

SPACE LIFT

Suborbital, Earth to Orbit, and on Orbit

A SPACECAST 2020 White Paper

(although this paper was collaborative work, comments may be directed to the primary author, [Major Chris Daehnick](#))

A VISION FOR THE FUTURE: In 2020, aerospace forces will be a reality. A notional composite aerospace wing, based in the continental United States (CONUS), would include a squadron of rocket powered transatmospheric vehicles (TAV). These Black Horse₁ vehicles, derived from the Question Mark 2 X vehicle₂ (fig.1) and described later in this article, will be fighter sized airframes capable of placing an approximately 5,000 pound payload in any low earth orbit (LEO) or delivering a slightly larger payload on a suborbital trajectory to any point in the world. Black Horse vehicles could accomplish either task within one hour of completion of mission planning, assuming that the payload was available at the base and the vehicles were on alert. When operating in support of a warfighting commander in chief (CINC), the aerospace wing will thus have the capability to put mission specific payloads on orbit (mission tailored satellites) or on target literally within a few hours of identification of a need. Most missions - except some suborbital operational and ferry/deployment missions - will require aerial propellant transfer from modified KCXX aircraft. These aerospace craft will use noncryogenic propellants- standard jet fuel and hydrogen peroxide- and will be designed for maximum logistics compatibility with the rest of the wing.

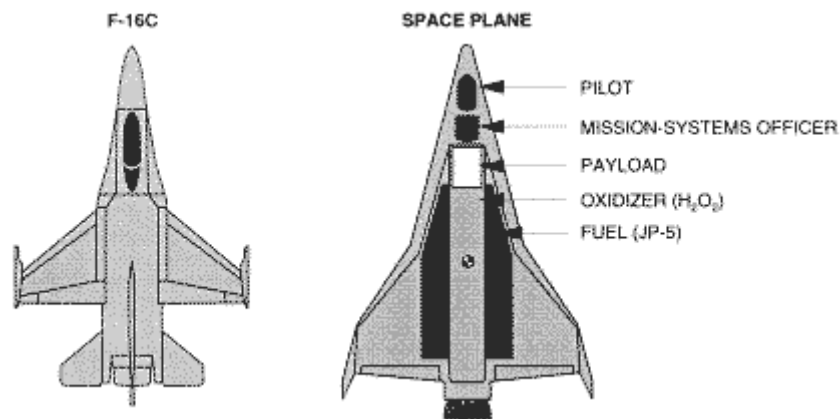


Figure 1. The First Black Horse TAV: "The Question Mark 2" X Vehicle (Planform Comparison with F-16C) (From a conceptual study done by W. J. Schafer and Associates and Conceptual Research Corporation for Phillips Laboratory, January 1994)



Maintenance and ground operations for the TAV will require no greater specialized skills than those for any other aircraft in the wing. TAVs returning from a mission would normally be serviced and returned to ready-for-flight status in less than a day and could be surged to fly multiple missions per day if necessary. If tankers were prepositioned in-theater, TAVs could also fly high-priority, global, cargo-delivery missions.

To fully exploit the TAV's capabilities, designers will adopt a new approach to satellite design—one that maximizes use of advances in miniaturization and modularity. Most space systems' designers thus will take advantage of the vastly lower cost-per-pound to orbit (less than \$1,000 per pound) that the TAV concept provides. Orbital payloads that are too large to fit in a single TAV can be designed as modules, launched in pieces, and assembled on orbit.³ Some high value satellites will be serviced, repaired, and modernized in space by space tugs, which will move payloads launched on the TAVs to the mission orbit. With space launch and operations made routine by the TAV, multiple new uses for space systems will emerge, and the design cycle for new systems will be greatly reduced. Such systems will be less expensive, simpler, and quicker to make; they will also cause less concern if one does fail and will allow more rapid inclusion of emerging commercial technologies.

The ability to orbit, upgrade, or even retrieve dedicated, special purpose, space support capabilities quickly and (relatively) inexpensively will dramatically change space operations. Satellites will perform navigation and most housekeeping functions autonomously. Central ground sites will monitor, update software, and assist these satellites in identifying repair requirements. Theater forces will task the mission payloads on these satellites directly by using deployable ground systems that require less lift into theater than 1990s communications/data display terminals. The result will be an array of space systems and operations that are fully integrated into global operations.

This description is not science fiction. It is an entirely plausible outcome of the development program described in this article. The initial reaction of many readers to these assertions and to the Black Horse TAV concept in general is that it is too good to be true and that the claims are reminiscent of shuttle or national aerospace plane (NASP) promises. In fact, Black Horse is substantially different in concept from either of those systems, and the numbers and assertions presented here are based on a preliminary but iterated design (i.e., several steps beyond a point design) performed by technically credible engineers. Following a brief discussion of the current lift problem, the article explains the steps needed to produce operationally effective TAVs and associated capabilities.

Problems with Space Lift

THE UNITED STATES must have assured and affordable access to space to expand or even sustain space operations. This means being able to place useful payloads in all relevant earth orbits with high probability of launch success and operation on orbit within hours instead of months or years. It also means the ability to operate flexibly in and through space to accomplish both manned and unmanned missions in support of US national and military objectives.⁴ By almost any measure, the current US spacelift (earth to orbit) capability is not sufficiently robust. Worse, it is not improving. Suborbital (operations through space) and orbital maneuvering capabilities are almost nonexistent. If the United States is to make full use of space in the next century, military planners must address these shortfalls.

This article proceeds from the assumption that assured access to space is crucial for many reasons: to enable future innovative ways of supporting combat forces, to counter threats from unfriendly spacefaring nations, and to create the conditions for a commercial market that may ultimately support and drive rapidly evolving space technologies. Numerous studies⁵ are available to support this assumption. Ultimately, expanded military, civil, and commercial use of space depends on assured and affordable access to space.

A review of the limitations of current launch systems suggests several specific problematic areas:

1. Current systems have severely limited abort capability because of such things as their predominantly intercontinental ballistic missile (ICBM) heritage and the use of solid rocket boosters.
2. Use of disposable hardware, manpower intensive operations, and the design of US lift systems in general result in large, recurring launch costs.
3. There is little or no standardization of launch vehicles, their interfaces, spacecraft buses, or payload interfaces.⁶
4. Tailoring rockets to fit payloads is costly, wasteful, and unnecessary.⁷
5. Solid rockets and disposable hardware are generally not environmentally friendly.
6. The current huge and highly specialized launch infrastructure (ranges, launchpads, personnel, etc.) causes expensive, lengthy, and unresponsive launch schedules. Unless an alternative is discovered, this launch infrastructure will be archaic well before 2020.
7. Spacelaunch and operations procedures are overly complex and nonstandard, requiring "white coat" specialists instead of "blue suit" operators.
8. Launch operations are "serial" events. One payload and one (dedicated) launch vehicle are readied interdependently and step-by-step, a process that does not allow parallel preparation of spacecraft and launch systems for flexible launch scheduling.
9. The US does not have a flexible, operationally responsive space launch system or the capability to reconstitute even a limited capability on orbit in response to a crisis or loss (deliberate or accidental) of any US space system.

This article does not propose a new national space policy, a new spacelift policy, or a "silver bullet" solution that provides unlimited or unconstrained lift. Rather, it proposes an alternative architecture of space lift and sub-orbital and on-orbit vehicle capabilities that will enable the country to perform new missions in space, provide a responsive and resilient spacelift/operations capability that is increasingly acknowledged as militarily essential,⁸ permit an escape from the current vicious cycle of cost-weight-size-complexity-risk-delay that frustrates US government space systems, and offer the potential for future commercial exploitation that not only would result in vast new commercial opportunities, but also would logically drive development of even better spacesystem capabilities.

This article proposes a spacelift system that can put usable payloads on orbit affordably, has extremely high operational utility, is responsive, requires little or no specialized infrastructure, operates like an airplane, and has the potential to change the approach to space as surely as the DC3 changed air travel. It also addresses potential suborbital missions that such a system would allow; discusses different ways of deploying, servicing, and redeploying space assets once they are on orbit; and explains why this is desirable in some (but not all) cases.

If our nation has no desire for expansion in the use of space (either militarily, scientifically, or commercially), it can no doubt continue tinkering with existing launch systems and gradually refine procedures to gain small, incremental improvements in efficiency. This would commit the United States to an ultimately selfdefeating cycle: the continuation of increasingly large and complex space systems - technologically obsolescent as soon as they become operational - and ever fewer yet higher performance launch systems to put them on orbit. The great risk, cost, and difficulty of replacement associated with failure of one payload during launch or while on orbit demand increasingly burdensome and unwieldy oversight focused on ensuring that nothing can possibly go wrong. In other words, not only will a policy of business as usual not enable a breakthrough in the use of space, it may ultimately cause some existing uses of space to become unaffordable and unattractive.

