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Comparative Analysis of

Rocket and Air-breathing Launch Vehicles

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Abstract

This paper compares and contrasts reusable rocket and air-breathing launch vehicles. Various rocket systems are compared including reusable Two Stage To Orbit (TSTO) and hybrid systems. Air-breathing systems include TSTO and Single Stage To Orbit (SSTO) designs. Both vertical and horizontal takeoff systems are investigated. Vertical takeoff, staged rocket systems are the clear choice for systems fielded in the next 10 years. Some vertical takeoff SSTO systems look very promising. Horizontal takeoff systems are much larger, have less margin and consequently higher growth factors.

Nomenclature

ATS	=	Advanced Technology Suite
CAV	=	Common Aero Vehicle, reentry vehicle
HC	=	Hydrocarbon
HTHL	=	Horizontal Takeoff Horizontal Landing
LH	=	Liquid Hydrogen
lox	=	Liquid Oxygen
OMS	=	Orbiting Maneuvering System
RBCC	=	Rocket Based Combined Cycle
RCS	=	Reaction Control System
RLV	=	Reusable Launch Vehicle
SOA	=	State of the Art
SSTO	=	Single Stage To Orbit
TBCC	=	Turbine Based Combined Cycle
TPS	=	Thermal Protection System
TSTO	=	Two Stage To Orbit
VTHL	=	Vertical Takeoff Horizontal Landing
WER	=	Weight Estimating Relationship

I. Introduction

THIS paper presents the results of many years of studying and modeling space access systems for the purpose of comparing and contrasting their merits and liabilities and assessing technology impacts. A wide range of vehicle types have been examined ranging from VTHL rockets to HTHL airbreathers, both TSTO and SSTO.

For the last few years we have been a member of the Reusable Military Launch System (RMLS) team. This is an ad hoc team composed of members from the Air Force, NASA and industry. Our objective has been to investigate the various reusable launch system options available for meeting national needs: Air Force, NASA and commercial. There are many concepts with widely varying attributes. This makes it extremely difficult to sort through them, find

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useful Figures of Merit (FOM) and make meaningful comparisons. This paper summarizes some of the team's findings.

II. Missions

We have been considering 3 possible mission categories:

1) Rapid Global Ordinance Delivery

The rapid global delivery mission is to deliver ordinance via CAVs to any place on the globe from CONUS. This is primarily a suborbital or once-around mission. Payload class is 15-40k lbs delivered to an easterly once-around orbit. Vehicle turn time is critical in order to keep the fleet size down and bring costs closer to those of regular bombers.

2) Operationally Responsive Space Lift

This mission stresses on-demand, flexible launch capabilities. Payloads are in the 10-15k lbs range delivered to an easterly 100 nm orbit, but at least 4k lbs delivered to a polar orbit. Again, rapid turn time is important, but probably not as critical. Both military missions have the most pressing need for rapid, low cost operations and probably the largest fleet sizes.

3) Low Cost Space Transportation

Commercial and NASA lift requirements are wide ranging, with NASA manned missions requiring the largest payload at around 60k lbs to an easterly low earth orbit. Turn times are not as critical as for the military missions.

This paper concentrates on reusable systems, but finding enough missions to justify a RLV is a major problem. The current number of worldwide launches is below 100 per year and The United States' share is much smaller. If the number of annual launches remains near present levels, expendable systems will continue to be economically viable. First partially reusable then fully reusable launch systems become more attractive as the number of annual launches increases, but only if costs, especially maintenance, can be kept low. For this reason partially reusable systems are included in this study.

For the purposes of this study, systems were sized to deliver an 8 ft diameter x 30 ft long 15k lb payload to an easterly orbit. The results are not sensitive to the payload size and are applicable over a wide range.

III. Measures of Merit

Ultimate figures of merit such as robustness, flexibility, risk, safety, mission cost and total life cycle cost are not very useful during the wide ranging conceptual phase of systems design and analysis. Needed are a few figures of merit which are good indicators for the above. This paper will make use of the following:

1) Empty Weight

Empty weight is a good indicator for development and acquisition costs. It is widely used at this stage of analysis, and is often used along with material types and complexity.

2) Complexity

Overall system complexity impacts development and acquisition costs and risks. Measuring complexity is not very quantitative and can be subjective, but is worth noting. One typically counts the number and type of major subsystems and the complexity of their interactions. Maintenance man-hours is a reasonable measure of this as well, though it does bring in the quality of the development process, in that the reliability of the subsystems are part of the equation.

3) Wetted Area

Wetted area is a good indicator for Thermal Protection System (TPS) related costs. TPS is a major contributor to maintenance man hours and turn time.

4) Uncertainty

Uncertainty estimates in conjunction with growth factors indicate technology readiness level and help set appropriate management margins for system development. The impacts on various uncertainties within the system are estimated using a Monte Carlo technique.

5) Growth Factor

There are many different growth factors. The one we are interested in is the empty weight growth factor. It is defined as the growth in system empty weight needed to restore full system flight performance in response to a change in weight. It is obtained by differentiating the system sizing equation with respect to a change in weight. It grows asymptotically as the system approaches its performance limit. High growth factors combined with uncertainties can yield extreme variations in the final size. This is especially true of HTHL SSTO systems.

6) Maintenance Man-Hours per launch cycle

Average total man-hours of maintenance needed to prepare the complete system for its next luanch is a major contributor to operating and life cycle costs. Modeling maintenance man-hours has been a major effort of team member Brendan Rooney and is reported in **Reference 1**.

As a final observation, gross liftoff weight is ***NOT*** a particularly good figure of merit for this type of wide ranging comparative analysis, because it does not differentiate between propellants and hardware. Hardware is extremely expensive to develop, acquire and maintain, whereas propellants, even hydrogen, cost practically nothing by comparison.

