Water Horizontal Take-off and Landing (HTHL) Reusable Launch Vehicle (RLV) Concept

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Airplane like operations have always been an attractive goal for the design of Reusable Launch Vehicles (RLV). However, analysis in regards to very large Horizontal Takeoff Horizontal Landing (HTHL) RLVs has shown that systems with Gross Take Off Weights (GTOW) above 1.5 million pounds face significant technological and operational challenges with respect to standard runway operations; not only does the vehicle weight approach the limit of the runway specification, but the vehicle itself is penalized with the need for many landing gears to distribute the load. In addition, the use of rocket propulsion during take-off can cause significant damage to the runway surface, driving the designer to use airbreathing propulsion instead and again adding system complexity and vehicle weight. All of these issues can be addressed if the vehicle is launched from a body of water instead of a land based runway. Additionally, a reusable booster capable of water take-off has unique (very attractive) options for returning the vehicle to the departure site, such as operation as an Ekranoplane, or even surface travel as a jet-boat.

Nomenclature

3STO	=	Three Stage to Orbit
GTOW	=	Gross Take Off Weight
HTHL	=	Horizontal Take-off / Horizontal Landing
L/D	=	Lift to Drag ratio
LEO	=	Low Earth Orbit
TSTO	=	Two Stage To Orbit
T/W	=	Thrust to Weight ration
WIG	=	Wing In Ground-effect

I. Introduction

Presently, the space launch industry is dominated by expendable systems. Reusable systems have long been envisioned to enable significant reductions in per-flight cost, at the trade-off of increased development cost and system complexity. If the premise of a reusable system is accepted, most often the modern aircraft is used as a benchmark in terms of system operability. A modern jetliner can takeoff and land at a large number of locations, and requires significantly less operations infrastructure and personnel in comparison to today's expendable launch vehicles. This operational advantage can be attributed in large part to the ability to process, takeoff, and land the vehicle horizontally (instead of vertically).

When adopting the Horizontal Takeoff Horizontal Landing (HTHL) paradigm to a launch vehicle with significant payload to orbit, the Gross Take Off Weight (GTOW) quickly becomes a driving design issue. Not only are existing runways limited to about 500 tons (1.1 million lb) GTOW, but the vehicle itself is burdened with a significant weight penalty if designed to leverage the infrastructure of existing runways. The complexity, weight, and number of the landing gear needed to distribute the takeoff loads without damaging the runway become major design drivers. To keep runway length requirements within commercial specifications, high thrust is needed, which in turn requires large airbreathing engines (additional complexity & vehicle weight), or the use of rocket propulsion during takeoff, which will damage the runway.

This paper discusses a reusable first stage booster that takes off from a body of water (ocean, lake, river, man-made water runway). A water runway provides ideal load distribution on the vehicle, is self-healing, and thereby provides a workaround to many of the limitations otherwise associated with HTHL RLV design.

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II. Historical Background

There are many examples throughout the history of aircraft development that showcase the concept of a flying machine that takes off and lands from water. In the early days of aviation, the largest aircraft developed were flying boats. This was due to the fact that large cities were located near a body of water and there was a fundamental lack of land based runways. In addition, landing gear technology was too immature to handle large gross weights, and by eliminating the landing gear altogether the aircraft could carry more passengers. The ultimate culmination of the flying boat concept was the Spruce Goose: it was the world's largest aircraft, constructed in 1947 by Howard Hughes. It had eight engines, a gross mass of 400,000 lb and a 11,430 ft^2 wing area (twice the size of a Boeing 747).

Figure 1: The Spruce Goose, a Japanese SAR Seaplane, and a Russian amphibious airliner

Today, flying boats are still used for a range of fire-fighting and search and rescue (SAR) missions. In addition, Russia built a number of amphibious jet powered aircraft that fly in ground effect (Ekranoplanes) to transport people and supplies across the Caspian Sea. The largest of these vehicles was the Caspian Sea Monster, which flew in 1964 and weighed a massive 1.2Mlb.