The SPACECAST lift team recommends that the Department of Defense (DOD) proceed with a modified space development program that emphasizes the lift and on orbit operations technologies highlighted in this article. This program must emphasize, above all else, increased operational flexibility and a concomitant reduction in specialized infrastructure. The top priority should be an X program to demonstrate the validity of the Black Horse TAV concept. The entire cost of such a program would be less than \$150 million (by comparison, a single Titan IV launch costs \$325 million).⁹ This type of system, although not capable of meeting all lift requirements, offers great potential for a breakthrough in making space operations routine and introduces multimission capability. It stands above all other spacelift ideas that have been evaluated.

Missions

THE TAV, LIKE THE airplane before it, has the capability to perform many different types of missions. The TAV concept is not intended to be all things to all people; in fact, SPACECAST explicitly recognizes that one system is unlikely to fully satisfy mission needs in every area. However, the TAV can perform a subset of missions across several mission areas. In this sense, it is like the C130 aircraft - basically a transport airframe but with AC, EC, KC, MC, and other versions. SPACECAST believes that the TAV can improve on this by using modular, interchangeable mission modules (satellite or weapons dispensers, for example) so that the same airframe - flying very similar mission profiles - provides a flexible, responsive, multimission capability. This capability provides tremendous leverage in achieving global reach-global power and contributes to the overall SPACECAST concept of "global view."

The core of the proposed spacelift and transportation architecture is an innovative space access capability that can operate like an air transportation system. The US space transportation capability of the future should include systems for moving payloads around, within, or through space (suborbital, orbital, or return from orbit). SPACECAST 2020 proposes pursuing a spacelift development strategy that provides solutions to the country's most pressing problems, while encouraging (but not assuming) future quantum improvements in space transportation technology.

Space Lift

If launch of a satellite becomes a less complex, less time consuming, and less costly task, engineers can design spacecraft for shorter lifetimes with ease of upgrade or replacement. Shorter lifetimes would reduce fuel requirements, much of the onboard redundancy, and other elements related to design life. Designers could avoid much of the current cost redundancy and complexity, creating smaller, less expensive, and more technologically up-to-date systems. Evolving toward such systems would make replacements easier to produce and launch, and the consequences of an on-orbit failure could be remedied as soon as a satellite was available. Satellites that must be large (e.g., optics - such as the Hubble telescope - that do not use interferometry) could be designed modularly and assembled on orbit. To take full advantage of this capability, the US would have to revisit most of its basic assumptions about space operations, starting with the type of spacelift system.[10](#)

It is important to note that a single system will not satisfy all needs, just as variants of a single airframe do not perform all air missions. For example, a Black Horse TAV will probably never launch a military strategic and tactical relay satellite (MILSTAR). Also, transitional measures may be necessary to preserve operational capabilities until new technology systems come online. This will undoubtedly include expendable launch vehicles in the near term. SPACECAST believes that the approach outlined below, while not addressing all spacelift problems, provides the maximum potential payoff for 2020 and beyond.

Any proposed lift system must address the operational concerns and problems highlighted earlier. Specifically, to be militarily useful, a future lift system must be responsive (capable of launch on demand), highly reliable, able to abort a launch without destroying the vehicle (soft abort), resilient, flexible, logistically supportable, and easily operated. An overriding concern for all users - military, civilian, or commercial - is that the system be affordable. These factors can be difficult to translate into specific numbers, so - rather than setting quantitative goals - this article seeks a system that offers a recognizable, *qualitative* improvement in the launching of payloads into space. Numbers relating to the initial design of the Black Horse TAV are mentioned here, but they show the capabilities of an X vehicle designed with current technologies and should not be interpreted as the upper limit of the vehicle's capabilities.

Force Application

A version of the TAV contributes to our national military strategy by allowing the United States to rapidly respond worldwide to future threats with overwhelming offensive firepower. It provides the national command authorities (NCA) and the CINC the ability to accomplish strategic-level effects in about an hour without using weapons of mass destruction. Rapid vehicle recovery, rearming, and relaunch on subsequent missions allow the CINC to continue the offensive through decisive follow-on attacks, thereby reducing the effectiveness of enemy interference with reconstitution and recovery attempts. Such a vehicle has the potential to escalate the pace of war fighting beyond SPACECAST's projection of future threat capabilities. The system capitalizes on three specific offensive advantages.

Speed and Surprise. The greatest single advantage of this weapon is surprise. Strategic surprise results from the ability to strike enemy targets at any depth with little or no warning. Because kinetic energy multiplies the effect of weapons delivered from a suborbital trajectory, the weapons themselves can be small (e.g., brilliant micromunitions); therefore, a single vehicle could simultaneously strike a large number of targets. Operational surprise results from the rapidity of the completed attack, which may be timed to catch an adversary in the process of deployment or employment of inadequately prepared forces. Tactical surprise results from a variety of suborbital profiles that these vehicles can use to exploit gaps in an enemy's defense. The speed of the system - the ability to put force on target anywhere in the world in a matter of minutes - also converts the global reach of the system into a form of "presence" that does not require constant forward deployment of forces.

Mass, Economy of Force, and Persistence. This concept can rapidly complete a strategic attack on multiple (perhaps even multithousand) aiming points with a small fleet of appropriately armed TAVs. The exact number will depend on vehicle payload capacity, final weapons designs, and cost. Rapid revisit times allow continued pressure on the enemy. The concept also contributes to solving the current concern of handling a number of major regional contingencies, since the surge rate of the weapon system should allow destruction of at least two widely dispersed regional opponents' key centers of gravity within several days. Finally, the simultaneous presentation of thousands of small reentry

vehicles to a surprised and defensively helpless adversary will likely overwhelm him, thus ensuring the success of our nation's objectives.

Synergy. The vehicle's ability to employ a variety of weapons allows tailored effects to prepare the battlefield for other weapon systems or to act as a force multiplier, allowing ground, air, and sea forces unimpeded access to the battlefield to accomplish followon missions. Results can also provide synergistic effects for other national instruments of power.

On-Orbit Operations

Putting things on orbit (into LEO, in particular) does not always satisfy operational demands. Some satellites must be lifted to higher orbits, and some key space assets may require redeployment from one operation to the next (altering orbits). Missions to retrieve high value assets for repair or upgrade (remotely on orbit, at a space station, or back on earth); to resupply space platforms with things like fuel, food, or weapons; or even to collect space debris and "dead" satellites from highly populated orbits are also possible.

As a result, the US may need a system of transportation between LEO and other orbits. This is essentially an extension of concepts already studied by the National Aeronautics and Space Administration (NASA) and DOD. The SPACECAST team believes that these types of systems complement any lift concept, permitting either larger payloads for a given booster or the launching of a given payload on a smaller system. For the TAV concept, postulation of a separate on-orbit transportation system opens up additional missions, but it is not a requirement for the TAV's performance of the basic missions described here.

The Vehicle

DESIGN OF A VEHICLE TO accomplish multiple missions is seldom easy. The history of the F111 aircraft serves as a strong warning, as do our nation's unsuccessful efforts (thus far) to accommodate all space users' launch requirements on a single vehicle.

The critical factor in designing an aerospace vehicle is ensuring that the mission profile (range, maneuverability, type of payload, etc.) and the performance requirements (speed and amount of payload, among others) of the proposed multimission vehicle are compatible. If they are, increased operational flexibility and cost savings through common logistics and operational procedures become possible. The SPACECAST team believes that this *is* the case with Black Horse vehicles for both the launch of spacecraft and the suborbital delivery of weapons or cargo. As mentioned earlier, the C130 is a good analogy in terms of design philosophy: simple and as rugged as possible, not necessarily the highest performance system, but inherently capable of multiple missions.

Spacelift Options

The size of the payload put into orbit by a launch vehicle should not drive the launch system design. In fact, small spacecraft have many potential advantages, mentioned earlier. Cost-per-pound to orbit should be a key measure, and if the cost is low enough, almost any mission payload can be repackaged to fit a smaller launch envelope or accommodated on several launches, if need be. Those payloads that absolutely must have a launch vehicle of a specific size will probably never be affordable, although overriding national security concerns may still require their launch.

The strategy advocated here - reducing payload size for a system that produces low operating costs - rests on four assumptions. First, the technology that drives space payloads (sensors, electronics, software, etc.) is advancing rapidly - even accelerating. This makes large, complex satellites (because of their lengthy cycles of design and construction) more vulnerable to obsolescence on orbit and favors an approach that regularly places more up-to-date systems on orbit. Second, these same technological advances increasingly allow more capability to come in smaller packages. Modularity, interferometry, bistatic radar techniques, and other technologies may even allow things traditionally believed to require large, monolithic platforms to be put in space incrementally and either assembled on orbit or operated as a distributed system. Third, economies of scale have proved elusive in space systems. Large boosters are not appreciably (an order of magnitude) more cost effective (dollars per pound on orbit) than small boosters, and no projected demand or incremental improvements will significantly (again, by an order of magnitude or more) reduce the cost of current boosters. Finally, military space operations will be increasingly subject to fiscal constraints because many national security requirements may no longer justify performance at any cost.