IV. Alternative System Concepts

Some of the system concepts evaluated are shown in **Figure 1**. Numerous rocket, scramjet and turbine propulsion combinations are considered. TSTO and SSTO systems are looked at, as are vertical and horizontal takeoff systems.

This paper reports on 17 different launch system concepts, and more are being added. All systems are fully reusable except the hybrid systems.

A brief description of each of the systems follows. More details can be found in the references. The system's identifying nomenclature is used in the included graphs.

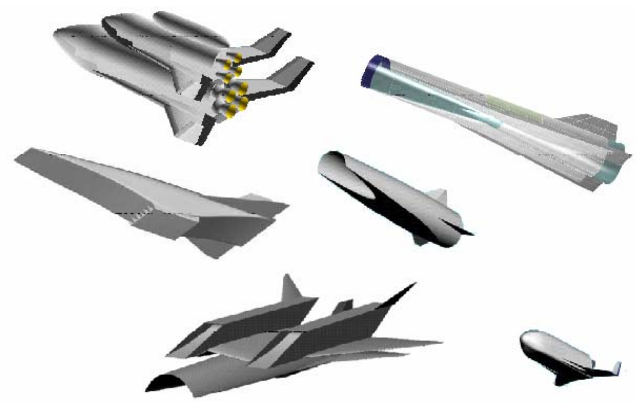


Figure 1. Some of the system concepts compared.

TSTO Rocket Systems

All of the TSTO rocket systems are VTHL and stage at 7000 fps. The boosters use turbofans to return to base. They are all serial burn. Earlier studies looked at parallel burn systems, including Bimese glide back boosters. They did not compare well to the simpler serial burn systems.

RP RP — RP1/lox engines in both stages

M M — Methane engines and subsystems in both stages

M M w — Methane engines in both stages, and Inconel structures

Multi-Stage Hybrid Rocket Systems

These systems all have reusable first stage boosters similar to the fully reusable boosters and stage at the same velocity.

RP RP — High performance RP1 /lox engines are used on the expendable upper stage

RP LH — LH/lox upper stage

RP S2 — Two solid rocket upper stages

VTHL SSTO Rocket Boosted Scramjet Systems

All of the VTHL SSTO systems use rockets to boost up to the scramjet takeover Mach Number. All of these systems use LH fueled scramjets, and all use LH/lox rockets for final insertion into orbit.

V HC 2D — RP1/lox boost rockets, 2D scramjets.

V HC Inw	RP1/lox boost rockets, One Inward turning scramjet

V LH Inw	LH/lox boost rockets, One Inward turning scramjet.

VTHL TSTO Rocket Boosted Scramjet Systems

The VTHL TSTO rocket boosted scramjet systems utilize reusable first stage boosters which stage above Mach 2.5 and glide back to base. All of these systems use liquid Hydrogen fueled scramjet upper stages with LH/lox rockets for final insertion into orbit

V HCR /2D	RP1/lox booster with a 2D scramjet upper stage

V HCR /SJ	RP1/lox booster with an inward turning scramjet upper stage

HTHL SSTO Scramjet Systems

All of the HTHL SSTO scramjet systems transitioned to scramjet above Mach 2.5. All of these systems use liquid Hydrogen fueled scramjets with LH/lox rockets for final insertion into orbit.

H LH 2D	LH/lox boost rockets with 2D scramjets

H LH Inw	LH/lox boost rockets with inward turning scramjets

H HC Inw	RP1/lox boost rockets with inward turning scramjets

HTHL TSTO Scramjet / Rocket Systems

All of the HTHL TSTO scramjet / rocket systems utilize scramjets on their booster stages and stage at approximately Mach 10. They all use a LH/lox rocket orbiter stage similar to the TSTO rocket systems, but with the addition of more TPS to deal with the more severe aero heating during ascent.

TBCC /R	Over/under turbo accelerator HC engines to above Mach 3.5 and 2D LH scramjets on the 1st stage

RBCC /R	LH/lox rocket engines to over Mach 2.5 and 2D LH scramjets on the first stage

V. Modeling Approach

The most difficult aspect of a comparative analysis as broad as this is maintaining consistency between concepts. All assumptions must be scrutinized to ensure fair treatment of all concepts. A fair comparison between traditional multistage rockets and airbreathing concepts has been our principle concern.

We are currently using 3 different software products for modeling launch systems and their components. Our original RMLS rocket system models were developed in-house using Mathcad and TechnoSoft's AML software. Mathcad was used to develop and document many of the components before transcribing them into AML and later into Astrox Corp's SIDE software. More RMLS rocket model details and results can be found in **Reference 2**. Our airbreathing systems have been modeled by Astrox using SIDE. To ensure comparable results from both products our RMLS model was translated into SIDE and comparisons made to ensure consistent results. Many of the designs have been recently published by Astrox in **Reference 3**.

This was reasonably successful but some adjustments were still needed by the time the results were in. Astrox's SIDE models have scramjet weight models that were originally correlated to more advanced materials than was assumed for the rocket models. These were corrected for. Every attempt has been made to be as fair as possible. We believe we have a reasonably accurate comparison. Having said that, there is still plenty of room for improvement and the work continues.

Model Accuracy and Uncertainties

Our rocket models are relatively mature. The models estimate weights of over 50 items which make up the empty weight. The Weight Estimating Relationships (WERs) are from numerous sources. Some were developed in-house and are physics based. All were compared and correlated with shuttle and other launch vehicle data. Our airbreathing systems models are not as advanced, but we believe they are adequate to judge relative attributes of systems. The airbreathing system models are currently undergoing refinement in the areas of integral conformal liquid hydrogen tanks and actively cooled engine structures.

