Summary

Launch vehicles or rocket boosters are used to deliver satellites to orbit or weapons to distant targets. However, most existing rockets, based on designs over a quarter-century old, are expended after use, making them less cost-effective for some missions and less competitive in the world launch market. A transatmospheric vehicle (TAV) or reusable launch vehicle (RLV) would be capable of returning to earth to be reused after refurbishment and refueling.¹ TAVs may have aerodynamic and operability characteristics similar to conventional aircraft, but would be capable of delivering payloads to low earth orbit (LEO). The promise of TAVs is that their reusability would potentially allow them to launch payloads into orbit at much lower cost than expendable launch vehicles.

Purpose of the Workshop

The Air Force asked RAND to examine the utility, feasibility, and cost of procuring a TAV capable of carrying out military missions. As part of this study, a workshop was held at RAND on April 18 and 19, 1995, to examine TAV utility, technical feasibility, and design issues. Experts from the Department of Defense, the National Aeronautics and Space Administration (NASA), and industry participated. A variety of commercial RLV and military TAV design concepts were presented and discussed, including designs submitted for the NASA X-33 and X-34 program competitions.

The focus of the workshop was to determine whether any technology “show stoppers” exist today that could seriously impede development of a TAV. Although several technology risk areas were identified, recent technological advances suggest there are reasons to be optimistic that a TAV with significant military utility could be developed.

Discussions held at the workshop raised a number of issues that we believed warranted further investigation. These subsequent ancillary analyses, included in this report for completeness, delayed publication of the proceedings.

¹We will refer to civil or commercial reusable launch systems as RLVs, and to reusable launch systems designed for military missions as TAVs. Recently TAVs have also been termed spaceplanes.
The results summarized here are subject to the following caveats. Proprietary presentations given at the workshop have been made nonproprietary to enable the widest possible distribution. Thus, the reader may find some important but sensitive pieces of information missing. In addition, the information cut-off date for this report is April 1995, with the except of data on X-33 vehicle concepts. Further analyses on some of the TAV concepts discussed at the workshop and new TAV or RLV concepts are not included in these proceedings.

Lessons Learned from Previous Programs

In the past few decades, a number of military TAV concepts have been proposed, and needed critical technology development work has been conducted, but no complete functional vehicle has ever been built. The first National Aerospace Plane (NASP) program, which took place from the late 1950s to the early 1960s, demonstrated a number of important technologies such as real-time air liquefaction and operations such as hypersonic refueling that could be important in Two Stage To Orbit vehicles. The second NASP program in the 1980s was equally ambitious. The later NASP design called for a Single Stage To Orbit (SSTO) fully reusable system based on a complex combined cycle propulsion concept that had several air-breathing engine components. Because of the high technological risk associated with this propulsion concept and other vehicle design aspects, NASP never proceeded beyond the technology development phase. The program was canceled after $1.7B was spent and it became clear that an operational prototype would have cost $10B or more. In light of the difficulties encountered with NASP, only TAVs based on existing or demonstrated jet and rocket engines were considered at the workshop.

Potential RLV and TAV Mission Needs

Potential RLV and TAV mission needs fall into civil, commercial, and military categories.

Potential Civil Needs

NASA’s space launch needs can be divided in two categories: launch of satellites for environmental monitoring and planetary exploration, and launch of astronauts and payloads for the U.S. manned space flight program. NASA’s most important need from a financial point of view is to replace the space shuttle with a follow-on man-rated vehicle. A shuttle follow-on could be smaller than the current system, but it may have to have a heavy lift capability to support the
space station logistically or future expansion or refurbishment of the space station. In either case, NASA will increasingly be motivated to develop a shuttle follow-on RLV with lower operating costs, as the shuttle consumes a large portion of NASA's current budget. Because an RLV may be needed in the 2005–2010 timeframe and because it may take a decade or more to develop, NASA has already embarked on an R&D path to do this by initiating the X-33 program.

Commercial Needs

Over a decade ago, U.S. companies dominated the international space launch market. Today, Arianespace with its line of Ariane launchers controls over 40 percent of the market. China and Russia have also aggressively marketed their launch vehicles. Restrictions on the price and number of Russian and Chinese launches have so far prevented serious market disruption or financial injury to U.S. launch vehicle providers. However, these cartel-like arrangements may not stay in place indefinitely.