Despite these assumptions, several possible alternative systems exist, most of which are familiar. They include Pegasus; Taurus; other light, expendable launch vehicles; converted sea-launched ballistic missiles; hybrid (mixed solid/liquid propellant) rockets (also expendable); a variety of reusable vehicles from NASP-derived systems to DCX-derived single stage to orbit (SSTO); carrier-orbiter concepts such as the German Sänger and Boeing's reusable aerospace vehicle (actually a trolley launched system); and even cannon or railgun launch ([table 1](#)).

Which System Is Best?

Most alternative systems actually do not offer a qualitative difference in the launching of satellites. Pegasus, Taurus, other expendables, and hybrid rockets fall into this category. A qualitative difference is important because even the most ambitious recommendations for improved conventional (expendable) boosters do not offer more than a 50 percent reduction in cost-per-pound to orbit¹¹ and in most cases still rely on antiquated range support systems and - to a lesser extent - launch procedures. Small expendables, though more flexible and more operationally effective than large boosters, typically cost even more per pound to orbit. In making a system acquisition decision, planners must carefully compare the lifecycle costs of reusable systems with those of mass-produced expendables - a comparison that is beyond the scope of this article. It is

worth mentioning, however, that one of the hidden costs of expendable rockets - particularly those using solid propellants - is environmental. Although difficult to assess, adverse environmental impact may be an overwhelmingly negative factor in the mass use of small, expendable launch vehicles.

Table 1

Qualitative Comparison of Launch Systems

System	DC-X	Black			Sea
Gun					
Capability	SSTO	Horse	Pegasus	Taurus	Launch
Launch					
Responsiveness	Good	Excellent	Good-	Poor-	Poor-
Excellent			Excellent	Good	Good
Flexibility	Good	Excellent	Fair	Poor	Fair
Poor					
Soft Abort	Fair-Good	Excellent	None	None	None
None					
Resiliency	Fair	Good	Fair	Fair	Fair
Good					
Logisitics	Fair	Good	Fair	Fair	Fair
Poor					
Reliability	Unknown	Unknown	Fair	Fair	Fair
Unknown					
Ease of	Good	Excellent	Fair	Fair	Fair
Fair					
Operations					
Environmental	Excellent	Good-	Poor	Poor	Poor
Fair-					
Excellent		Excellent			
Cost	Good-	Good-	Poor	Poor	Poor
Excellent					
(lbs to orbit)	Excellent	Excellent			

Cannon/railgun systems may be attractive in terms of cost-per-pound to orbit but have some severe limitations. Payloads must withstand accelerations of 1,000 Gs or greater (this does not facilitate building less costly satellites with fewer constraints on the use of commercial parts), and the US would become more - not less - dependent on specialized infrastructure. Barring a revolutionary advance in propulsion technology (which is as unlikely in the next 20 years as it is unforeseeable), the SPACECAST team believes that

fully reusable lift systems integrated with mainstream aerospace operations offer the best hope for qualitative change in space lift.

Problems with Reusables and General Design Goals

From basic intuition through the justification for the space shuttle to the most recent studies,¹² fully reusable systems offer the greatest operational flexibility and potential cut in launch costs. Three problems continually recur: (1) how to build a system that is completely reusable and has acceptable performance; (2) how to justify the nonrecurring costs (infrastructure investment as well as hardware development) to get the eventual benefits of lower recurring costs; and (3) how to reduce recurring costs to the point that one can expect an eventual payback. The space shuttle's problems in these areas and others have disillusioned people, but a radically different design may finally vindicate the notion of a reusable launch system.

Problems with fully reusable launch vehicles may stem from misplaced attachment to old paradigms of space systems (e.g., at least 20,000 pounds of lift capacity are needed to place useful payloads in orbit). The reason for this is twofold: first, it reflects assumptions about satellite design that do not account for advances in miniaturization and modularity (i.e., what has become possible) and second, it assumes that payload size is the primary determinant of a launch system's utility (as opposed to, say, cost-per-pound of payload in orbit or the ability to launch on extremely short notice). This mindset drives performance to the edge of the envelope, creates tremendous development costs and dependence on immature technologies, usually fails to address operational implications sufficiently, and produces huge specialized infrastructure requirements that further drive up recurring and nonrecurring costs. These crippling problems can be overcome if designers challenge the old assumptions about space lift.

Space authorities have now acknowledged the negative relationship between trying to get the maximum number of pounds of payload onto a given rocket and optimizing cost/reliability.¹³ Further, as discussed above, the vicious cycle of large satellite design and the opportunities provided by miniaturization and other advancing technologies argue in favor of smaller, standardized satellite designs.¹⁴ Finally, authorities on military space have expressed frustration with the "custom rocket" approach that comes from attempting to squeeze every last ounce of lift out of a given booster.¹⁵ The time is ripe to design an operationally sound launch vehicle - one that utilizes existing, common infrastructure; one that can be maintained by well-trained high school graduates; and one that can be operated by well-trained college graduates without scientific expertise. One can then build payloads to fit it.

Development costs and dependence on immature technologies are linked to the performance issue. Because performance requirements are so high, only exotic fuels, engines, or design concepts can possibly meet them. As a result, billions of dollars in research and development are required to validate (and sometimes invent) the enabling technologies. All too often, the success or failure of a given approach cannot be determined until the system is actually built, and even a prototype incorporating many

advanced technologies may be prohibitively expensive. As an alternative, the SPACECAST team proposes an affordable X-vehicle development program that has clear, near term military relevance and traceability to an operational system.

Failure to take into account the operational implications of a launch system - not just the launch crew but the support infrastructure for such things as fueling, maintenance, logistics, or basing - has been crippling in terms of cost and the eventual utility of systems. NASP-derived and two-stage (carrier vehicle and space plane) concepts seem particularly vulnerable to this shortcoming, although they still represent an improvement over the huge, archaic, expensive, inflexible, and manpowerintensive procedures required for current lift systems.¹⁶ From the start, operational and infrastructure considerations must have top priority. Space operations must become as routine and non-exotic as air operations.

Black Horse TAVs

To address these concerns, we can assume that maximum performance (in terms of specific impulse for rockets) is not necessary or even desirable. This assumption permits consideration of noncryogenic propellants, which offer several advantages. If these propellants are sufficiently dense, a workable lift system can be designed. The British did so with the Black Arrow and Black Knight programs, using 1950s technology, because factors such as a reduction in tankage volume, a decrease in engine complexity, and an improved engine thrust-to-weight ratio make up for much of the (propellant) performance loss (fig.2). Interestingly, one of the most attractive combinations of noncryogenic propellants is jet fuel (nominally JP5) and hydrogen peroxide.¹⁷

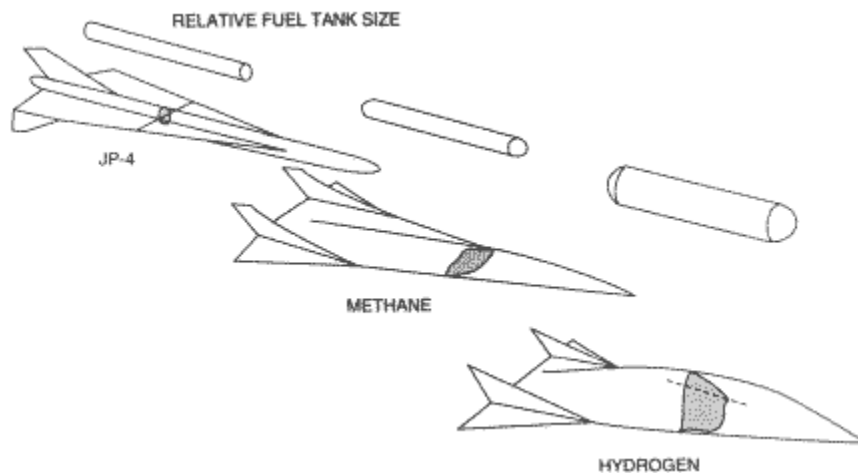


Figure 2. Notional Vehicle Cross Sections for Different Fuels (From Bill Sweetman, *Aurora: The Pentagon's Secret Spy Plane* (Osceola, Wis.: Motorbooks International Publishers and Wholesalers, 1993))

The real attraction of this propellant combination is in the operational arena. The propellants are easily available (hydrogen peroxide is commonly sold for industrial uses at 70 percent purity; vendors could provide higher purities, or the commercial product

could be refined on-site), storable, and pose no significant logistics problems. Rocket engines using these propellants also have excellent reliability histories, both on the Black Arrow and Black Knight programs and on the NF104D research aircraft. The NF104D program started such an engine (using JP4 and H₂O₂) at least two times on every flight, experienced no rocket-engine-related emergencies during 11 years of operation, and was serviced and maintained with "essentially conventional maintenance procedures and normally trained personnel."¹⁸ Storage and handling of high-purity H₂O₂ is not inherently dangerous and requires primarily discipline - not extensive safety equipment.¹⁹ The Black Arrow and NF104D programs routinely used 85-90 percent pure hydrogen peroxide; there are no known chemical reasons why operations with higher purities would be any more difficult. Finally, servicing a vehicle that uses cryogenic propellants requires many more steps (and is thus much slower) than servicing a noncryogenic-fueled (such as JP5 and H₂O₂) vehicle. Even on the DCX SSTO demonstrator, which had ease of operations as a design goal, fully 80 percent of the preflight checklist items were cryogenics-related.²⁰

If readily available and easily stored propellants are used, the only reasons why a reusable vehicle could not operate from any location would be specialized requirements for assembly/loading, launch, and landing. Although a vertical takeoff and landing system has advantages in terms of empty weight and choice of launch/landing sites (theoretically it needs only a small pad), the SPACECAST lift team believes that a horizontal takeoff and landing system is a better near-term approach.

