. Dornheim, "Follow-on Plan Key to X-33 Win," *Aviation Week and Space Technology*, 8 July 1996, p. 20.

SOURCE: NASA Marshall Space Flight Center, Internet Web Address: http://rlv.msfc.nasa.gov
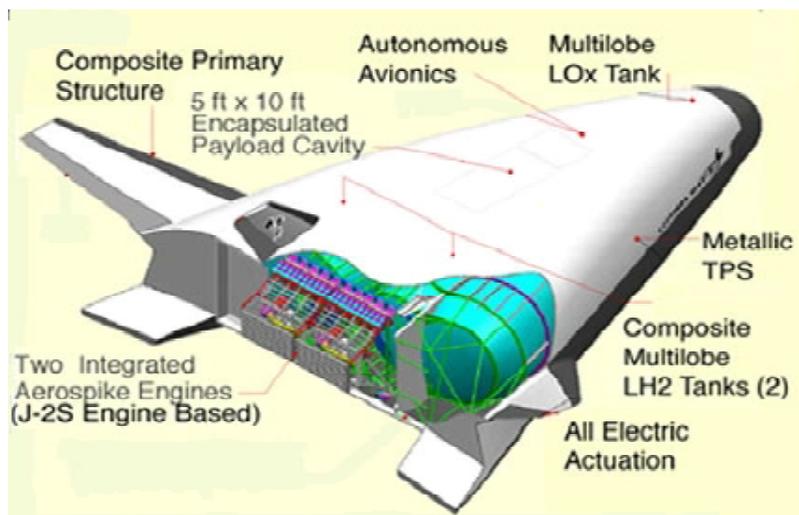
Figure 3.3—Features of the LMSW X-33 Design

altitude. Engine weight would be reduced because engine gimbals, mounts, actuators, and hydraulics will not be used. Instead, thrust vectoring will be accomplished by throttling different engine segments.

Another attractive feature of the full-scale RLV aerospike engine design is that it will operate at a relatively low chamber pressure of 2250 psia, which should

increase engine lifetime and may reduce the need for engine refurbishment. It should be noted, however, that the aerospike engine will have to operate at 445 sec of Isp (in vacuum) in order for the LMSW X-33 to demonstrate SSTO feasibility.

A second innovative aspect of the LMSW X-33 design is the use of metallic TPS on all external surfaces except for the leading edges, where advanced carbon-carbon composites will be used. The use of metallics is made possible by the lifting body design because this body shape reduces heating loads and surface temperatures during reentry. Metallic TPS may be more durable and require less refurbishment and repair than ceramic tiles, thereby enabling low cost RLV or TAV operation and increased vehicle responsiveness.

The main vehicle structure will be composed of graphite epoxy composite except possibly for the oxygen fuel tanks, which may be made of aluminum, and the control surfaces, which will be made of titanium.

At the workshop, it was remarked that there may be major differences between a military TAV and a commercial RLV. For example, a TAV may require a horizontal take-off capability to enable it to operate out of many different airbases. And it may require a significant cross-range capability in either suborbital or orbital missions to deliver payloads quickly to their required destinations. In contrast, an RLV designed to serve the commercial launch market need not have either capability mentioned above. To minimize infrastructure costs, a commercial RLV would operate from only one launch site and may well be a vertical launch system like the LMSW X-33. It is also important to note that the lift-to-drag ratio of the LMSW X-33 lifting body design may not be not high enough (it has an L/D of 1.2 at hypersonic speeds and a maximum L/D of 4.5 at subsonic speeds) to carry out military missions where a significant cross-range capability would be needed.

McDonnell Douglas

The McDonnell Douglas X-33 entry was a VTVL SSTO design with ballistic hypersonic characteristics. McDonnell Douglas X-33 and full-scale RLV designs are illustrated in Figure 3.4. The full-scale RLV would be about as tall, at 185 ft, as the Space Shuttle on the launch pad. It would be 48.5 ft across. RLV GLOW would be about 2.4M lb and it would have a dry weight of 219,000 lb. The RLV would use eight new Rocketdyne LOX/LH2 rocket engines.[13]

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[13]"NASA Nears X-33 Pick," *Aviation Week and Space Technology*, June 17, 1996, p. 29.

