The Hypersonic ETO Space Transporter as an Enabling Element for Acquiring Commercial Human-rated Space Transportation Capabilities

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ABSTRACT

It is postulated that a true Spaceliner-class transport system will be needed to enable any prospective commercially-based human space transportation era to be successfully entered upon, and then sustained in growth on a large-scale, long-term basis. The governing design characteristics for this advanced class of transportation system are stated, as oriented to the demanding, human-qualified Earth-to-orbit and return flight stages to be performed on all spaceflight voyages. A generic system definition is the immediate result. Then, two previously documented specific designs that potentially satisfy this definition are referenced. For these systems, extended hypersonic airbreathing flight operations uniquely contribute to the high orbital mass fractions attained. Such are needed to achieve an acceptably safe, dependable and affordable aircraft-like spaceflight vehicle system design. It follows that extended hypersonic airbreathing-propulsion is deemed enabling for the realization of a true Spaceliner.

I. THE INITIATING AND CONCLUDING STEPS OF ALL SPACE VOYAGES

A. Earth-to-orbit and Return Flight: A Universal Spaceflight Requirement

In the larger context of a prospective commercial human space transportation enterprise, the critical importance of the highly-energetic journey-initiating Earth-to-orbit (ETO) space transportation step, and the Earth-return concluding step, is to be underscored in this presentation. A yet-to-be-developed vehicular means for performing future ETO and safe-return missions is held up as being vitally needed in coming decades, if spaceflight is to be effectively pursued on a sustainable, commercially productive basis. This new vehicle type, identified here as the “Hypersonic ETO Space Transporter,” is seen as a flight system that can achieve a true Spaceliner status. This would entail future space-faring counterparts to today’s large transport aircraft. As such, this system can fully execute those critically important transportation means for safely, affordably and dependably expanding the future of human spaceflight.

B. A Space Development and Commercialization Initiative

SpaceWorks Engineering, Inc. (SEI) recognizes the need for those companies involved in aerospace engineering fields to communicate and relate the benefits of future space activities to the public-at-large. Despite the enormous benefits offered to our planet’s economy, quality of life and societal welfare, the average citizen is often unaware of the far-reaching benefits derived from an active space program. In response to this obligation, SEI has initiated two new research and outreach focus areas to be supported by company-provided internal research and development funds. One theme involves planetary protection against asteroids and comets that have the potential to impact the Earth. The other focuses on commercial space development. SEI technical staff members participate in one of the two research themes as a small part of their overall company activities.

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This latter theme involves research into, and promotion of the commercial development of Earth-to-orbit space access and eventually cis-lunar space – i.e., promotion of a true space economy with commercial businesses providing goods and services according to the rules of a capitalistic economy. The benefits to the world populace in terms of wealth creation, new high-skill jobs, technological advances, and improved quality of life are potentially considerable. Among the many areas of endeavor to be explored and appropriately developed within this focus theme will be: space tourism for everyday citizens, emplacement of orbital and lunar/planetary stations and habitats, harvesting of space resources, space-based energy, and advanced commercial space transportation systems.

Spaceliners, the subject of this paper, will be the future space-faring counterparts of today’s large commercial and military air transports. Like current airliners, once in service, Spaceliners will be extremely safe, highly dependable and fully user affordable. Their acquisition will play a decisively enabling role in the development and commercialization of space, and are therefore complementary to measures for the development of space, generally leading to the achievement of many of the other research topics in this second theme.

Further, of high significance to prospects for enlarging the economic base supporting the acquisition of a Spaceliner, this class of flight system should also prove to be directly applicable to the many-faceted aspects of high-speed transglobal transportation service, a potentially large military and commercial market. Point-to-point Earth-bound high-speed traffic service, once initiated, could easily exceed that going into space.

C. Initiating and Concluding Routine Round-Trip Space Voyages: Spaceliner is Key

Viewing the long-term pursuit of an expanding human spaceflight future, one initiating and sustaining round-trip voyages into cis-lunar space and beyond, it must be recalled that the first and last transportation steps to be undertaken by tomorrow’s human explorers, scientists and engineers, and space-tourists, will be the ETO and return-to-Earth legs, those initiating and concluding steps of the overall journey. While the return leg’s phase is likely to remain largely non-propulsive, being conducted via conventional atmospheric-deceleration reentry flight means, still a safe and dependable descent, approach and landing will likely be engine-dependent to a significant degree. Here, minimization of fuel usage will be especially critical. This points up the need for conventional airbreathing-engine operating capabilities, to be potentially integrated within the vehicle’s ascent propulsion system hardware make-up.