A horizontal takeoff and landing space launch system has many advantages. First, sufficient airfields are available for any conceivable mission. Second, fuel supplies and logistics infrastructure (crew equipment, administrative support, ground transportation, and maintenance and other ground personnel) are already located at airfields. Finally, a horizontal takeoff and landing vehicle would almost certainly be more robust. Its advantages include a larger abort envelope, the ability to land with all engines out, and greater crossrange on reentry. Although there is a performance penalty associated with this approach (hence, the DCX design), there is also an ingenious way to compensate for it - aerial propellant transfer.²¹

True SSTO vehicles must lift all the propellant they need to reach orbit from the ground. This in turn drives the gross takeoff weight of the vehicle (including the wing and landing gear for horizontal takeoff and/or landing), as well as the vehicle's size and the engine and structural margins needed for safe takeoff or launch abort. Much of this structure is deadweight long before the vehicle leaves the atmosphere (hence, staged designs). To date, two design approaches have attempted to eliminate this problem for SSTOs: NASP, which is an air breather for much of its flight, and the carrier vehicle/space plane two-stage concept. Both approaches have numerous drawbacks.²² However, if the TAV can be launched with minimum propellants and then rendezvous with an aerial refueler to load the remainder of the propellants, a different, more flexible design is possible. The choice of noncryogenic propellants is essential here, and the properties of a JP5 hydrogen peroxide engine (H₂O₂ is almost twice as dense as jet fuel, and the engine operates at a

1:7 fuel-to-oxidizer mix by weight) make it attractive for transferring the bulk of the oxidizer after takeoff.

At least initially, designers have conceived the Black Horse TAV as a manned system. Without addressing whether or not a crew is or always will be necessary, designers have planned for a crew for these reasons: A crew is essential for the initial X-vehicle development program, although that same program could test technologies that would enable later unmanned versions (unmanned aerial refueling, for example); a crew is desirable for several of the suborbital missions described below; and a crew may be desirable for some operations in space. If the vehicle has an austere (U2-like) cockpit and is not designed for long duration orbital missions (as will almost certainly be true for the X vehicles), the effects of loss of payload weight will be minimized. The issue of whether manning the system causes unacceptable costs is not a valid concern since this system is not a piece of long-range artillery (e.g., an ICBM) converted for transport use. It is, essentially, a fast, high-flying aircraft with no greater risks to crewmembers than any other developmental system.[23](#)

In summary, the Black Horse TAV is a new concept of aerospace vehicle. It is not a new version of the space shuttle or NASP and explicitly contains design choices in terms of size, performance, and mission profile to ensure that experiences with those vehicles will not be repeated. Specifically, Black Horse is a small vehicle with low weight when empty and low weight on orbit, factors that historically correspond to cost. Black Horse - at least the initial X-vehicle concept as described below - is designed around existing technologies for full reusability (unlike the space shuttle) and ruggedness at the expense of the highest possible performance. Any comparison to NASP is particularly inappropriate: aside from horizontal takeoff and landing, no similarity exists. Because of the airbreathing engine, the low-density fuel, and the requirement to fly hypersonically in relatively dense air, NASP required multiple technological breakthroughs in propulsion and materials. By comparison, the thermal and structural requirements of Black Horse are much less stringent.

The structure of the Black Horse was designed according to standard aircraft practice. That is, given the factors of maximum propellant offload from a KC135 tanker; estimated structural weight (from the volume required to enclose fuel, crew, payload, etc.); and assumed weights for payload, crew, thermal protection, and other subsystems, engineers designed a wing to provide sufficient lift throughout the flight envelope. This design was then iterated to ensure internal consistency. The resulting design has a relatively low structural mass fraction when compared to that of other orbital vehicles. This is true for two reasons. First, the propellants are substantially denser than "traditional" rocket fuels; thus, the enclosed volume of the vehicle (hence, the structural weight) is low. Second, by transferring the bulk of the propellant, the designers avoid the penalty of sizing the wing, landing gear, and supporting structure for a fully loaded takeoff. This technique results in a savings of 4,200 pounds for the landing gear alone,[24](#) and essentially makes the concept possible. Critics of the concept have expressed doubts about the numbers, but others - including Burt Rutan of Scaled Composites - have no doubts about the technical

feasibility of the structure. Indeed, Rutan believes that the structure could be made even lighter using composites instead of aluminum, as the designers assumed.[25](#)

Other structural issues include the design of the payload bay and the thermal protection system. Although the payload bay was not designed in detail, additional structure was assumed, based on aircraft requirements for internal cargo or weapons carriage. A thermal protection system of blanket-insulating material and carbon-silica carbide (for the nose and leading edges) with a weight of 1.1 pounds per square foot was included in the design.

The baseline design is for a vehicle weighing 48,450 pounds at takeoff (and 187,000 pounds after aerial refueling), powered by seven rocket engines. Two engines suffice for takeoff and the full refueling profile and are optimized for performance in lower altitudes; the remaining five provide the additional thrust necessary for global reach or orbital insertion.[26](#)

The performance of the engines and fuel (JP5 and hydrogen peroxide) was estimated using NASA standard codes and incorporating losses from geometry, finite-rate chemistry, viscous drag, and energy-release efficiency. This results in a specific impulse of 323 seconds for the low-altitude engines and 335 for the orbital-insertion engines.[27](#) In terms of thrust-to-weight ratio for the engine itself, the performance is no higher than what the British obtained from the Gamma engines (using kerosene and hydrogen peroxide) designed and built in the 1960s. The designers believe that this is a conservative estimate of potential performance.

The final element of the design is the payload deliverable on orbit. This depends on several factors, but - as a figure of merit - the designers chose a 1,000 pound payload in a 35 degree inclined, 100 nautical mile circular orbit (due-east launch from Edwards AFB, California, from a refueling track at 40,000 feet and .85 Mach). This assumes, of course, that the TAV also goes to orbit; flying a suborbital trajectory allows a significantly greater payload (6,600 pounds) to be placed in orbit, even after the weight of an upper stage (a 4,765 pound STAR 48V) is subtracted. If weapons or cargo delivery is the goal, 5,000 to 10,000 pounds could be delivered on a suborbital trajectory to almost any point on the globe, using the baseline design.[28](#) The designers believe that all these numbers can be improved through better engines, lighter dry weight, potential fuel additives, and a bigger vehicle (if so desired for an eventual operational system).

Design Requirements for Weapons Delivery

There are several alternatives for delivering weapons, including the TAV described previously, ICBMs, satellite basing, and intercontinental cannons. The SPACECAST lift team believes that operational flexibility greatly favors the TAV approach.

An appropriately configured version of the TAV can perform both ground and spaceforce application missions with near-term technologies. Some key characteristics of the air-refuelable, rocket-powered TAV that are particularly relevant are the ability to operate as

flexibly and responsively as an aircraft (with similar operations, maintenance, and logistics infrastructures), an inherently low-observable nature from most aspects (no inlets, blended surfaces), and the ability to conduct manned missions. The vehicle can also exploit the advantages of space basing (low reaction times and high energy states) with far greater operational flexibility and additional defensive capabilities to survive future threats. Although the ideas presented here were conceived independently, this concept is not new. Several other studies recommend similar vehicles.[29](#)

The system must have specific characteristics to accomplish the force-application mission. First, it must be able to launch from a quick-reaction alert status. This ability enables the short response times critical to the success of any future weapon system. The Black Horse TAV is capable of fulfilling this requirement in large part because of its use of noncryogenic fuels.

Second, the vehicle must be designed to incorporate modular weapon systems sized to fit the payload bay of the TAV. This concept allows use of the vehicle for a variety of military missions, from force enhancement through force application, thereby increasing cost-effectiveness. The TAV should be hard-wired to provide necessary infrastructure requirements (for example, basic power and communication links) to the module while the module reports fault/degradation information to the operator or controlling computer on the TAV. Note that these interfaces would not be significantly different from those required to launch a satellite. The largest part of the necessary weapons delivery infrastructure should be designed, as much as possible, into the clip-in module rather than the carrier vehicle.