SOURCE: NASA Marshall Space Flight
Center, Internet Web Address:
http://rlv.msfc.nasa.gov
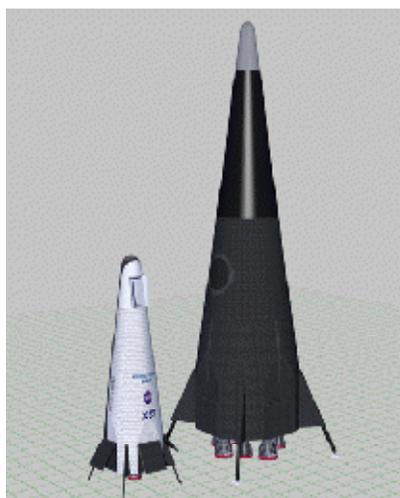
Figure 3.4—McDonnell Douglas X-33 and Full-Scale RLV Vehicles

The payload capability of the RLV would be 45,000 lb to LEO, 22,000 lb to the space station, and 16,000 lb to geostationary transfer orbit. It would have a payload bay size of 16.5 by 35 ft. The estimated cost to build the full-scale RLV after successful completion of the X-33 program is $4–7B.

The primary structure would probably be made of composites as would the LH2 propellant tanks. The LOX tank would probably be composed of aluminum-lithium alloy. One of the design issues discussed at the RAND workshop was that if the primary structure were comprised of composites, would a very large autoclave be needed to produce the full-scale vehicle—i.e., would the full-scale vehicle have to fit inside of the autoclave?

The McDonnell Douglas X-33 design relies on ceramic TPS materials and most likely employs advanced carbon-carbon composites at leading edges and on the nose cap. This X-33 vehicle would be about a 50 percent subscale model of the full-scale RLV. In addition, this design relies on a single Space Shuttle Main Engine (SSME) for the main propulsion system. Key propulsion technology risk areas identified by Dr. William Gaubatz at the workshop were the thrust to weight ratio and throttling capability of the main engine or engines.

Dr. Gaubatz also identified significant weight uncertainties in the propulsion, tankage, TPS, and structures areas, regardless of which design was selected in the X-33 competition. The weight uncertainties identified in these subsystems were 5 percent of total vehicle empty weight for propulsion, 3 percent for tankage, 3 percent for TPS, and about 2 percent for structures. These

uncertainties will have to be reduced in the X-33 program to proceed with confidence in building a full-scale SSTO RLV.

Some other important issues discussed by Dr. Gaubatz were

- mass fraction characterization (i.e., adequate margins to account for weight uncertainties identified above),
- achieving aircraft-like operability/supportability over a 10 to 20 year vehicle lifetime,
- propulsion systems with high Isp and thrust to weight ratio and with excellent operability, enabling cost-effective number of flights between repairs and engine overhauls, and
- aerodynamic designs with sufficient cross-range, stability, and control during reentry.

McDonnell Douglas emphasized the experience base it has acquired with the DC-X program. The DC-X1 is a 1/3 scale vehicle made to demonstrate quick turnaround operations with a rocket-powered vehicle. It is not intended to validate a VTVL SSTO design. It was emphasized that DC-X was not just a vehicle demonstrator but a total system in which the aerodynamics, controls, and operations and support are demonstrated. One of the goals of the DC-X is to go from a six-day turnaround time to three days. One of the features it has to demonstrate is the ability to accommodate failures at any time during the flight envelope and still be able to return safely (i.e., without catastrophic failure).

Rockwell

This design concept is a VTHL SSTO vehicle with a composite wing and tail, aluminum/lithium (Al/Li) LOX tanks, composite LH2 tank, and an improved bad weather landing capability using durable and survivable TPS materials. The Rockwell X-33 and full-scale RLV designs are illustrated in Figure 3.5. The RLV GLOW would be about 2.2M lb and the vehicle would have a dry weight of 296,000 lb. Mass fraction goals for the vehicle are a 89.5 percent propellant mass fraction and a 2 percent payload mass fraction. The full-scale vehicle would be 213 ft long and have a wingspan of 103 ft. It is estimated by the contractor that it would cost about $5–8B to build a full-scale RLV.[14]

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[14]Briefing presented at Rockwell X-33 RLV User Expo, Downey, California.

Figure 3.5—Rockwell X-33 and Full-Scale RLV Vehicles

The RLV would be capable of placing a 43,000 lb payload in LEO and a 12,000 lb payload in geostationary transfer orbit, and it would be able to accommodate large payloads in its 45 by 15 ft payload bay. Rockwell considered both a solid and a cryogenic upper stage, but is not yet fully convinced that the latter can be carried safely in the RLV payload bay. The full-scale vehicle would also be capable of landing on a 10,000 ft runway and so could land in an emergency at a number of runways around the world.