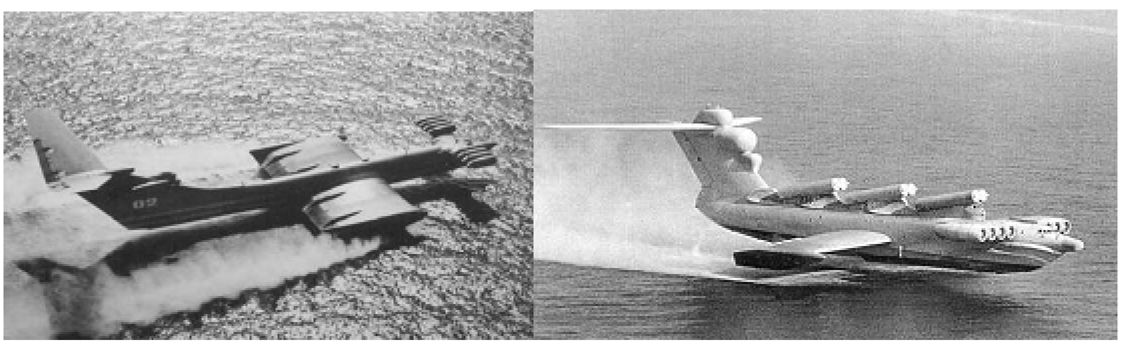

Figure 2:The Caspian Sea Monster Ekranoplan.

In the 1960s, American spy satellites photographed this peculiar object floating about in the Caspian Sea within the borders of the then Soviet Union. It was airplane shaped, and it was gigantic (310 feet in length), but its wings were too small to enable conventional flight. The American intelligence service attached the name of "Caspian Sea Monster" to the vehicle, and it was not until many years later that the true capabilities and nature of the concept were made public.

III. Water HTHL RLV Concept

This paper describes a possible configuration for a water takeoff/landing RLV system. The concept presented is not the result of an exhaustive trade-study of all available options, but was selected to illustrate the potential benefits of the water takeoff / landing approach. Many schools of thought exists regarding the fundamental design decisions required to define an RLV concept; the following work intentionally glosses over some of these issues to instead focus on the attributes most relevant to the water takeoff / landing paradigm.

A. Vehicle Design

There are four key system characteristics to be selected by the designer of a RLV. Each of these has its own trade tree associated with it, and the decision will be driven by the desired application of the resulting system.

1. Mode of takeoff and landing (horizontal vs. vertical)
2. The number of stages
3. If/how each stage is returned to the launch site
4. The type(s) of propulsion system(s) for each stage

When considering the issue of vertical versus horizontal takeoff, aspects of safety (engine out recovery), operability (aircraft like operations), and performance (use of lifting surfaces to assist ascent and recovery) speak in favor of horizontal takeoff concepts. On the other hand, the added vehicle weight of lifting surfaces, landing gear, and airbreathing propulsion are generally cited as favoring vertical takeoff solutions. This paper focuses on addressing the negative issues associated with HTHL concepts through the use of water takeoff and landing.

While there is no theoretical limit on the number of stages for a launch vehicle, the practical range is generally considered to be from 1 to 3 for Low Earth Orbit launch systems. Single Stage To Orbit (SSTO) concepts are exceedingly sensitive to the dry mass of the system, and are thus poor candidates for a design that is additionally burdened by the weight of reusable systems. Three Stage To Orbit (3STO) systems face additional challenges in the recovery of the middle stage, as it is very far downrange, yet has insufficient velocity to circumnavigate the planet. However, 3STO concepts with expendable second stages can be very attractive. This concept baselines, a reusable first stage (booster), with the possible pairing of a reusable second stage, or expendable second and third stage.

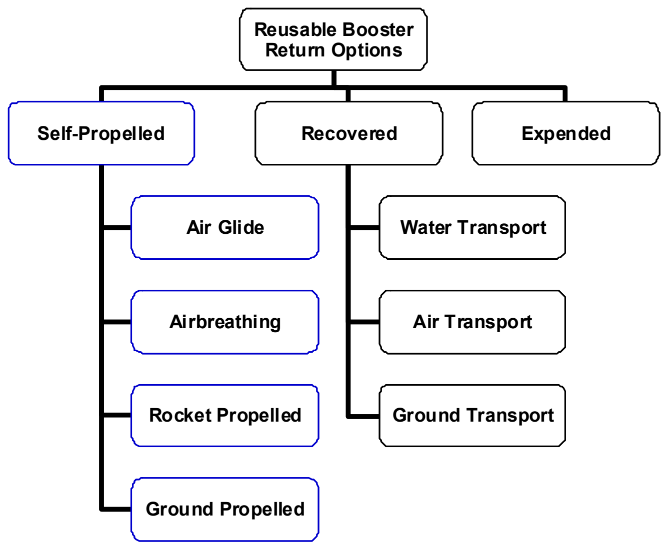

Figure 3: Reusable Booster return options trade tree.