The idea of weapon modules serves several purposes. With this approach, the vehicle is able to accomplish force enhancement missions until it is needed for weapons delivery; in other words, it is rapidly reconfigurable for different missions. In addition, the weapons modules can be preloaded with "wooden rounds," stored until needed, and then quickly loaded on the vehicle. Maintenance or upgrades can be performed on the ground-based weapons, ensuring maximum reliability and capability. Finally, the module concept offers quick reloads, which facilitate rapid turntimes and sustainability. By analogy with current dispensing systems, the deliverable payload should be approximately 75 percent of the vehicle's total payload capacity.[30](#)

Third, for survivability and maximum offensive potential, the vehicle must have global reach from a suborbital flight path. Global reach provides operational flexibility while allowing the vehicle to launch and recover from secure areas. The suborbital requirement contributes to self-protection tactics. Additionally, since the suborbital flight path requires less propellant than does orbital insertion, greater weapon loads than those for orbital payloads should be possible. Since weapons will generally be denser than spacecraft, this should mean that an efficient, multipurpose, payload-bay design is possible. Again, the Black Horse TAV satisfies this requirement.

Fourth, the TAV must allow rapid turnaround to follow-on missions. This maintains the initiative and offensive advantage for the CINC and allows rapid followon targeting. It is

unrealistic to assume that the military will have enough vehicles to engage all possible target sets with a single mass launch. Actual requirements for turnaround times will depend on the number of vehicles, the payload capacity for each, the number of aiming points, and the threat. Any attempt to fix a hard number in relation to these requirements requires some detailed operations analysis, but a 12 hour cycle rate seems a reasonable minimum. The TAV and associated aircrew to airframe ratios should meet this requirement.

Fifth, the system should maximize the use of existing military infrastructure. This requirement is levied to allow launch and recovery from the widest possible number of bases, which - in turn - provides some measure of survivability through dispersion and mobility. The TAV provides a limited solution to this requirement and is restricted only by airfield length/capacity and refueling support.

Sixth, the issue of designing this vehicle for humans is important only in the near term. Technology has not progressed to the state whereby a computer can replace humans in all operations - specifically, those in unpredictable environments or in degraded equipment modes. The SPACECAST lift team recommends designing early vehicles for human operators. Although such a design will result in higher weight and lower G capability (the latter is probably not an issue for typical mission profiles), a human operator allows for rapid, autonomous (in accordance with the commander's intent) decision making when confronting the technologically advanced threat of the twenty-first century. When the database is developed and hardware and software technologies are sufficiently proven, human operators theoretically could be removed from the vehicle. Virtual reality is not a solution in the interim. Communications links are vulnerable to an advanced enemy, who could jam or exploit them. Taken together, all these reasons argue that human pilots and human systems operators will continue to provide significant advantages - at least in the near term.

Finally, payload size may be a limiting factor in some specific employment scenarios. SPACECAST believes that the Black Horse TAV concept offers sufficient payload potential to perform a number of militarily useful missions. As mentioned earlier, a TAV capable of putting itself and 1,000 pounds of payload on orbit can deliver significantly more payload on a suborbital trajectory; further, the significant growth potential in the basic design (sizing the vehicle around the fuel offload from a tanker larger than the KC135, for example) could lead to larger deliverable payloads.

Weapons Options

Three classes of weapons are appropriate for this vehicle: kinetic-energy, high-explosive, and directed-energy. In general, all weapons should be palletized or containerized to ensure maximum flexibility in switching missions and to allow incremental upgrades and maintenance while the weapons are in storage.

In summary, a TAV capable of employing modular military payloads would provide the United States a sustained counterforce capability for use against a wide variety of targets defended by increasingly capable threats.

On-Orbit Operations Vehicles

As mentioned earlier, the ability to maneuver payloads on orbit provides enhancements to any lift system. This section addresses some general issues but does not assume the use of any specific vehicle design (for example, the STV of NASA's Marshall Space Flight Center) or associated operations concepts. In other words, SPACECAST is not advocating that on-orbit operations vehicles be tied to any specific satellite architecture. However, the lift team does recognize that tradeoffs will be an integral part of any decision to pursue on-orbit operations vehicles (i.e., Is it better to repair/service/upgrade a particular satellite or replace it?).

Two key issues are important to this concept: the utility of reusable on-orbit transportation systems and the utility of on-orbit satellite servicing and repair. With regard to transportation systems, a study by the Directorate of Aerospace Studies (DAS) of Air Force Systems Command (now Air Force Materiel Command) in 1989 identified two basic vehicle configurations or capabilities: an orbit transfer vehicle (OTV) for moving things from LEO to higher orbits and an orbital maneuvering vehicle (OMV) for moving things around within a designated orbit and docking with and servicing satellites. This architecture is superior to the current approach (expendable upper stages and/or propulsion systems integral to the spacecraft bus) for several reasons. Expendable upper stages are, by definition and design, thrown away after use and become "space junk." More importantly, however, although unit costs of expendable systems are less than those of reusable vehicles, reusable systems are "generally less expensive on a per mission basis" over their lifetime.³¹

The DAS study also addressed the issue of whether or not it is more advantageous to use an on-orbit transportation capability to service and/or repair satellites or to continue fielding expendable satellites. As expected, there is no clear answer. On the one hand, the authors of the study conclude that "it is reasonable to believe that there will be future circumstances which offer cost advantages to repairable satellites."³² On the other hand, the analysis was sensitive enough to the estimated characteristics of future satellites (e.g., mission duration, mass, cost, subsystem reliability, and launch costs) that the results were not conclusive for all satellites in all orbits. In general, satellite repair becomes more attractive as constellation size and satellite mass, cost, and mission duration increase and as launch costs and satellite reliability decrease. It is much more attractive from a cost standpoint if satellites use modular, standardized/common subsystems.

The utility of reusable on-orbit transportation systems for satellite servicing and repair in 2020 depends heavily on the types and quantities of satellites in orbit at that time, as well as on the capabilities and costs of US launch systems. Given our assumptions of increasingly capable small packages and the ability to put them responsively on orbit, it is not at all clear that either repair or resupply of existing satellites is an attractive mission.

On the other hand, if smaller but more cost-effective launch vehicles make on-orbit assembly and fueling of larger satellites desirable, many of the technologies discussed below will be needed. Ironically, the present large-satellite paradigm and its associated high cost-per-pound to orbit prevent testing the on-orbit repair concept.

Operations Concept

THE TAV WOULD BE readied for flight at an aerospace base differing from an air base only by the H₂O₂ storage and first-level maintenance equipment, all of which could be deployed. It would be fueled with 100 percent of its JP5 and approximately 7 percent of its H₂O₂ capacity. It would then be loaded with its payload, taxi and take off, rendezvous with a tanker and load the entire tanker's capacity of H₂O₂, turn to the correct heading, and depart for orbit. The time from push-back to orbit would be less than an hour.

After completing its orbital mission, the TAV would deorbit and return to its own or any other suitable base - again, a very short process. A suborbital mission would be similar, and there would probably be no need to refuel before returning to base. Turn-around time is somewhat speculative at this point (the X-vehicle program would provide an answer), but a preliminary look at the technologies (rocket engine, thermal protection, etc.) suggests it will be a matter of hours or - at worst - no more than days. Unlike the space shuttle, the TAV would be designed so as not to require extensive refurbishment between flights.

Two technical areas are key to the ability to "turn" the TAV quickly: thermal protection and engines. For the former, the combination of the aerothermal environment (less stressful than that for the space shuttle, due to Black Horse's low wing loading and deceleration high in the atmosphere) and advances in materials since the space shuttle was designed should make a fully reusable system possible. For the engines, the AR2 used on the NF104D provides a baseline: it routinely operated with two hours of firing time (and numerous restarts) between overhauls³³; the Black Horse designers believe that an improved design could do better. Although one of the purposes of an X program would be to test the limits of reusability of a TAV, the SPACECAST team does not believe there are any showstoppers here.

This concept will provide vastly increased flexibility and responsiveness in launching spacecraft and performing suborbital missions, tremendously reduced operations and logistics infrastructure compared to other lift concepts, increased reliability, suitability for manned flight, and significantly reduced cost of space launch. It also builds on aerial refueling - currently an operational strength of military aviation, performed hundreds of times a day - versus airborne separation of large manned vehicles, performed only a few hundred times in history in the development of new spacelaunch capability. A squadron of eight Black Horse vehicles, each flying only once per week, would provide access to space *hundreds* of times per year, making space operations truly routine.