The Rockwell X-33 design would be a 50 percent subscale vehicle capable of suborbital flight demonstration using 1 SSME and 2 RL-10-5A engines. Rockwell has decided not to use an aerospike engine because of the technical risk involved. One of the risks identified at the RAND workshop is controlled flight using aerospike engine thrust vectoring at max Q, which occurs at about 25 kft. The X-33 vehicle would be designed to take full RLV thrust loads and major portions of the vehicle, including the thrust structure, wings and LH2 tanks, would be composed of graphite epoxy composites.

The full-scale RLV concept would depend on the use of supercooled propellants. This provides a 10 percent volumetric savings with the LOX tanks and a 6–7 percent volumetric savings with the LH2 tank. This technology would be demonstrated with the SSME in the X-33 program.

Rockwell planned to use six Rocketdyne RS-2100 engines in the full-scale system, with the goal of not having to refurbish the engines (including turbopumps) for 20 flights. No cost estimates were given for engine development costs. The RS-2100 would have a vacuum Isp of 450 sec, a thrust to weight ratio of 83 to 1, and would operate at a relatively high chamber pressure of 3250 psia.

The Rockwell X-33 and RLV designs would rely on TPS blankets on all exterior surfaces except the leading edges, where high-density ceramic tiles with a density of 20 gm/cc would be used. Ceramic tiles may still have to be used on some high-impact surfaces, however. Rockwell had an operability goal of reducing the time needed for TPS refurbishment between flights by more than a factor of ten (relative to the space shuttle) to about 1500 hr.

NASA X-34 Program

The purpose of the NASA X-34 program is to provide low-cost and early opportunities to test new high-risk RLV technologies that cannot be test flown on the shuttle and that may be too risky to use in the X-33 program. Originally, the X-34 program was awarded to an industry team composed of Orbital Sciences Corporation (OSC) and Rockwell. However, because of program cost growth and differences between the industrial partners over the choice of engine, the partnership was dissolved. The original program goals included the development of a suborbital air-launched vehicle capable of reaching speeds of between Mach 12 to 14 at a peak altitude of 100 miles. The full-scale system, if developed, would then deploy payloads to orbit by using an upper stage. Another goal of the original X-34 program was to gain early RLV operations experience and to discover flight test "lessons learned" that would be useful in the X-33 program.

Orbital Sciences Corporation (OSC) X-34 Design

The OSC X-34 is composed of a hypersonic reusable rocket system and a conventional carrier aircraft. A design goal is to reduce launch costs from $12M for Pegasus to $5M for an X-34-derived vehicle. Originally, the X-34 was to be air-dropped from the L1011 or air-launched from a NASA B-747 SCA. The two original versions of the X-34 were quite different. It appears that the B-747 version may be more risky because significant wing area would be required and could impact the vehicle mass fraction.

The original X-34 development and flight test plan had the following components. Two airframes were to be built. The first airframe without propulsion system was to have undergone static load ground and captive carry tests. The second airframe was to have been test-fired at Phillips Lab on a test bench with full loadings during a simulated launch sequence using flight software. Suborbital flight tests would have then taken place to assess TPS endurance. A steep flight path angle was planned, to quickly heat the vehicle to

a high temperature and thereby model reentry from orbit. The test flights were planned for late 1998 and 1999.

After the original X-34 industry team was dissolved, the X-34 contract was recompeted and awarded to OSC. The program was restructured to accommodate reduced program funding. The new vehicle will be much smaller than originally planned. It will be 58 ft long, have a wingspace of 28 ft, and a GLOW of 45,000 lb. In comparison, the original version of the X-34 had grown in GLOW to 140 klb, or a two-thirds scale shuttle.

The current version of the X-34 will be designed for 25 flights per year. The original X-34 contract was structured with NASA paying $70M of program costs, while OSC and Rockwell were to pay $50M each. For the new contract, NASA will contribute $50M and OSC an unspecified amount.[15]

Northrop Grumman (NG) X-34 Concept

Although this vehicle design concept was not formally submitted in the X-34 program competition, it is an interesting design and could have value as a TSTO air launched military TAV. This vehicle would be launched from on top of a NASA B-747 SCA and deliver a 1-6 klb payload to LEO. The B-747 launch platform would transfer LOX and LH2 fuels to the orbital vehicle.