Having decided on a reusable first stage (booster), the method by which the booster returns to the launch site becomes a key design characteristic. Figure 3 shows the trade tree for the various options available to the designer. The RLV concept developed here uses a booster that returns to the launch site under its own power.

The last of the key characteristics discussed here is the selection of the propulsion systems on each stage. The reusable booster concept uses rocket propulsion as its primary method of ascent, and any of the four options (glide, jet, rocket, ground) as its method of return – either individually or in combination.

B. Ascent Configuration

The booster configuration presented here (Figure 4) is a point-of-departure concept to illustrate the potential advantages for a water takeoff/landing system; it is not based on a conclusive trade-study. The vehicle uses two separate propellant tank stacks parallel to each other, and joined by a center wing. Additional lifting surfaces are arranged as a tandem wing to minimize the required rotation – and enable the use of flaps – during takeoff.

The booster is intended for use with either an expendable two-stage upper stage (making it a 3STO system) for cargo delivery, or a reusable orbiter for crew delivery (making it a TSTO system). As a concept sizing mission, the shown configuration is aimed at delivering 100,000 lb of unpressurized cargo to the International Space Station (ISS) orbit; resulting in requirements for staging point conditions of 1,020,000 lb payload (upper stage ignition mass), 6,000 ft/sec staging velocity, 200,000 ft altitude, and a flight path angle of 45 degrees. The upper stage is positioned on top of the center wing to protect it from exposure and for ease of operations. Prior to stage separation, the vehicle performs a roll maneuver to place the upper stage below the booster.