Today, U.S. launch vehicles either cost more or have smaller payload capability than do foreign competitors. The challenge faced by U.S. industry is to meet the low launch prices currently offered by Russian and Chinese launch providers. An RLV developed and owned by U.S. industry may be the best way to meet this competitive challenge.

Most commercial satellites today are medium-sized, and most commercial satellites are launched by medium launch vehicles (MLVs). Consequently, an RLV designed for the commercial market would most likely be an MLV.

Potential Military Needs

Potential military TAV needs can be grouped into three mission areas: space launch support, space control, and space force application.

**Space Launch Support.** Many current and planned DoD payloads require an MLV launch. These needs could be satisfied by expendable boosters or possibly by a commercial RLV.

In the future, the DoD may rely more on commercial and civil satellites. However, it may not be possible to optimize the regional coverage supplied by commercial or DoD satellites that are stored on orbit far in advance of hostilities. However, optimal regional coverage can be obtained if “gap filler” satellites are deployed rapidly at the onset of crisis or conflict. A highly responsive small launch vehicle (SLV) or a TAV could quickly deploy such “gap filler” satellites.
**Space Control.** The United States may require new space control capabilities in the near future to counter increasingly capable foreign and commercial satellites. A highly responsive TAV could rapidly deploy space control payloads during crisis or war. Recent RAND research indicates that a variety of useful space control payloads would be small enough to be launched by an SLV or TAV.\(^2\)

**Space Force Application.** The development and employment of space weapons or the delivery of weapons through space would first require a national decision. However, there are reasons to consider acquiring such capabilities: to counter or deter ballistic missile attack or the invasion of allied countries by enemy ground forces, and to attack heavily defended high-value or very threatening targets in hardened facilities or deeply buried bunkers.

If appropriate weapons were available, a highly responsive TAV could attack ballistic missile launchers within minutes after TAV launch. Such a capability could have significant deterrent value and could provide a global counterforce capability. Similarly, if a TAV could quickly deliver such weapons against terrestrial targets such as armored vehicles, it could serve as a deterrent to regional aggressors or slow invading armies, perhaps within minutes after the border was crossed and before allied cities or industrial facilities were captured.

Another advantage of TAV-delivered weapons is the high kinetic energy such weapons can impart to a hardened or deeply buried target, enabling increased target penetration and weapon lethality.\(^3\) A TAV capable of delivering such weapons against hardened and heavily defended targets would add an important new capability to the U.S. arsenal.

**Launch Vehicle Responsiveness**

Responsiveness is one of the most important attributes of a military TAV. We define launch vehicle responsiveness as the time needed to prepare a new vehicle or one that has just returned from space for launch. Nominal responsiveness estimates for current U.S. launch vehicles versus their payload delivery capabilities to LEO are plotted in Figure S.1.

From the figure it is apparent that current medium and heavy lift launch vehicles are not responsive and that vehicle responsiveness improves dramatically with decreasing payload delivery capability. Consequently, existing U.S. launch

\(^2\)Further discussion of this subject is beyond the scope of this report.  
\(^3\)Sandia Laboratories, unpublished research made available to RAND.
Figure S.1—Responsiveness and Payload Capabilities of U.S. Launch Vehicles

vehicles, with the possible exception of Pegasus, could not support the timelines required to effectively carry out the military missions described above.

However, if a TAV could be launched within minutes or hours of a launch order, it may be possible to effectively carry out these missions. This degree of responsiveness may be possible only if TAVs could be operated like aircraft and be put on alert like bombers. Aircraft-like levels of responsiveness imply aircraft-like levels of supportability and reliability. Aircraft-like supportability in turn implies a much higher level of reliability than that of current launch vehicles. The data in Figure S.1 suggest that an operationally useful military TAV should be built to handle as small a payload as possible in order to maximize TAV responsiveness.

*Excludes time delays caused by launch vehicle failures
Military and Commercial Needs Differ

The combination of a rapid launch-on-alert capability, unpredictable launch schedule, fast turnaround time, and rapid reconfigurability to handle a variety of payloads appear to result in a set of requirements that is uniquely military.