The orbital vehicle would resemble a scaled-down space shuttle and would have its aerodynamic characteristics. It would have a GLOW of about 180,000 lb and a cross-range capability of 1100 nm. The fully loaded orbital vehicle would have a higher wing loading than an empty shuttle. Consequently, care must be taken to guarantee positive vehicle separation and to provide adequate clearance from the aircraft during the staging maneuver. The contractor has indicated that vehicle drag may be reduced relative to the shuttle by 20 percent, making this maneuver easier to execute. This reduction in drag would need to be confirmed using computational fluid dynamics.

The vehicle would use two D-57 Russian engines, which have been licensed from the Russians by Aerojet. These engines are fully throttleable and could run with a smaller nozzle (88 in. versus 143 in.) than originally designed. The two engines would produce 88 klb of thrust each. The Russian engine manufacturer has built 105 engines and Phillips Lab has performed over 53,000 seconds of engine testing. Given the performance of the D-57 engine, Northrop Grumman has

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[15]"NASA Gives Orbital Second Shot at X-34," *Aviation Week and Space Technology*, June 17, 1996, p. 31.

estimated an orbital vehicle payload delivery capability of 1,000 to 3,500 lb to polar orbit and 3,000 to 6,000 lb to an easterly orbit. These payload weights carry no margins.

The technology risks identified by Northrop Grumman at the RAND workshop were structural weight uncertainty, TPS weight and performance, safe vehicle separation from the 747, and Aerojet capability to produce the Russian engines. The TPS materials used would be different from the materials used on the shuttle. The new materials would have an average density of .5 lb/sq ft. A major concern is further reduction in TPS weight.

Other options for this vehicle concept are to configure the orbital vehicle for a two-person crew or to develop a modified vehicle that would be capable of using high-density propellants and of executing an independent ground take-off, aerial refueling, and ascent to orbit mission profile.

Additional TAV Design Options

Several small TAVs with varying levels of technological maturity that may have military utility were proposed at the RAND TAV workshop. Further analysis and systems definition work are required to assess the feasibility of these designs and their mission utility. Some of the issues surrounding these concepts are discussed below.

Black Horse

Black Horse is an aircraft-like vehicle that would be about the size of an F-16C (see Figure 3.6). It would use H_2O_2 (peroxide) and kerosene as propellants. At GLOW, it is estimated to have a weight of 184,000 lb. This concept uses in-flight propellant transfer to provide the delta-V needed to reach orbit. Gross TAV take-off weight would be 25,000 lb. A KC-135Q tanker with isolated tanks built for the SR-71 program would off-load the bulk of the peroxide needed to achieve orbit. A major issue is whether effective flight control can be maintained during refueling. Because the lift to drag ratio of the TAV changes from 9 at hook-up to 4 at ascent, an additional engine may have to be started during the propellant transfer process.

The payload mass fraction that the Black Horse concept can achieve and the maximum payload size this design option can scale up to require further careful analysis. RAND carried out an independent analysis of Black Horse payload mass fraction capabilities using POST, a NASA trajectory analysis program, and
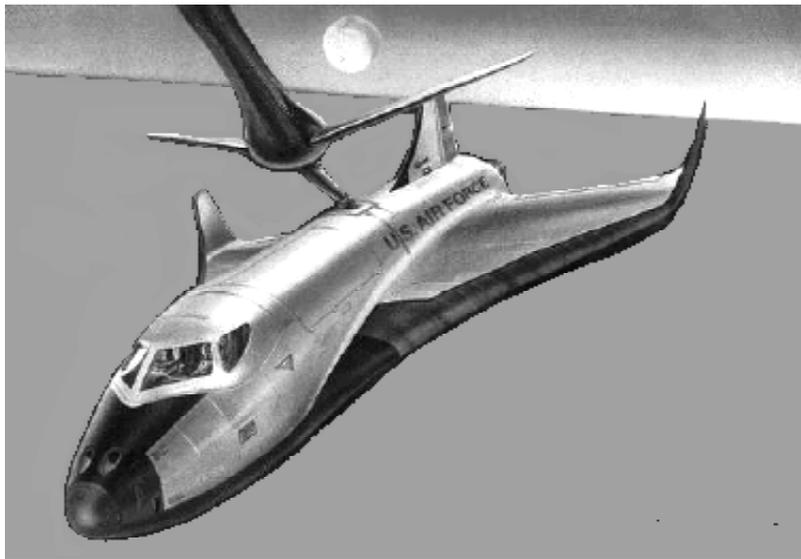
SOURCE: Ferrand, Kerry, Spacecraft and Technology Images, Internet Web Address:
http://202.50.196.210/kk/st.html