A Threat-based System

Future threats to the United States would have a far greater effect on offensive operations than would current threats. Several types of threats are possible: hostile satellites, ground and space-based directed-energy weapons, ICBMs, third world nuclear weapons, and other weapons of mass destruction. An armed TAV could negate future threats through a combination of countermeasures, tactics, and survivable basing.

First, the construction of the vehicle should include as many low-observable techniques as possible. Although today's low-observable technologies will gradually lose their utility, they will force adversaries to confine defensive systems to particular (and therefore predictable) techniques. They have the further benefit of reducing the detection envelope of enemy acquisition systems and therefore making the adversary's targeting problem more difficult.

Second, this system permits the use of onboard, active defensive systems. By using a suborbital trajectory during the attack profile, a TAV may use such disposables as chaff, flares, towed decoys, and active defensive munitions to defeat weapon systems without creating hazardous space junk. The design of the operational TAV could also accommodate modular electronic countermeasures (ECM) systems - weight and power budgets permitting.

Third, the TAV concept permits surprise. Even if an adversary has spies operating in the vicinity of airfields or if commercial media satellites detect operations in progress or if the enemy detects unusual launch activity, the specific aiming points, axes of attack, and timing of attack are less easily predictable. Launch to a single, suborbital weapons-delivery pass followed by reentry and landing compresses the time the adversary has to respond - especially an adversary with neither space-surveillance capability nor intercontinental-launch detection. The enemy has minutes to observe the mission, assess intentions, make the appropriate decision, get the defensive capabilities in place, and complete the intercept. Multiple, simultaneous, inbound trajectories compound surprise.

Fourth, the inherent flexibility of a TAV enhances unpredictability. Again, the single suborbital pass serves as an example. Since the vehicle starts from ground alert, the enemy cannot predict the mission's time over target. The vehicle's ability to establish a variety of suborbital trajectories, as well as approach the target from differing orbital planes, also confounds the adversary's predictive ability and may negate many of his defensive systems.

Fifth, a squadron of TAVs translates into mass. The United States will more than likely have a small fleet of these reusable vehicles. The ability to mass several vehicles from single suborbital passes at the time and place chosen by the CINC allows the commander to overwhelm the enemy's defensive systems as well as concentrate the appropriate amount of firepower to achieve required effects. In the absence of great numbers of vehicles, the same mass effect is maintained through the ability of each vehicle to deliver a large number of weapons.

Sixth, assuming the existence of an appropriate family of weapons with sufficient crosstrack (to the sides of the delivery vehicle's trajectory), the TAV will have standoff capability. Thus, the vehicle can release its payload outside the range of many possible threat systems.

Seventh, several vehicles working in concert can use advanced countermeasures as well as suppress threats for each other. The clip-in module for one vehicle, for example, might be a countermeasures suite, while the clip-in modules for other vehicles in the flight would be weapons.

Finally, TAV bases can easily be dispersed. Although threat systems surely will have the ability to find and target aiming points in the United States by the year 2020, their capabilities can be reduced through dispersion of the TAVs to a wide number of bases, through mobile operations, and through good deception plans. (An enemy's problem would be compounded if a large number of commercial TAVs also exists.) Any attempt to force this system to consolidate operations at a single, fixed location would be unnecessary and should be resisted because it obviously provides the adversary a fixed, high-value target. Logistics concerns can be adequately addressed by designing a vehicle that shares existing aircraft infrastructure to the maximum extent possible.

In summary, the ability of the TAV to accomplish its weapons-delivery mission from a single suborbital pass, while using both passive and active countermeasures, compresses the adversary's decision loop and results in increased survivability. The addition of low-profile basing complicates the threat's targeting problem and ensures that fewer assets are placed at risk during enemy attack. This combination results in a survivable system able to fight in the highthreat environment of the twentyfirst century.

On-Orbit Operations

To a large extent, the types of operations performed on orbit will be determined by the capabilities that new vehicles provide, whether OTV, OMV, or TAV. Orbit-transfer vehicles could reduce the need for upper stages on launch systems and increase the amount of payload delivered to orbit. Maneuvering vehicles could provide some repositioning or on-orbit shuttle capabilities, a function that would help make orbital operating bases (space stations) functional. Both of these vehicles will facilitate on-orbit maintenance and upgrades to extend satellite lifetimes and combat technological obsolescence.

Even the TAV has implications for orbital operations. Besides capturing satellites and returning them to earth, the TAV may be the best means of changing a satellite's inclination. Assuming it is not easier to launch a new satellite to the relevant orbit, the TAV could go to orbit without cargo (to conserve fuel), capture a satellite, reenter, perform an aerodynamic maneuver to align itself with the new orbit (perhaps in extreme cases, even refueling again), and then return the satellite to space. Although the Black Horse studies to date have not included calculations of the fuel required for on-orbit rendezvous, this is a potential mission if the vehicle does not go to orbit fully loaded;

unlike shuttle operations, launching an empty vehicle would not be a cost-prohibitive operation.

Links to Other SPACECAST Areas

THE CONCEPT OF THE TAV connects many SPACECAST proposals. The logistics of space lift with a militarily capable TAV are now linked to the proposal on global view. This combination uses the proposed architecture to identify and pass coordinates of critical targets to the TAV prior to its weapons-release point, cutting to an absolute minimum the time from initial target detection to destruction. This ensures that the TAV uses the most effective targeting intelligence to gain the greatest possible strategic effects.

SPACECAST's proposals for force application address various weapons and their suitability. The TAV offers a platform for their use with significant military advantages over other techniques, such as satellite basing. System architectures are compatible with the weapons-delivery vehicle. Finally, proposals for offensive counterspace benefit from a TAV-based weapon system that could use directed-energy weapons without our building, deploying, operating, and defending an orbiting "battlestar."

Other linkages include the ability of the vehicles described here to support the "motherboard" satellite concept described in SPACECAST's space modular systems proposal, as well as the utility of a space traffic control system in accommodating both the TAVs and increased on-orbit activity. Finally, many of the concepts in SPACECAST depend heavily on improving and reducing the cost of access to space—the heart of the concept of the Black Horse TAV.

Potential Technologies

ALTHOUGH A WORKING TAV in the form of an X vehicle can be built with existing technologies, improved technologies and/or supporting capabilities will enhance performance in several areas.

Structures

The initial study on the feasibility of an aerial-refueled space plane³⁴ concluded that an F16 sized X vehicle TAV built according to standard fighter-aircraft design criteria and incorporating aluminum structures could place itself, a crew, and 1,000 pounds of payload into orbit. However, further analysis of structural requirements and application of modern design techniques and materials could significantly reduce structural weight. As mentioned earlier, Burt Rutan of Scaled Composites believes that this possibility is within current design and fabrication capabilities. Since Black Horse is a single-stage-to-orbit vehicle, every pound of dry weight saved is an extra pound of payload.

Engines

The same study baselined an engine no more sophisticated or efficient than the one used by the Black Arrow/Black Knight program (1950s technology).³⁵ A modest development program could certainly improve this level of performance (efficiency and thrust-to-weight ratio) while improving reliability and maintainability. Further, a hybrid engine such as a ducted rocket³⁶ (admittedly a separate development program) could offer both increased performance and reduced noise - both potentially critical factors for widespread commercial use of TAVs.

Propellants

Although the intent of the program is to stay away from exotic or hazardous materials, certain options increase specific impulse without sacrificing operability. Some possibilities are fuel additives such as quadricyclene, denser hydrocarbons (JP8 or 10 instead of JP5), or - in the far term - high-energy-density substances such as metastable fuels. As long as the fuel continues to meet operability and logistics concerns, this area has tremendous potential payoff. An increase of one second in specific impulse would increase payload on orbit by 128 pounds for the initial Black Horse design.³⁷

Thermal Protection System

The feasibility study mentioned above baselined durable tailored advanced blanket insulation (DuraTABI) material, which weighs 1.1 pounds per square foot, for area ("acreage") coverage and carbon-silica carbide (C/SiC) for the nose, wing, strake, and rudder leading edges. Detailed aerothermodynamic reentry calculations may indicate a less stringent requirement for thermal protection than was assumed in the initial design, possibly even allowing an all-metal skin (Rene 41 or Iconel 617). On the other hand, retaining excess thermal protection - perhaps by applying more advanced thermal protection systems - could give the vehicle a larger reentry envelope and even more operational flexibility.

Refueling Vehicle

Designers sized the TAV around the maximum amount of propellant that a single KC135Q could transfer. These aircraft are in the inventory and already have separate aircraft fuel tanks and offloadable propellant tanks. Thus, they would require minimum modification. The availability of a modified KC10 or large commercial aircraft derivative to offload H₂O₂ would greatly increase the potential size and payload of the TAV without significantly changing (except perhaps to reduce) the costperpound to orbit. Although this is more a programmatic than a technical issue, there are potential areas for investment in higher capacity pumps and perhaps a dual-tube boom refueling system to transfer both fuel and oxidizer at once.