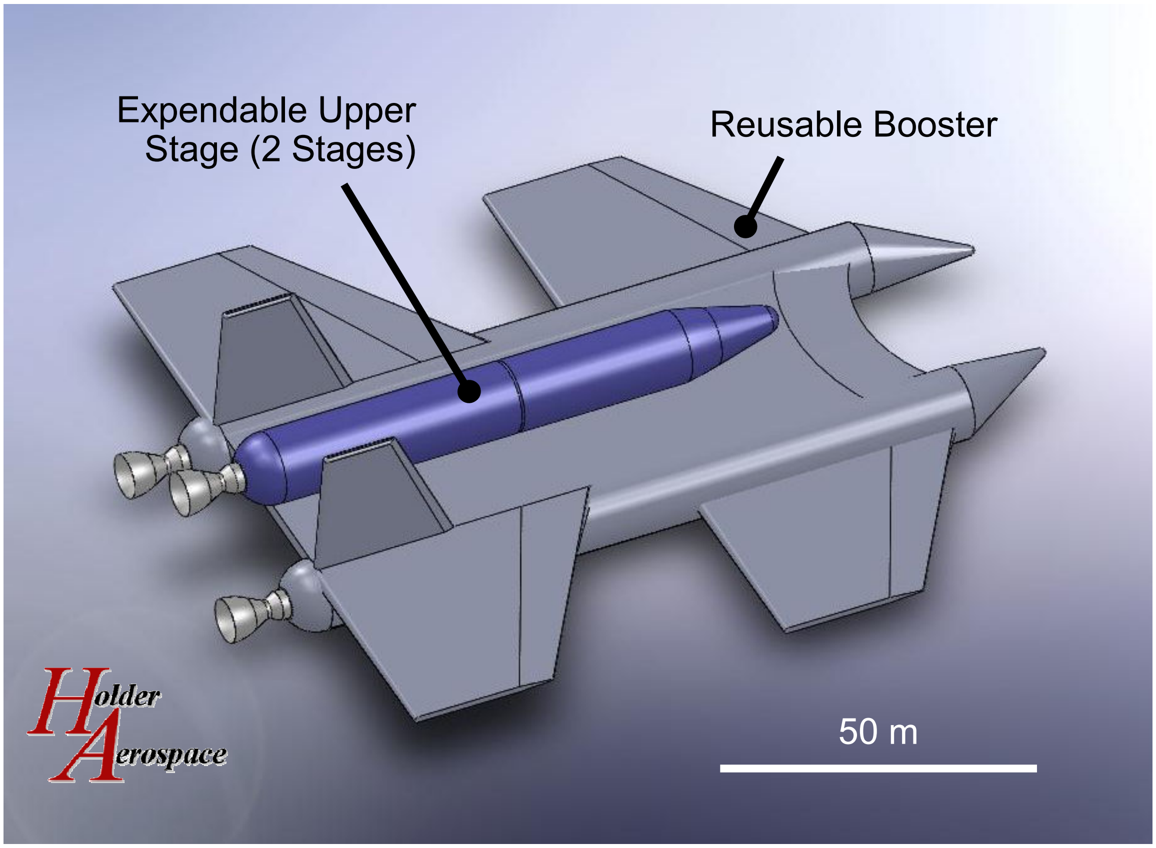

Figure 4: Water takeoff/landing HTHL RLV Booster point-of-departure concept.

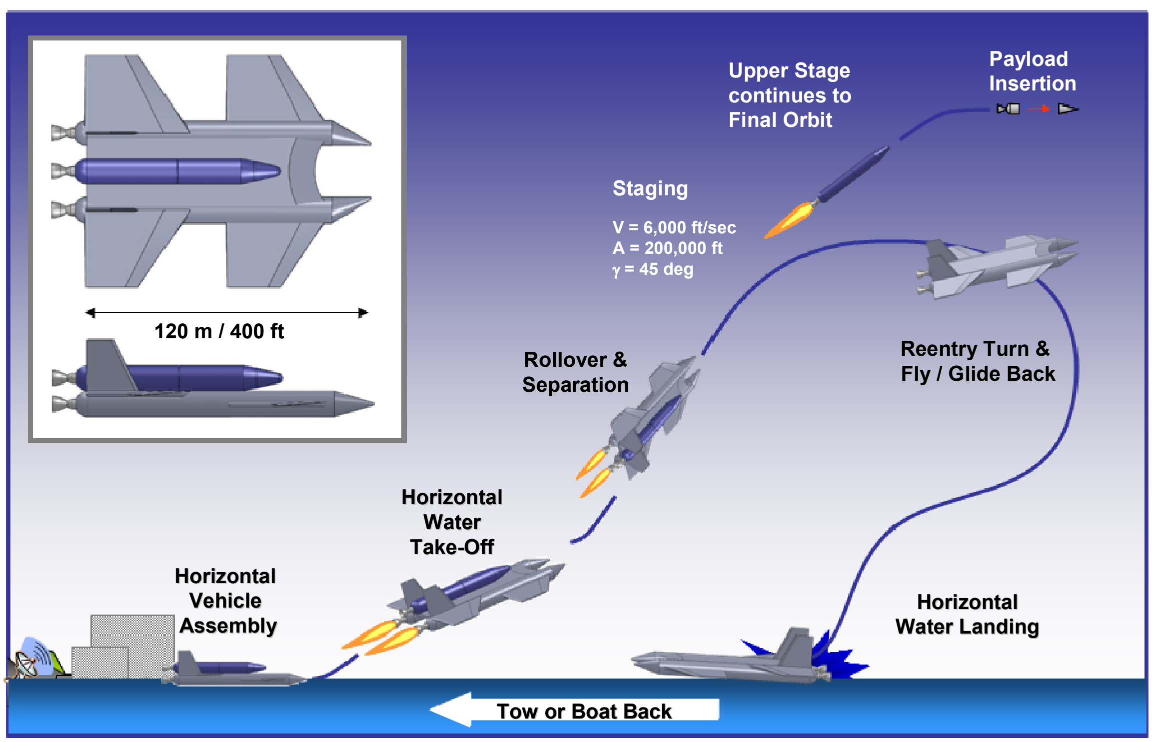

Figure 5: Possible Mission Profile for the water takeoff/landing HTHL RKV Booster concept.