Integral conformal hydrogen tanks form the bulk of the fuselage, and low weight tanks are critical. The shapes of both 2D and inward turning scramjet fuselages lead to tank shapes which are not particularly good pressure vessels. The best way to design these tanks, and how they compare to cylindrical rocket tanks, is a current area of investigation. For the purposes of this study all integral conformal hydrogen tanks were assumed to be 150% of the weight of a cylindrical tank of the same volume. Optimum pressures in these tanks have not been established but will be lower than in corresponding cylindrical tanks due to their non-circular shapes. We believe that the more curved tank shapes should be lighter, but no advantage has been taken of this possible reduction in weight.

Our models typically estimate the areas of up to 5 temperature regions (including actively cooled areas) and allow for the estimation of unique TPS weight and maintenance for each. The scramjet vehicles' actively cooled surface areas are (depending on the concept) 5-15 times greater than the TSTO rocket engines' area. Actively cooled panels have significant weight and maintenance. Weight and maintenance uncertainties are still high, but data is being collected and models are being constructed to improve our current estimates.

VI. Model and Technology Assumptions

Rocket Engines

Figure 2 shows existing rocket motors and two square regions that represent the state-of-the-art for high pressure HC/lox and LH/lox rockets. Performance levels are more than adequate to achieve reasonable closures for TSTO optimally staged rocket systems. An elliptical region shows the projected performance of advanced long life methane/lox engines. Advanced methane engines appear to provide a number of design, development and maintenance related advantages which more than offset their reduced density impulse. Technology is needed to improve reliability, maintainability and life.

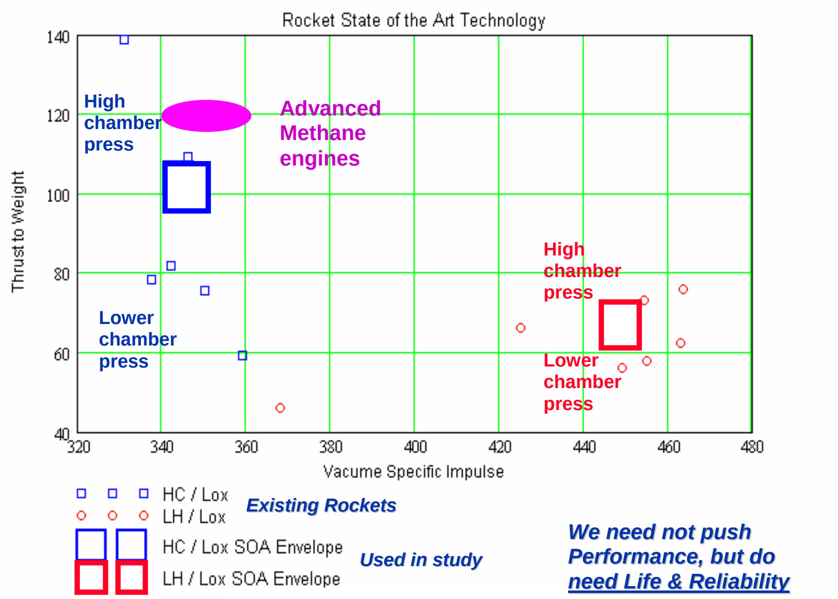


Figure 2. Rocket performance

Scramjet Engines

Two types of dual mode ram-scramjets were used in this study: 2D and Inward Turning. 2D scramjets have been extensively studied and evaluated for the last 15 years. A reasonable, but by no means complete, body of literature and data exists for them. Inward turning or streamlined traced scramjets are just as old but have not been studied to the same extent; however, this is starting to change. The Crown inlet scramjet research from the 1960's is a prime example of both an inward turning and streamlined traced design.

Adequate scramjet data and technology are still a few years in the future. The study is using what I would call nominal engine performance estimates. We did attempt to use conservative scramjet weight estimates to reflect use of existing materials. For the purposes of this study, actively cooled panel weight was assumed to be 8 lbs per square foot, and maintenance models were made sensitive to cooled area. No data exists on the probability of damage of these areas, so data on SSME rocket nozzle maintenance was used as a starting point. Our scramjet maintenance models are still emerging and only cursory results will be reported here.

Airframe Technology

Structure for the systems is assumed to be primarily Aluminum and Aluminum-Lithium alloys. An exception is the use of Inconel in some vehicles as noted. Both rockets and air-breathing systems assume integral tanks with TPS.

The impact of weight saving advanced structures is not being reported in this paper, but the assessment approach is explained in the results section. Graphite composites are being considered for tanks and other structures to save weight, and hot and warm structures are being examined to reduce TPS coverage and associated maintenance.

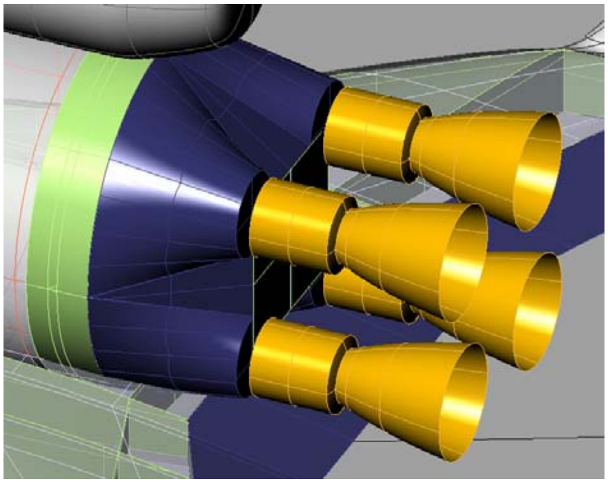


Figure 3: Nacelle Concept for Engine/Vehicle Interface

Thermal Protection Technology

The baseline TPS suite included technology consistent with shuttle TPS with the exception of extensive use of TUFI tiles in place of HRSI. Advanced Carbon Carbon is assumed for leading edges.

Fluid Related Subsystems

The subsystems for the baseline systems are similar to those of the Space Shuttle, just fewer of them. The ATS includes numerous advances. Autogenous RCS, OMS, APU and main propellant pressurization systems are assumed. Hydraulic and helium systems are eliminated. Fluid types are reduced down to lox, liquid methane (or similar), liquid nitrogen, and water.