A military vehicle capable of being launched on alert from a number of continental U.S. (CONUS) bases could be very different from a commercial RLV designed for a predictable launch schedule and operation from only one launch site. All the X-33 competitors sized their commercial RLV designs to handle substantial payloads of 20,000 to 45,000 lb to LEO. If history is any guide, it will be difficult to make these large vehicles responsive. In contrast, for many military missions, and in particular for potentially important space control and force application missions, a payload delivery capability of only 1,000 to 5,000 lb to LEO may be adequate.

Design Options and Issues

A variety of TAV and RLV designs were presented at the workshop. Vertical take-off and landing (VTVL), vertical take-off and horizontal landing (VTHL), or horizontal take-off and landing (HTHL) TAV concepts were discussed. HTHL concepts have the advantage that they may be able to use existing infrastructure and runways. VTVL concepts may entail higher operational risk because of the requirement for powered rocket landing.

Vehicles also came in a number of staging concepts, including SSTO, Two Stage to Orbit (TSTO) air-launched, and TSTO aerial-refueled concepts.

Table S.1 lists most of the RLV and TAV design concepts presented at the RAND TAV workshop. Several of these designs are based on detailed technology and design studies, such as the X-33 entrants, while others reflect promising but newer and less thoroughly explored concepts. The level of maturity of these concepts is indicated by the legend in the table.

Several TAV concepts presented at the workshop have been under active investigation in DoD, including the Black Horse concept. Subsequent to the workshop, RAND performed an independent analysis of Black Horse’s payload capability and found it could not reach orbit. RAND performed a similar analysis of the Northrop Grumman (NG) TAV and was able to verify the contractor’s claimed payload delivery capability.

The NG TAV concept appears promising and could be well suited for several military missions. It could potentially deliver a 1-6 klb payload to various LEO
Table S.1
Recent RLV and TAV Concept Proposals

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Contractor/Lab</th>
<th>Staging</th>
<th>Payload</th>
<th>Propulsion</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-33</td>
<td>Lockheed Martin</td>
<td>SSTO</td>
<td>Heavy</td>
<td>LOX-LH2</td>
<td>Lifting body, VTHL, aerospike engine</td>
</tr>
<tr>
<td>X-33</td>
<td>Rockwell</td>
<td>SSTO</td>
<td>Heavy</td>
<td>LOX-LH2</td>
<td>VTHL</td>
</tr>
<tr>
<td>X-33</td>
<td>McDonnell</td>
<td>SSTO</td>
<td>Heavy</td>
<td>LOX-LH2</td>
<td>VTVL</td>
</tr>
<tr>
<td>X-34</td>
<td>OSC</td>
<td>Air-drop</td>
<td>Small</td>
<td>LOX-storable</td>
<td>HTHL, L-1011</td>
</tr>
<tr>
<td>REFLY</td>
<td>Rockwell</td>
<td>Air-drop</td>
<td>Very small</td>
<td>Noncryogenic</td>
<td>L-1011, B-52, reusable upper stage</td>
</tr>
<tr>
<td>NG TAV</td>
<td>Northrop Grumman</td>
<td>Air-launched</td>
<td>Small</td>
<td>LOX-LH2</td>
<td>Boeing 747</td>
</tr>
<tr>
<td>Black Horse</td>
<td>Phillips Lab</td>
<td>Aerial-refueled</td>
<td>Small</td>
<td>H2O2-kerosene</td>
<td>KC-135Q tanker</td>
</tr>
<tr>
<td>Neptune</td>
<td>Phillips Lab</td>
<td>Air-launched</td>
<td>Small</td>
<td>LOX-LH2</td>
<td>B-1B</td>
</tr>
<tr>
<td>TAV</td>
<td>AMC HQ (Snead)</td>
<td>Air-launched</td>
<td>Medium</td>
<td>LOX-LH2</td>
<td>Boeing 777</td>
</tr>
</tbody>
</table>

- ■ Under development (NASA)
- ○ Design proposed
- □ Concept proposed
- □ Concept performance verified
- X Concept performance problem identified
orbits and would be launched from on top of a Boeing 747. The orbital vehicle resembles a scaled-down Space Shuttle and would have its hypersonic characteristics and a significant cross-range capability.