The two main propellant tanks also serve as the floatation system, both during takeoff and landing. In order for the vehicle to remain afloat, the weight of the displaced water must equal that of the vehicle. Assuming a circular cross section for the tanks, the following equation relates the weight of the vehicle, the radius of the tank, and the resulting height of the waterline when the vehicle is at rest.

$$r = \sqrt{\frac{GTOW}{2 \cdot \rho_{H20} \cdot L}\left[2 \cdot a\cos(1-f) - \sin(2 \cdot a\cos(1-f))\right]^{-1}}$$

The parameters are the radius of each tank (r), the length of the tanks (L), the height of the waterline expressed as a fraction of the radius (f), the weight of the vehicle as it rests in the water (GTOW), and the density of the water ($\tilde{\rho}_{H2O}$). Figure 6 shows a plot of required tank diameter vs. desired water line for a 120 m / 400 ft long vehicle when floating in salt water.

For example, a vehicle with 400 ft length, and 24 ft diameter tanks, weighing 4 million lb at takeoff, would have a waterline at 28% of the tank radius; resulting in 3.4 ft of the tank being submerged in water.

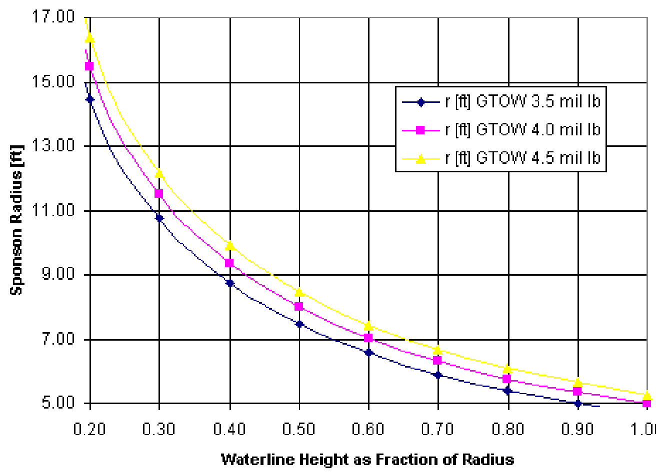

Figure 6: Water-line height vs. tank radius.

The horizontal takeoff configuration has significant safety advantages: the vehicle has the ability to recover from a non-catastrophic engine failure and land intact (after dumping propellants), or gain sufficient altitude to allow for a safe crew-escape before it is abandoned. The lifting surfaces also provide a modest performance gain during ascent. The high thrust available by using rocket propulsion during takeoff reduces total wing size requirement, and the center wing is capable of sustaining very high wing loads.

C. Return Configuration

A major driver of all reusable booster designs in the method of returning the vehicle to the original launch site. Even if the vehicle lands downrange, it still needs to be transported back somehow so that it can be reused. The configuration of the booster discussed here offers several possibilities for the return portion of the trajectory. With the propellant tanks nearly empty, the available lifting surface area makes the vehicle capable of sustained level flight, and reasonable landing speeds can also be achieved.

If equipped with turbojet (airbreathing) propulsion, it can return to the launch site using “wing in ground effect” flight; as pioneered by the Russian built Ekranoplan design. If greater propulsive simplicity is desired, the vehicle could use ramjet propulsion to extend the flyback range following separation, and glide to a final landing. Lastly, if no airbreathing propulsion at all is the most desirable solution, the vehicle could glide to a landing downrange of the separation event (or as close to the launch site as its gliding range allows), and travel back as a water-vessel using a gas-turbine driven propeller or “jet-boat” propulsion method. A more detailed trade study will be needed to identify the most suitable approach for a mission-optimized booster design; however, the point is that a vehicle design capable of water takeoff & landing opens up several unique options in the trade space.

IV. Summary

This paper describes the possibility of a HTHL RLV concept that takes off and lands on a body of water. The water takeoff/landing approach addresses many of the challenges for HTHL RLV design, and opens up unique additional options in the trade space. A point-of-departure concept is shown to illustrate the potential of the water takeoff/landing approach, which can server as a starting point for an in-depth conceptual design study.