Maintenance Operations

Baseline maintenance actions are derived from the Shuttle database and the knowledgeable people at Kennedy Space Flight Center who do its maintenance. They are derived from the Shuttle, but they are not Shuttle numbers. They reflect the same kinds of activities, but on a much simplified system. ATS features include numerous design improvements such as discussed above and shown in **Figure 3.** A ventilated rocket nacelle concept should significantly reduce engine removal and replacement maintenance. Maintenance assumptions are covered extensively in **Ref 1**.

VII. Study Results

The SSTO Rockets could not be sized with SOA or the ATS used, but their trend lines are shown in **figures 4-9** for completeness. The weights shown were estimated using SOA weight estimating relationships. Weight savings due to advanced technologies can be easily estimated using the graphs and the weight statements for the systems in question.

Graph Notation

The circles are the final solution weights. Plotted along with most circles are lines which indicate the empty weight uncertainty for the system. The solution circles are conservative, so they are on the high end of the uncertainty lines. Blue lines are used for systems that contain only LH and lox. Red lines are used for any system that uses RP1 in some segment of its flight. Magenta is used for the systems with methane. The different fuels show slightly different trends.

Uncertainty

Probabilistic (Monte Carlo) simulations show that the uncertainty for the rocket models is in the neighborhood of 4% of the vehicle empty weight fraction, so that value has been used for every rocket system plotted. The uncertainties in the airbreathing models are greater, but not well quantified. A 6% band is assumed for all of them and seems reasonable, if not optimistic, given the state of our airbreathing models. The resulting length of the line is caused by the uncertainty and the growth factor of the system being modeled. Systems which are harder to close (i.e. have less margin) will have higher growth factors. If the system concept is beyond the reach of the technology, asymptotic weight growth occurs and no closure is possible at any weight. Green regions indicate reasonably good solutions.

Gross Weight Trends

Figure 4 shows gross weight trends plotted versus empty weight for the different systems

Gross weight trends are frequently given, but don't indicate whether the weight is propellant or structure. Most of the gross weight for rocket systems is in the form of inexpensive propellants, primarily lox. For Airbreathing systems a much higher percentage of the gross weight is in structures and propulsion. All of the vertically launched systems, both rockets and airbreathers, have considerably lower empty weights than the horizontally launched systems, with the exception of the SSTO rocket which did not achieve closure, i.e. could not be sized.

An examination of the details shows that there is a large weight penalty associated with the larger takeoff wing and gear needed for the horizontally launched systems. The wing and gear weight is much lighter for the vertically launched systems, which only need the wing for high speed flight and the gear and wing for landing while nearly empty. Also, rocket engines weigh little, so installed thrust-to-weight ratios above one do not impose much penalty. In the end, the weight penalty for increasing the size of rocket engines and associated structure is less than for increasing the size of wings and gear.

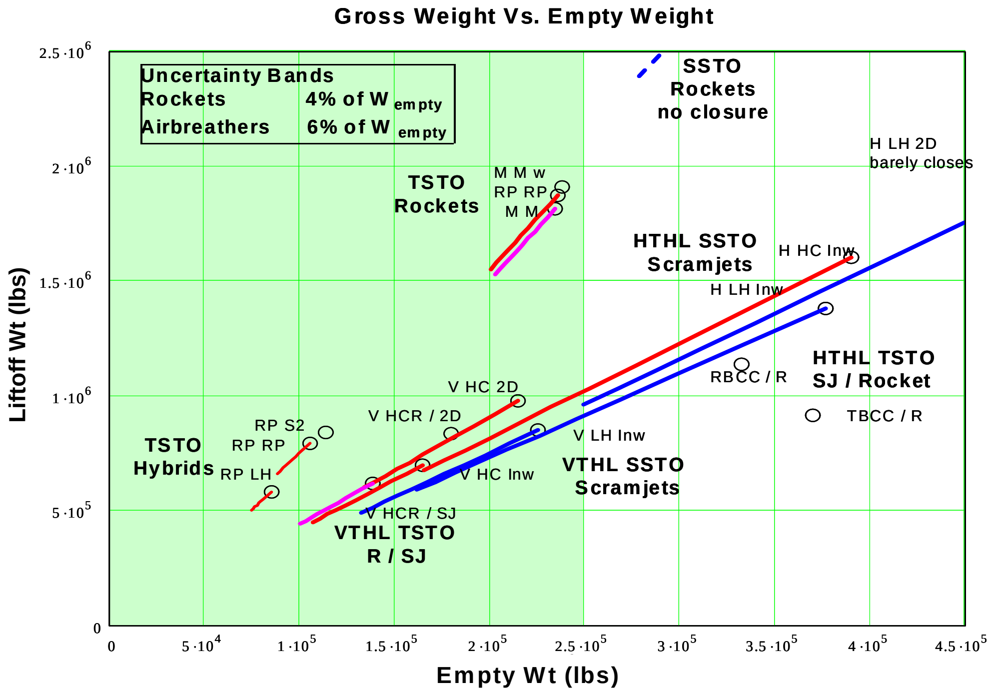


Figure 4. Liftoff Weight vs. Empty Weight in (lbs)

Empty Weight Trends

In **figure 5,** empty weights are plotted against the empty weight fractions. This chart clearly shows how the uncertainty in empty weight fractions affects the various systems. Notice the extreme effect uncertainty has on the HTHL SSTO launched systems. This indicates that they have less inherent design margin.

This chart can also be used to show the impact of weight saving technology on the empty weight of the systems. First, you have to estimate how much the advanced technology will reduce the weight of the components. Then, for each specific design, determine what fraction the effected components are of the empty weight fraction. For example, let us consider the impact of graphite composite technology on the advanced methane design. If graphite composite tank technology decreases tank weight by 15%, and the tanks make up 10% of the empty wt, and the systems empty weight fraction is 12%, then the technology will reduce the empty weight fraction to:

$$(1-.15*.1).12 = .1182$$

The “M M” methane system with SOA WERs weighs about 240k lbs. If we reduce its empty weight fraction to .1182 it will weigh about 220,000 lbs.