Relatively little design and development work has been done on TSTO TAV concepts when compared to the work done on SSTO concepts. A broader set of air-launched and aerial-refueled TAV concepts deserves study, including study of high-density propellants and air-launch separation dynamics at supersonic and subsonic speeds.

The X-33 competition, much like the NASP program, has focused attention on SSTO vehicles. RAND believes TSTO TAV concepts deserve equal attention if delivering small- to medium-sized payloads to LEO is viewed as a primary mission need. Air-launched TSTO TAV concepts appear particularly promising from a cost standpoint because the first stage aircraft could be based on a commercial civil air transport. In addition, they may provide an evolutionary development path to full reusability and aircraft-like levels of responsiveness for orbital vehicles. In contrast, SSTO systems may be more challenging technically, much more costly to build, and would be so large they could not meet military responsiveness needs.

Technology Challenges

Developing a highly responsive and cost-effective TAV regardless of the design approach chosen will be challenging, but is certainly possible given the advances made in key technology areas in the past few decades. Much remains to be done, especially in propulsion.

Advanced Materials and Structures

Minimizing vehicle empty weight is important for any vehicle concept and critical for SSTO concepts. This will require the integration of lightweight composite materials into the vehicle airframe and subsystems. Modern composite materials have higher strength and stiffness than standard metals, which can significantly reduce overall vehicle structural weight. For example, per-unit-weight graphite epoxy is five times stronger than aluminum alloy, the material the space shuttle airframe is composed of. According to some analyses, advanced composite materials and lightweight metal alloys may permit launch vehicle structure weight to be reduced by up to 35 percent.
**Propulsion**

A TAV’s rocket engines will have to be efficient and provide the thrust levels needed to reach orbit. Rapid turnaround and low-cost operations also require that engines be durable, damage-tolerant, easily inspectable, and capable of rapid and safe shutdown.

From performance and reliability standpoints, the best bi-propellant engines use cryogenic liquid hydrogen (LH2) and liquid oxygen (LOX). However, cryogenic fuels introduce handling complications that may reduce TAV responsiveness. Hydrogen leaks are especially difficult to contain, pose an explosion hazard, and introduce additional operability concerns. Further research is needed to find ways to efficiently handle LH2 in a military operations environment.

High-density propellants are not as efficient as cryogenic propellants, but they may provide operability advantages that could be especially useful for military TAVs. In addition, vehicles based on high-density propulsion could be significantly smaller in size, which could provide special advantages for TSTO air-launched concepts. Research is needed on high-density propellants to determine whether these possible benefits can be realized.

The highest-thrust LH2/LOX engine available today is the Space Shuttle Main Engine (SSME). The current SSME does not have the performance levels needed for a full-scale SSTO RLV, and even planned improvements to this engine may not be adequate for this purpose, calling into question the feasibility of building an SSTO RLV with conventional rocket engines.4

The current SSME must be pulled from the shuttle after every flight to replace the turbopumps, although planned engine upgrades may reduce engine replacement time to once every ten flights. The Russian D-57 LOX/LH2 engine provides slightly lower performance than the SSME and is smaller, but has adequate thrust levels for the TSTO NG TAV concept and would have to be pulled from the vehicle only once every ten flights. This level of durability should be adequate for a military TAV. However, if even more durable engines can be built, TAV responsiveness could be increased and launch operations costs could be reduced further.

LOX/LH2 aerospike rocket engines, like those planned for the Lockheed-Martin X-33, may have significant performance advantages over conventional rocket engines.

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4The current Block II+ SSME has a thrust-to-weight ratio of 58, which NASA is planning to improve to near 70 in the Block III SSME. The National Research Council has reported an SSTO RLV would require a thrust-to-weight value somewhere between 75 and 80.
engines. They may be able to deliver nearly the same level of performance as the SSME, but have the higher thrust-to-weight levels needed for SSTO applications. This is an area where the Air Force and DoD could benefit substantially from work being done for NASA.

Finally, tri-propellants may offer performance advantages and higher densities, potentially leading to smaller, less-expensive vehicle designs. However, past investigations have been discouraging. Nevertheless, because of their potentially high payoff, tri-propellants warrant continued research.