On-Orbit Operations Vehicles

As mentioned earlier, on-orbit operations vehicles complement most lift concepts. These vehicles have distinct technology development, demonstration, and validation needs.

Technologies required to implement on-orbit operations architecture include high-efficiency, reusable, space-propulsion systems. Cost, performance, and operational-utility analyses are needed to select from among the various potential technologies. Candidates include conventional chemical, electric, nuclear, and solar-thermal propulsion systems. Issues to be addressed would include power sources for electric propulsion concepts; radiation shielding, high temperature materials, launch safety, and waste disposal for nuclear propulsion concepts; solar concentrator fabrication and high temperature materials for solar thermal propulsion concepts; and longlife performance/reliability demonstrations for all concepts.

The on-orbit operations vehicles will require robotics for docking, grasping, repair, and resupply operations and/or telepresence/virtual reality/artificial intelligence technologies in some combination for on-orbit operations. Planners need analyses to determine the extent to which humans must participate in repair/servicing operations. Considering the technologies expected to be available in 2020, planners need to know what tasks can be done only by human beings, what tasks can be done remotely with humans in the loop, and what tasks can be done autonomously. Artificial intelligence technologies could reduce the requirement for human-in-the-loop operations in circumstances in which this would be difficult or present technical challenges. Again, this requires further analysis.

Spacecraft design would have to change significantly to obtain maximum utility from the TAV concept. Docking operations would require some degree of spacecraft bus standardization. Refueling operations would require standardization of the propellant feed system. Such design approaches as standard spacecraft buses and standard, modular, miniaturized subsystems and interfaces would facilitate repair/upgrade operation. External structures such as solar arrays and antennae might have to fold to withstand the accelerations associated with high-impulse spacecraft maneuvers or to stow the spacecraft in the bay of a TAV for redeployment. It is important to note that many of these changes will happen with or without the development of on-orbit servicing. They are driven by the need to reduce the costs and timelines associated with the earth-to-orbit segment of the transportation system.

OTVs may need supporting "bases" in certain critical locations. For transportation to high altitude, low inclination orbits, unmanned co-inclination platforms in LEO would serve as cargo-transfer and jumping-off points for OTVs. Orbits containing large numbers of higher-cost satellites or fewer extremely expensive satellites would require co-orbital, unmanned platforms where OTVs could transfer payloads to OMVs for final orbit insertion or docking/repair.[38](#)

NearTerm Technologies and Operational Exploitation Opportunities

DESIGNERS CAN USE EXISTING and proven technologies - aluminum structure and Dura-TABI thermal protection - to develop and fly an X vehicle to demonstrate the feasibility and operational utility of the Black Horse. As an interim step, existing AR2 engines could be used to fly the vehicle through all of its atmospheric flight profile, testing handling, formation flying, refueling, and suborbital trajectories, while a concurrent engine development program produces the higher performance engines needed to reach orbit. The basic concept is for a crewed vehicle approximately the size of an F16 (but with only 70 percent of its dry weight) that could take off from and land on virtually any runway, load the bulk of its propellant (all oxidizer) from a KC135Q (or T) tanker at approximately 40,000 feet and Mach 0.85,³⁹ and then carry out an orbital or suborbital flight. An experimental program could allow testing of the TAV as the US has tested aircraft for decades, with a gradual expansion of the performance envelope to meet the necessary objectives.⁴⁰

The primary areas for design and development are the vehicle aerodynamic configuration, higherperformance rocket engines, and the vehicle structure. A study by W. J. Schafer and Associates and Conceptual Research Corporation⁴¹ indicates that there are no technological roadblocks in this area and that a vehicle could be designed and tested with existing technologies, although there is room for improvement using advanced materials.

Areas that require some careful design work but no technological breakthroughs are the need for thermal protection, the need to cycle landing gear through the thermal protective surface, and the use of structural composites. It therefore appears that an X-vehicle program could proceed *with existing technologies*.

Although cost is not the single driving issue in this study, several comparative estimates of a two TAV, 100flight (including orbital) X-vehicle program suggest that the military could conduct such a program for a reasonable amount of money. Using actual X29 and X31 cost data, the Question Mark 2 TAV X-program would cost about \$78 million (M). A cost model for the Lockheed Skunkworks program yielded \$96M. The Rand Corporation Development and Procurement Costs of Aircraft (DAPCA) IV model gave a total program cost of \$118M. Finally, a cost estimate by an Aerospace Corporation analyst came up with \$120M.⁴² Although these are rough estimates and although a vehicle of this type has never been built before, the fact that differing methodologies independently came up with similar numbers is somewhat encouraging.

Initial estimates, using a cost model based on actual expense data for the SR71, suggest that a Black Horse vehicle could place payloads into LEO at a cost of less than \$1,000 per pound (the model yields costs between \$50 and \$500 per pound, depending on assumptions), with a per-sortie cost of around \$260,000 and an annual operating budget

for an eight-TAV unit (with support) of approximately \$100M. This model may be particularly appropriate because the operations of an air-refuelable TAV and the SR71 would be similar in several ways, not the least of which is use of the same tanker. The model includes - and is sensitive to - overhead costs (assumed to be the same as for the SR71), number of vehicles and sorties, payload (assumed to be 1,000 pounds), and fuel costs. A key point is that this system is not "cheap" to operate relative to most aircraft; in fact, the numbers are comparable to SR71 operating costs. The cost-per-pound to orbit, however - even under fairly pessimistic assumptions (smallest payload, relatively few flights, and high non-flying operations cost) - is still quite low, compared to that of other launch systems. Perhaps this shows just how expensive our current space operations really are (at \$10,000 per pound to orbit and up) and how large the potential for improving that figure is with reusable launch vehicles. Cost-sensitive basing schemes and logistics concepts - such as the USAF's "Rivet Workforce," which consolidates maintenance skills - could further reduce recurring operations and maintenance costs.

On-Orbit Operations

There are several near-term programs that would expand our ability to provide on-orbit services. These include the space surveillance tracking and repositioning (SSTAR) experiment (formerly called the electric insertion transfer experiment [ELITE]), an Air Force-TRW cooperative research and development agreement, a potential flight test of the ex-Soviet TOPAZ nuclear reactor, and the space nuclear thermal propulsion program. These deal primarily with propulsion systems but - particularly in the case of SSTAR - also with supporting technologies such as navigation, autonomous operation, and potential mission-oriented payloads. Unfortunately, all of these programs have suffered funding setbacks and are on hold or in danger of cancellation.

Commercial Opportunities

Cheap, reliable transport to, from, and through space offers innumerable possibilities.⁴³ It is the enabler for everything anyone does in the future in space. All of the technologies and techniques described above have potential commercial application, but a prescription for their use is beyond the scope of this study. Instead, this article highlights some of the opportunities they may create and reasons why a robust commercial space market is ultimately essential for government use of space.

Cheap space lift is a market enabler that will open up the use of space for things not currently practical or even anticipated. Some obvious possibilities include the extremely rapid delivery of people and cargo from one point on the earth to another, while the ability to carry passengers safely and at a reasonable cost could open a new market for space tourism. Availability of technology that enables the economical use of space will, in turn, spur development of a true commercial market for all things related to spaceflight and operations. This will eventually drive the real cost of access to and operations in space down even further, as jet transport has done in the commercial aviation market.

If US manufacturers of launch vehicles pursue innovative technologies with true marketcreating potential, they could find themselves in a globally dominant position, just as the US aircraft industry did following the introduction of the Boeing 707 and the DC8. Dramatic expansion of the market for space transport, which will not happen without dramatic reductions in the cost of space access, is also absolutely necessary if the US launch industry is to remain commercially viable. The alternative is to risk becoming like the current US shipbuilding industry. Increasingly inefficient and shrinking, this industry is unable to compete with low-cost and/or subsidized foreign producers and stays alive only because of government subsidies.

Government support in the initial stage of development is vital. The market for space is not large enough to drive the kind of productive and creative explosion in space-related hardware that has occurred in electronics, for example. The main prerequisite for this market-rapid, reliable, affordable space lift-is missing. Government and the military, whose performance requirements for launch on demand are the most stressing now, must take the lead in this area and produce the technological/operational breakthrough that will enable expanded future exploitation of space and the development of a large market to unleash the powers of commercial development. Industry cannot and will not make the investments needed for such breakthroughs on its own. It faces a market similar to that for air transport prior to the introduction of the DC3, while development of a TAV will require an effort much like the one that produced the first jet transports. Development of jet transports would not have been possible without government investment in jet engine technology and large aircraft (e.g., the B47 and B52), despite an airtransport market that was already fairly large.