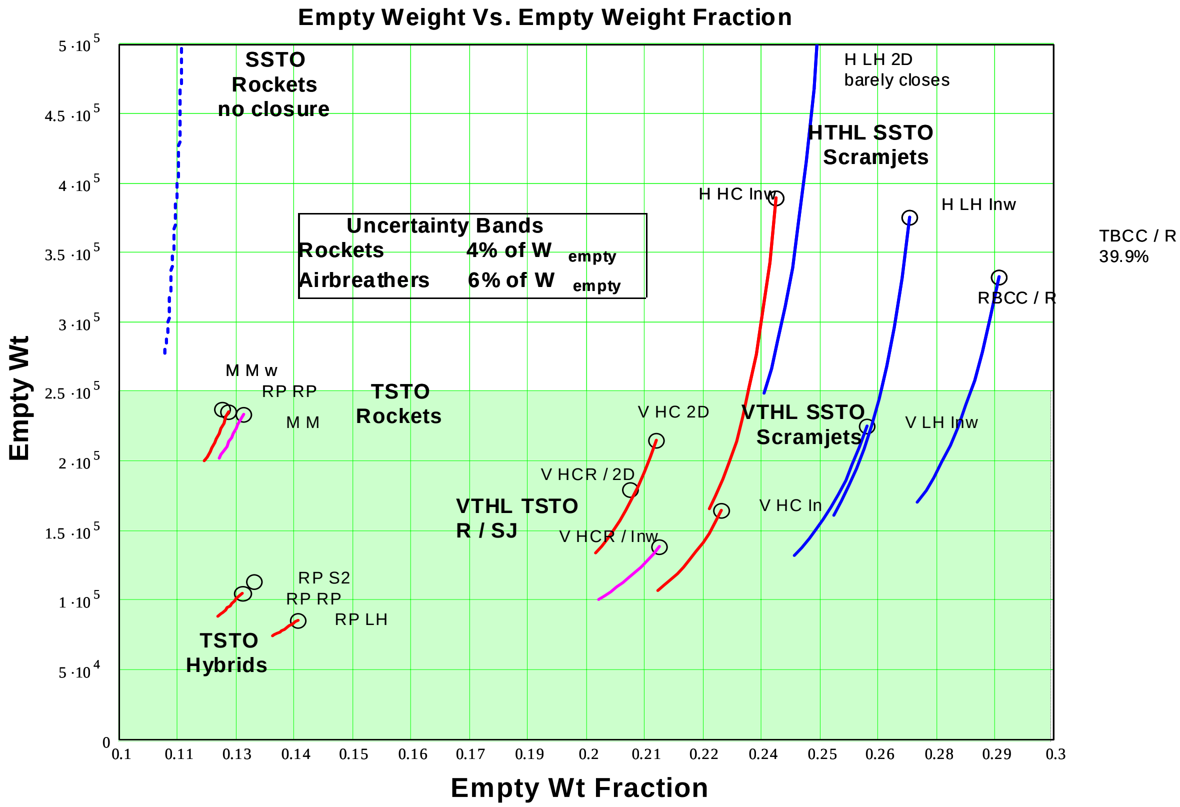


Figure 5. Total Empty Weight (lbs) vs. Empty Weight Fraction

Growth Factors Trends

Figure 6 shows a plot of Empty Weight Growth factors vs. Empty Weight. The growth factor is the derivative of the empty weight with respect to a change in the “scaling empty weight” of the vehicle. It measures how sensitive the design is to empty weight uncertainty. As can be seen, the large empty weight uncertainty bands are associated with systems with high growth factors or high uncertainties or both. All of our rocket designs are plotted with 4% empty weight fraction uncertainty and the airbreathers with 6%.

Examination of the following system sizing equation illustrates the general nature of the trend lines. W_g is gross weight, w_{pyld} is payload weight, $w_{fx.n}$ is fixed weight items and f_s and f_p are the scaling and propellant weights divided by gross weight. For a given system, the payload and fixed weight items are constant by definition. The scaling empty weight fraction is assumed to be constant for a given design concept as is the propellant fraction. In practice these are very good assumptions in a neighborhood around the solution point. As the sum of the scaling empty weight fraction and propellant fraction approach unity, the gross weight grows asymptotically large.

$$W_g = \frac{w_{pyld} + w_{fx}}{1 - f_s - f_p} \qquad dW_{e\_dws} = \frac{w_{pyld} + w_{fx.n}}{\left[1 - \left(1 + \frac{\Delta ws}{w_s}\right) \cdot f_s - f_p\right]^2 \cdot w_s} \cdot f_s^2$$

In reality the fractions are not exactly constant, but they are very close to constant. A small correction factor was introduced, and this equation was used to nicely curve fit the results of our computer models. The empty weight growth factor equation is then derived as shown.