**Thermal Protection Systems (TPS)**

Rapid turnaround between missions, cost-effective operation, and high payload mass fraction characteristics will also require development of a lightweight, robust, and durable TPS. Our review of TPS materials reveals that it should be feasible to design a durable TPS from advanced metallic alloys, provided the reentry path and the vehicle’s aerodynamic design result in reentry temperatures that are less severe than those found on the space shuttle. Peak temperature locations would probably still require reinforced carbon-carbon to withstand reentry thermal loads, but most other locations on the vehicle should be protectable by combinations of metallic panels. Although metallic panels would have higher density than ceramic tiles, a metallic TPS may be lighter and simpler by eliminating the need for the complex adhesive system used on the space shuttle. The panels may also serve as aerodynamic load-bearing structures, eliminating the necessity for an underlying airframe.

Furthermore, by optimizing the vehicle’s aerodynamic design, it may be possible to reduce the thermal loads on the vehicle, thereby decreasing the degree of thermal protection required. These improvements could result in a TPS that is more reliable and less expensive to maintain than that of the current space shuttle ceramic tile system that requires 17,000 man-hours for refurbishment after every flight.

**Vehicle Integration**

A significant engineering challenge is the effective integration of lightweight high-strength composites and metal alloys into vehicle structures and the integration of durable metallic TPS and efficient and durable rocket engines into the vehicle. A TAV that has these technologies and subsystems effectively integrated would likely have desirable payload delivery characteristics and could responsively carry out a range of military missions.
Multimission Capability and Cost

Cost is of course an important design consideration. A military TAV capable of supporting only one mission area, such as launching small satellites into LEO, may not be cost-effective, except possibly over the long term (in terms of total life-cycle costs). For a small military TAV, such as the NG TSTO TAV concept, a budget of about $760M would be required to build one subscale prototype X-vehicle and one full-scale operational prototype.\(^5\)

A military TAV should therefore have a multimission capability to justify an expenditure of this size for TAV development in today’s austere budget environment. Before any development decisions can be drawn from the above discussion, a thorough analysis of TAV mission cost effectiveness should be performed and the results compared with the capabilities of other platforms. Such a mission analysis is beyond the scope of this report.

Conclusions

TAVs could potentially launch payloads into space or toward distant targets at much lower cost than expendable launch vehicles. In addition, if they could be operated more like aircraft and less like expendable rockets, they offer the promise of carrying out space operations with much greater flexibility and responsiveness than is possible today.

Discussions at the workshop and subsequent investigations reveal that despite the efforts of past programs, significant technology challenges remain, especially in the areas of propulsion, thermal protection systems, and overall vehicle integration. Stringent mass fraction limits will have to be met for the vehicle to reach orbit with its intended payload. Overall vehicle design is very important. It is too early to know which sort of vehicle design has the best chance of meeting required mass fraction limits. More research is needed in propulsion, thermal protection systems, and overall vehicle design. The NASA X-33 program will provide important new data in all three areas, but the DoD needs to pursue research in all three areas as well.

A reusable launch vehicle could satisfy civil, commercial, and military space launch needs. However, our analysis reveals that civil and commercial launch needs differ in some important respects from emerging military needs. The highest priority for civil and commercial users is to reduce the cost of access to

\(^5\)See Section 2 and Life Cycle Cost Assessments for Military Transatmospheric Vehicles, MR-893-AF, 1977, for further details regarding this cost analysis.
space. Military users are also concerned about reducing costs, but launch vehicle responsiveness and flexibility are critical for some military missions. These differing needs have an important bearing on vehicle design and imply that a military TAV may differ in important ways from an RLV designed exclusively for the commercial launch market.

Finally, reducing launch vehicle costs will at best address only half the problem of reducing the overall cost of access to space. Payload costs need to be reduced as well. Furthermore, there are subtle interactions between payload and launch costs. As launch costs increase, so do payload costs. To reduce the risk of on-orbit failure and the probability of relaunch, some payload subsystems are made triple redundant, increasing the cost and weight of the satellite. If launch costs can be reduced significantly, it may no longer be necessary to design to such high levels of redundancy. In addition, TAVs may make it possible to recover payloads in orbit, and if payloads were designed modularly, they could be quickly repaired on-orbit. Such payloads could cost considerably less than existing satellites. TAVs might enable a new era of low-cost access to space.