Figure 3.6—Black Horse TAV During Fueling Operation

determined that the vehicle in its current configuration could not achieve orbit. Even if the Black Horse refueling operation could be safely executed and the vehicle could be modified to reach orbit, a potential drawback of this design may be that it will be capable of lifting only very small payloads (i.e., less than a thousand pounds) into LEO. An issue is whether very small satellites could satisfy military mission requirements.

The orbits accessible by Black Horse may also be limited. Satellite delivery to polar orbits may not be feasible, and it may not be possible to deliver satellites to equatorial orbit without significant redesign of the system. A number of options to overcome these payload limitations were suggested at the workshop: use of an upper stage, use of an air-breathing engine, or refueling ballistically (by flying two aircraft on parallel trajectories, transferring oxidizer to the orbiter, and then returning the dry aircraft). These options could possibly increase payload capability to perhaps 10,000 lb, but would introduce additional system development and complexity.

The use of kerosene and peroxide would require development of a new engine. Although this type of engine was developed and used by the British in the Black Knight project, the latter's design may not be directly applicable to current designs, such as Black Horse.

The H_2O_2-kerosene rocket engine design may have significant technical risk. An important engine performance issue is whether the chamber pressure is too high,

which raises maintenance and operability concerns. A staged combustion cycle is used in which a catalyst decomposes H_2O_2 into steam and oxygen before entry into the turbopump. A concern was raised by workshop participants that a high-temperature, oxygenated environment raises serious turbopump survivability issues.

The aluminum Black Horse structure weight was independently checked by Boeing. Boeing's weight estimate is 8 percent higher than the original one, introducing another concern regarding the design feasibility.[16]

The impact of life support systems is yet another source of concern and uncertainty for this concept. Pressure suits for crew members would be required, putting a limit on how long a pilot could remain in orbit. Fatigue becomes a significant factor after 8 hours in a pressure suit, and a 24 hour mission is considered unacceptable.

Air-Launched TAV

Ken Hampsten of Phillips Laboratory presented an initial three-stage-to-orbit air-launched TAV design that would use NK-31 and D-58M Russian rocket engines. The first stage carrier aircraft would be a B-1B. A modified NK-31 engine would deliver 90,000 lb of thrust and an Isp of 355 sec using a 114 in. nozzle and would power the air-dropped vehicle's first stage. The third stage orbital vehicle would use a D-58M, which would burn LOX and kerosene and deliver 19,000 lb of thrust and an Isp of 353 sec.

This concept is designed to provide first- and second-stage mass fractions of .88 and .83 with 12,000 lb of propellant. It was indicated the orbital vehicle would have a 2,000 mile cross-range and could deliver payloads measuring up to 8 ft in diameter.

Boeing Advanced Concepts

Vince Weldon of Boeing discussed design and propulsion issues associated with TSTO air-launched TAVs.

One approach briefed is to modify a B-747 to carry LOX/LH2 propellants for a medium lift TSTO air-launched vehicle and LOX/CH_4 propellants for a military TAV (to take advantage of the higher density of methane). However, one

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[16]Comments made by Boeing Co. representatives at the RAND TAV workshop.

drawback of using methane as a TAV propellant is that there are no engines currently available off-the-shelf. A second approach is to modify the B-747 with GE-90 engines on the two inboard pylons. This would provide a 53 percent increase in thrust for the first-stage carrier aircraft. Boeing has investigated using the Integrated Powerhead Demonstration Engine being developed at Phillips Lab for the second-stage TAV. Boeing estimates that an air-launched TAV using this engine could carry up to 30,000 lb to LEO at the Eastern Test Range using a LOX/LH2 propellant combination.

Finally, Boeing has investigated the feasibility of LOX in-flight transfer (it is dense and so should pump rapidly), stable separation of a fly-back wing design, and landing site needs for air-launched TAVs. If in-flight TAV LOX fueling were employed using a second tanker aircraft, air-launched TAV GLOW could be doubled from 250,000 lb to 500,000 lb.