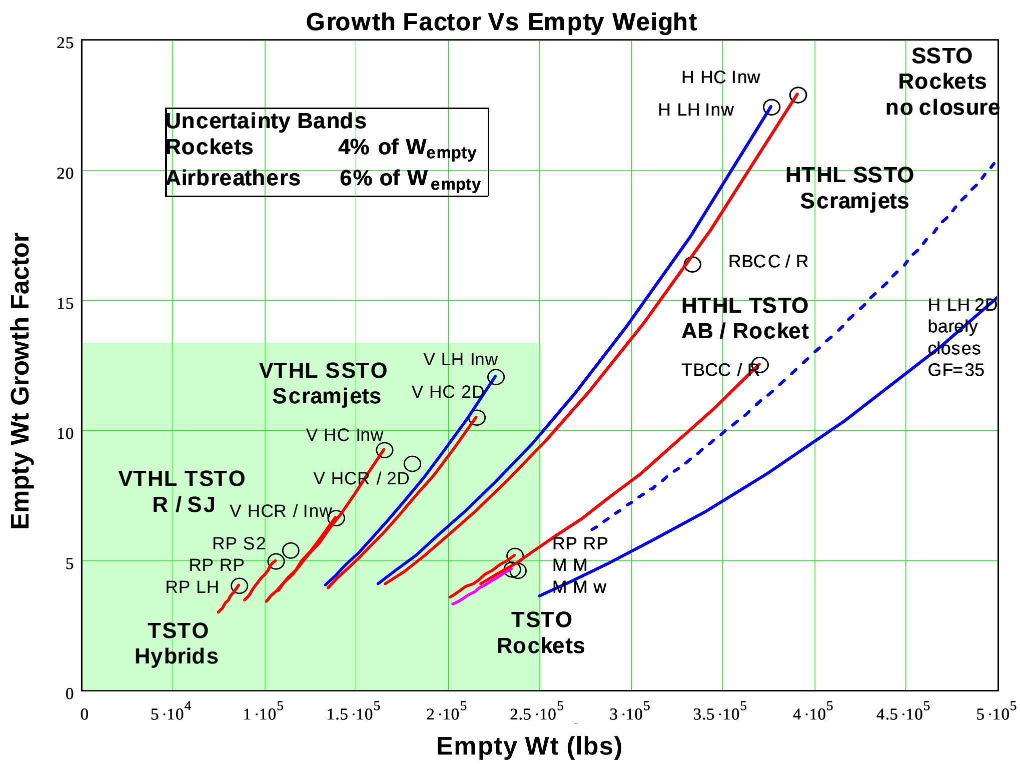


Figure 6. Growth Factor vs. Total Empty Weight (lbs)

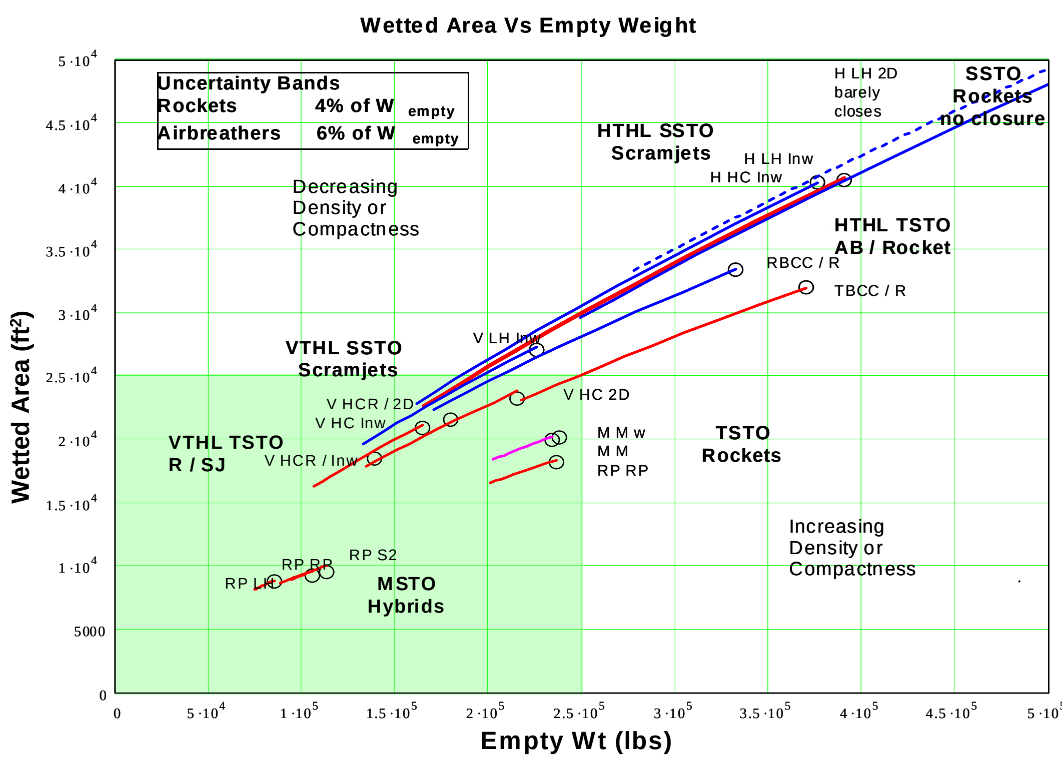


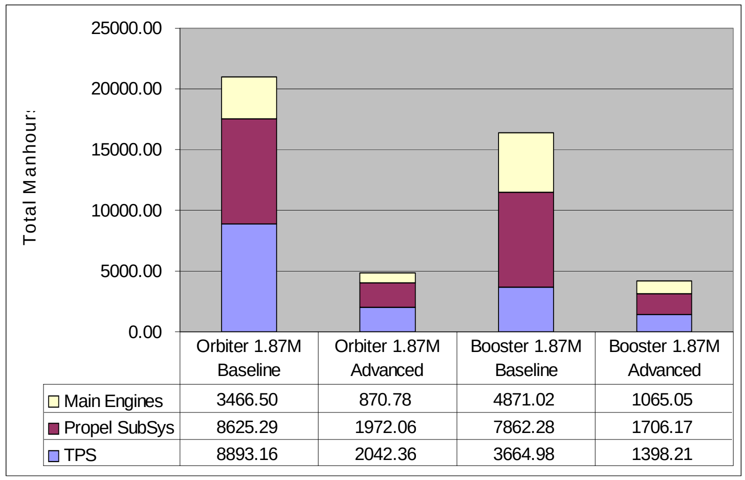
Figure 7. Wetted Area (ft^2) vs. Total Empty Weight (lbs)

Wetted Area Trends

Figure 7 plots Wetted Area vs. Empty Weight. You can see the nonlinear variation of the wetted area with size. The wetted areas are nearly proportional to the empty weight to the 2/3 power as would be expected with scaling which is nearly, but not quite geometric. You can clearly see the effect of the horizontal takeoff requirement. The wetted areas are two or more times larger than for the vertical systems. Some of this can be removed by increasing the takeoff velocity. HTVL systems also have the lower density LH fuel to contend with, and when one tries to increase the density by using HC during the early boost phase one just drives up the wing size, with the net result being no gain. The effect of HC during the early boost phase is completely different for the vertical takeoff systems. The use of HC always reduces the wetted area for vertical launched systems.