Summary

THE CORE CONCEPT OF this article is the Black Horse TAV. The initial reaction of most people to the concept is, It sounds great, but if it would really work, why hasn't anyone thought of it before? There is no simple answer to this question. The United States did flirt with transatmospheric vehicles in research and X-vehicle programs but decided in favor of expendable boosters because of a combination of materials limitations, engine-performance requirements, and other technical factors, coinciding with rapidly increasing satellite weights. It seemed that only large boosters could put the required payloads in orbit. The rocket community discarded noncryogenic propellants for similar reasons. The rocket equation dictates that noncryogen-fueled vehicles have a propellant mass fraction of about 95 percent; cryogenics reduce this to about 90 percent. Since all the structure, as well as the payload, must fit in the remainder, vehicles fueled with noncryogenics did not seem able to orbit useful payloads.

Since then, however, much has changed. Miniaturization and other technologies now allow smaller satellites to do more than they once could, while large, complex systems have become increasingly unaffordable. In other words, it is now possible to get away from the tyranny of the payload and think first about designing a launch vehicle for operability and even cost, and then building satellites to fit it. In turn, by assuming a

reduced payload requirement; adding 20 years of additional knowledge in materials science, structural design of aerospace vehicles, and liftingbody research; and recognizing that the greater density of noncryogenic fuels compensates somewhat for their reduced performance, the outline of a TAV concept begins to emerge. The final key element is the transfer of aerial propellant.⁴⁴ Putting air refueling together with the other elements - in many ways a classic example of what John Boyd calls "destructive-creative" thinking⁴⁵ - led to the Black Horse concept.

Black Horse vehicles have the potential to revolutionize the way the military (and perhaps eventually the commercial world) uses and even thinks of space. They are true aerospace vehicles, with tremendous operational implications. A first-cut analysis indicates not only that the concept is feasible, but also that it can be done with no new technologies. We must now perform a more rigorous and detailed design and then press ahead with a Question Mark 2 X-vehicle program to validate the system. □

Notes

1. The name *Black Horse* has multiple origins. It is first a tribute to the British Black Arrow and Black Knight programs, which demonstrated the basic propellant concept many years ago. The name also is a link to the SR71 Blackbird, which provides the tanker aircraft and the basis for the operations-cost model. These connections are explained in more detail later in the article. The *Horse* part of the name honors an animal that has carried cargo and people in peace and in war. Finally, *Black Horse* sounds a lot like *dark horse*, which is certainly true of this system in the launch-systems race.

2. In honor of the first aircraft to demonstrate aerial refueling. Thanks to Dr F. X. Kane for reminding us of the lineage of experimental programs and for suggesting this name.

3. For example, much monolithic satellite design (sizing, folding/deployable elements, and so forth) is based on making maximum use of a single launch-vehicle envelope. In contrast, under this approach, a prewired structure, solar panels, subsystem modules, and payload modules could be designed with relatively simple, quick-connect interfaces (work on the spacestation assembly process would probably be used here) for manual or automated assembly. Active structural control would ensure that necessary alignment tolerances were met after assembly.

4. See, for example, Air Force Mission Need Statement 20292, *Military Aerospace Vehicles*.

5. The "Visions" study of the US Air Force Space and Missile Systems Center (SMC/XR), for example. Almost all space panels conclude that space lift is the critical element in developing space applications.

6. Hon Sheila E. Widnall, secretary of the Air Force, speech to the National Security Industrial Association, 22 March 1994.

7. Ibid. This situation is often referred to as "the tyranny of the payload."

8. Senate Armed Services Committee, statement of Gen Charles A. Horner, CINC, United States Space Command, 22 April 1993.

9. DOD Space Launch Modernization Plan, April 1994.

10. Ibid. See also "Space Traffic Control: The Culmination of Improved Space Operations," in *Spacecast 2020*, vol. 1 (Maxwell AFB, Ala.: Air University, June 1994), D1.

11. See the Vice President's Space Advisory Board, "The Future of the US Space Launch Capability: A Task Group Report," November 1992 (the Aldridge report) for cost goals for Spacelifter. Other sources (cited in Air Force Institute of Technology alternative lift briefing) generally give higher costs-per-pound to orbit for the small, expendable lift systems than for large expendables.

12. Aldridge report, NASP studies, Delta Clipper studies.

13. Edward C. Aldridge, interview with author during first Advisory Group visit, January 1994.

14. For example, the Defense Advanced Research Projects Agency's (DARPA) Advanced Space Technology Office has produced several articles on the capabilities, operational benefits, and potential cost savings of small, modular satellites.

15. Horner; Widnall.

16. Operations costs for Kennedy Space Center, Florida, and Vandenberg AFB, California, run into billions of dollars per year, and it takes weeks to months to refurbish a launchpad following a launch for the next event.

17. Clapp and Hunter, "A Single Stage to Orbit Rocket with Non-Cryogenic Propellants."

18. Ibid.

19. David Andrews, "Advantages of Hydrogen Peroxide as a Rocket Oxidant," *Journal of the British Interplanetary Society*, July 1990. See also "Propellants for Supersonic Vehicles: Hydrogen Peroxide," Project Rand, RA15046 (Douglas Aircraft Company, 12 August 1947).

20. Capt M. Clapp, DCX crew member, interview with author, January 1994.

21. Of course, this technique is not limited to horizontal takeoff and landing vehicles; it was even considered for the Apollo mission, according to Dr F. X. Kane. However, a winged horizontal takeoff and landing vehicle offers the best performance match (hence, the least expensive option) to existing tanker assets.

22. For NASP, drawbacks include structural design and materials problems due to sustained hypersonic airbreathing flight, fuel tankage, and engines. For carrier/orbiter concepts, they include a large, expensive, unique carrier vehicle with considerable development costs of its own.

23. The environment in which a TAV must operate is no more hostile to human life than the environment in which a U2 or TR1 routinely operates.

24. Conversation with Capt M. Clapp, USAF Phillips Laboratory, May 1994. The number comes from the rule of thumb that landing gear will weigh approximately 3 percent of gross takeoff (or landing, whichever is greater) weight.

25. Ibid.

26. Full details are contained in the paper and briefing from W. J. Schafer and Associates and Conceptual Research Corporation, January 1994.
27. Ibid.
28. Briefing, USAF Phillips Laboratory (Capt M. Clapp) to SPACECAST team, Maxwell AFB, Ala., 29 April 1994. Performance numbers and flight profiles were validated using NASA's Program to Optimize Simulated Trajectories (POST).
29. *Project Forecast II* (U), 6 vols. (Andrews AFB, Md.: Project Forecast II Office, June 1986); Mission Applications Document (22 July 1990); and Force Applications Study (13 June 1991).
30. Technical Order 11M34, SUU64/B, *Tactical Munitions Dispenser*, 31 May 1991, 1-110.
31. DASTR891, *Comprehensive On-Orbit Maintenance Assessment (COMA)* (Kirtland AFB, N.Mex.: Directorate of Aerospace Studies, 31 March 1989), 61.
32. Clapp interview.
33. Briefing, Rocketdyne, subject: NF104D Program, undated (on file at Phillips Laboratory).
34. Paper and briefing from W. J. Schafer and Associates and Conceptual Research Corporation.
35. The design assumes an injector that is 98 percent efficient, for example. Current engine designs (the main engine of the space shuttle, for example) achieve 99.8 percent efficiency.
36. A ducted rocket uses the combustion and exhaust mechanisms of a conventional rocket but gets its oxidizer (atmospheric oxygen) by using air intakes instead of an onboard supply. This has particular advantages at lower altitudes and speeds. Martin Marietta Corporation, among others, has design concepts for this type of system.
37. Based on Phillips Laboratory parametric studies.
38. AFSC/DAS study.
39. According to figures in the KC135Q "Dash1," the tanker will be volume constrained (not by weight or center of gravity) in the amount of hydrogen peroxide it can carry. This restriction results in a maximum load of about 147,000 pounds. The entire amount can be transferred in approximately 11 minutes. The KC135Q offload rate is 1,200 gallons per minute, and since hydrogen peroxide (at 11.92 pounds per gallon) is substantially denser than jet fuel, this results in a propellant weight transfer of about 14,300 pounds per minute.
40. Clapp and Hunter.
41. Paper and briefing from W. J. Schafer and Associates and Conceptual Research Corporation.
42. Phillips Laboratory XPI, memorandum, 20 March 1994.
43. See, for example, briefing, G. Harry Stine and Paul C. Hans, The Enterprise Institute, subject: Economic Considerations of Hypersonic Vehicles and Space Planes, 1990.

44. Aerial refueling is now as common in military air operations as beverage service is on commercial flights, and it is usually (and rightly) thought of as a way to extend the range and endurance of aircraft. What hasn't been fully appreciated is the fact that aerial refueling has also affected the design of aircraft (i.e., a fighter can have global range - if it can refuel often enough - without carrying all that fuel at takeoff). What's new is applying this concept to a spacefaring vehicle. For the concept to become commercially viable, commercial operators will also have to embrace air refueling as a routine operation, though this leap should be no greater than that of the first commercial aircraft or the first commercial jets.

45. John Boyd, "SPACECAST," lecture, Maxwell AFB, Ala., October 1993.

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