Maintenance Trends

The RMLS operations and maintenance model **(Reference 1)** is being developed to provide design and technology sensitive parametric estimates of man-hours and clock-time needed to support and maintain different types of launch systems. It builds up estimates of failure probabilities and maintenance man-hours from low level component failure modes and associated maintenance actions. Parametric, probabilistic models of these "maintenance actions" are developed and made sensitive to design, technology, and development parameters. For example, TPS tile maintenance is sensitive to total area covered, average tile size, type of gap seals, probability of



	Orbiter 1.87M Baseline	Orbiter 1.87M Advanced	Booster 1.87M Baseline	Booster 1.87M Advanced
Main Engines	3466.50	870.78	4871.02	1065.05
Propel SubSys	8625.29	1972.06	7862.28	1706.17
TPS	8893.16	2042.36	3664.98	1398.21

Figure 8. Man hours for SOA 'RP RP' **and ATS** 'M M'

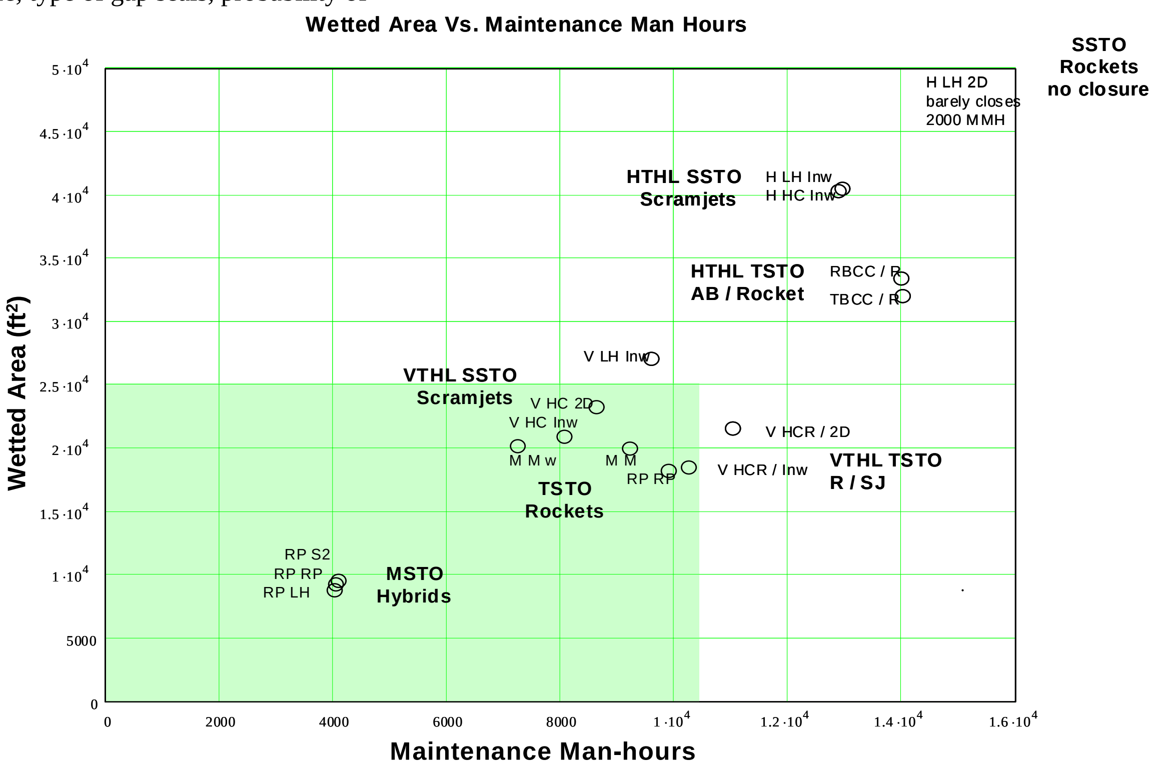


Figure 9. Wetted Area (ft^2) vs. Maintenance Man-Hours

damage, location on vehicle, type of attachment and water proofing needs. Some parameters are adjusted for vehicle design differences, such as TPS area, others for technology improvements such as more durable TPS, which would reduce the probability of damage.

Statistical models for main engines, fluid related subsystems, and TPS have been built up. These account for most of the maintenance actions. Fluid related subsystems include: all pressurization systems, RCS, OMS, APU and cooling systems. The 'main engine' and 'fluid related subsystems' models are primarily sensitive to their number, type and quality, and not as sensitive to their size. Conversely, the TPS maintenance is directly related to wetted area as well as to its type and quality. **Figure 8** shows an example of a comparison between a SOA RP1/lox (RP RP) system and an ATS methane/lox (M M) system. The ATS system has a range of improvements in technology, design and development. Advances in TPS, fluid related subsystems, engines, integration all contribute to the large reductions in maintenance.

The maintenance models for the airbreathing components have been defined, but as noted earlier, there is little data with which to correlate our models. Work is ongoing, but some initial estimates can be made. If we assume that each of the systems contains similar advanced rockets and subsystems, they should have similar maintenance hours for each stage for these items. There are two exceptions, the 'TBCC / R'**,** with its more complex booster, and the hybrids with expendable upper stages. We are currently tracking about 2,800 average man-hours per sortie to maintain the main engines and the fluid related subsystems for each advanced TSTO rocket 'M M' stage. I have used this as an estimate for all advanced Methane stages and 3300 man-hours for advanced RP stages. To account for airbreathing systems' TPS and scramjet maintenance, we are currently assuming that most of the scramjet maintenance will be related to its actively cooled panel area. The actively cooled panels, seals and actuator maintenance should all be strong functions of cooled area. The scramjet systems' TPS heating load is more severe than the rocket systems', and they have 5 to 15 times the amount of active cooling. The maintenance per square foot will certainly be worse than the rocket systems, but by how much is hard to say. As an initial estimate, we are assuming 0.25 man-hours per square foot for all the scramjet vehicles. This is about what our advanced orbital maintenance is, so this estimate is optimistic.

Figure 9 shows that the systems with the lowest maintenance are the hybrids. They only have one small booster to maintain; however, many millions of dollars worth of upper stage hardware are thrown away per launch. SSTO vertical takeoff scramjets and TSTO rockets still appear to be favored if fully reusable systems are desired.

VIII. Promising Concepts and Future Work

RMLS 102 is our current baseline reusable system concept. It is an optimally staged TSTO VTHL System. It has serial burn HC/lox rockets on both stages. It is designed to be able to lose an engine on either stage at any time during the launch and still make the mission. RP1 and other hydrocarbons have been investigated. Cryogenic hydrocarbon fuels look attractive for their ability to simplify fuel related subsystems and operations. We will be looking at methane very closely for all of our HC rockets. We will further investigate the complete removal of high pressure hydraulic and helium subsystems through the use of autogenous pressurization and electric actuators. We will be trying to get down to 4 fluids: methane (or similar), lox, water and liquid nitrogen. We will further investigate the use of warm and hot structures for aero surfaces in order to minimize TPS maintenance. RMLS 102 is one of the smallest and simplest of the fully reusable system concepts investigated to date.

RMLS 107 is our hybrid system concept. The reusable booster is a smaller version of our RMLS 102. This system concept seems to be a rational step between expendable and fully reusable systems.

RMLS 401 is a SSTO VTHL HC/lox rocket boosted LH Scramjet system. It transitions to scramjet mode at about Mach 4 or slightly higher. The scramjet has minimal variable geometry and should be capable of Mach 4 to 14. It features an inward turning semicircular or kidney bean shaped Busemann Inlet. A 2D scramjet will be carried along as well. A large portion of the vehicle fuselage skin is designed to be in tension to minimize structural weight and simplify construction. Integral LH tanks are used. A LH/lox rocket is used to finish acceleration into orbit. This is an RBCC with the rockets integrated into the scramjet nozzle just downstream of the combustor. They are stored flush when not used. The RMLS 401 is the smallest, simplest SSTO airbreathing concept investigated to date, and it appears to be competitive with TSTO Rocket systems.

RMLS 304 is a TSTO VTHL HC/lox rocket boosted Scramjet system. The upper stage is a nearer term technology version of the 401. It is staged at about Mach 4. The booster glides back to base, perhaps with a small amount of "boost back". The scramjet is assumed to be less capable: Mach 4+ to 12+. If the 304 is designed around the hybrid booster, it would be able to launch a payload of greater than 15,000 lbs.

IX. Conclusions

- **Numerous reusable and partially reusable rocket systems are attractive and technically achievable now**, but sufficient numbers of annual missions and reduced costs are needed to justify their development. They are all two or more staged systems, and are vertically launched. The partially reusable systems are comprised of a reusable booster with expendable upper stages. Vehicle turn times of one to two weeks appear to be achievable with existing technology by using "ops-focused" design and development practices. The desired time of 24-48 hours (to be more "aircraft like") is beyond the state of the art but is within reach with a reasonable level of, again, "ops-focused" technology investment. Further reductions of turn time and operations costs will require technical advances to support development of durable, operable thermal protection systems, rocket engines, and fluid related subsystems. Maintenance and turn time is dominated by these subsystems.

- **Technology development, design and system development must be focused on operability**. A thorough (more aircraft like) development program will be necessary to obtain the levels of operability desired. Such a program could easily extend up to 10 years. Systems with considerable design margin make development easier. To this end, it is paramount that we keep our requirements lean, focus on simple systems and optimize them for high operability.

- **Horizontal launch does not improve the turn time of launch systems, it increases it.** This is due to the increased maintenance associated with their larger size. Times to mate, transport and fuel should be similar for both horizontal and vertical launch, while vertical launch pad mating, erection and fueling can be made small relative to the maintenance times of large horizontally launched systems. Systems such as Zenit have shown launch times of a few hours by automating the procedures.

- **"Aircraft-like" operations for "access to space" should not necessarily imply turbine based horizontal takeoff systems.** Conventional wisdom is sometimes wrong. These launch systems fare very poorly against vertically launched rocket and combined rocket/scramjet based systems. Horizontally launched TBCC/rocket systems are among the worst, being larger, having heavier empty weights and much greater wetted areas, including extensive amounts of actively cooled area. They are more complex, contain three different types of engines, and will have significantly larger amounts of maintenance. Having said all of this, there are hypersonic cruise missions where TBCC may be the engine of choice, but not for pure access to space.

- **Airbreathing propulsion for "access to space" should focus on vertically launched rocket/scramjet systems with an eye to SSTO.** Good scramjet performance in the Mach 10-15 régime, light weight integral tanks and advanced thermal protection systems are critical in achieving this goal. It is very difficult for a TSTO airbreathing concept to compete with a TSTO rocket system; having said that, a TSTO rocket boosted scramjet would be a lower risk first step towards SSTO. This system could launch considerable payload using the small hybrid class booster, and pave the way for SSTO. Above all we need to keep these scramjet designs as simple as possible without giving up too much margin.

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