But for the ETO ascent flight, it is obvious that a full-time propulsion system means must be used to lift the human transporter up through Earth’s deep gravity well, and to secure it in a stable low Earth orbit (LEO). In fact, this initial ETO leg is a highly energetic step. It entails a characteristic incremental velocity change of 7.9 km/s (26 kft/s). This “delta-v” increment quantitatively approaches that required for an in-space flight increment from LEO to the surface of the Moon and back again (presuming a full aerocapture atmospheric deceleration maneuver on return). This in-space mission calls for 10.1 km/s, such that with the addition of that ETO-leg increment (7.9 km/s), a total velocity increment of 18 km/s must be provided for the round trip. Impressively, the initial ETO increment amounts to as much as 44-percent of this total, fully denoting the highly energetic contribution of this first flight step, as a prerequisite for all spaceflight journeys to be undertaken in the years ahead.

So, in summary, a Spaceliner-class ETO transporter is deemed essential for conducting future human space-access journeys. It must first dependably deliver crew, passengers and high-value cargo into low Earth orbit, a highly energetic mission step. In the mission-concluding descent and landing phase, it must also provide airbreathing propulsion means to ensure a well-controlled, safe return to the Earth’s surface. This mandatory power-on capability applies to both routine and emergency-recovery flight situations. It becomes clear that major propulsion design challenges must be met if these system capabilities are to be achieved.

D. Background: What Constitutes a True Spaceliner Class ETO Transporter?

1. Advanced ETO Transports: Spaceliner- and Spacelifter-class Systems – With the need to advance human spaceflight capabilities in mind, considerable informed thought over the years has been given to responding to the pivotal question of “what the next generation ETO space transport ought to be.” Studies of numerous and diverse candidate vehicle concepts and their propulsion systems abound. But the defining characteristics, those absolutely
needed are widely agreed to: These flight systems must be safe, dependable, and affordable. In short, they must be “aircraft like.”

2. Emulating Aviation -- In the pursuit of “the right answer” to this leading question, the sensible emulation of the familiar service attributes of today’s commercial and military large aircraft is a dominant advocacy theme in advanced space transportation planning circles, worldwide, in government and industry, and in the involved university community. This is signified by the working titles for such aircraft-like systems in widespread use, such as Spaceliner and Spacelifter. These aircraft-proxy designations are often used in addressing future civil/commercial and military space-transportation applications, respectively. A pertinent example used by defense system planners is: ORS, for operationally responsive Spacelifter.

3. A Step-function Transportation Upgrade Is Needed -- For tomorrow’s servicing of the host of spaceflight missions’ ETO and return flight needs for humans and high-value, modest-sized cargo items, such a Spaceliner-class system is deemed essential. From a U.S. perspective, in the human exploration timeframe of interest starting sometime before 2015, the Space Shuttle will, by today’s plans, have been retired. Further, the EELVs’ descendents of that day, however modified, may not meet the stringent flight-safety and mission reliability standards required of human flight, as geared up for increased-traffic missions. Besides these critical limitations, expendable systems may inherently be too costly, pointing up the ultimate need for reusable flight systems.

As now planned, future transportation elements of the U.S. exploration initiative will feature partial reusability, including the recoverable Crew Exploration Vehicle (CEV) system named Orion. This spacecraft is to be launched by the semi-reusable Crew Launch Vehicle (CLV) system largely based on the Space Shuttle and Apollo derived vehicle and propulsion elements. This vehicle is designated Ares I.

A significant upgrade of ETO spaceflight, over these existing and planned transport alternatives, would appear to be mandatory when looking ahead to the future. Planners must look beyond these NASA-pursued exploration initiative’s specialized systems such as Orion/Ares I, and its follow-on heavy-lift vehicle system (Ares V), both of which may see only limited flight applications. Clearly, a new commercially-fielded airline-type system will be needed for transporting future astronaut and non-astronaut passengers to and from their space destinations.

To this end, NASA recently established an initial commercial orbital transportation services (COTS) program opportunity in support of future International Space Station logistic needs. An office has been set up at the Johnson Space Center to provide successful space transportation contractors of up to $500 million over a four-year period. Contract awards have recently been made to two companies. More generally, NASA Administrator Michael Griffin has envisioned an expanded commercial transportation presence beyond this early ISS service operation: “So, if the plan for stimulating the development of ISS commercial crew rotation capability is successful, it becomes possible to envision the crew launch phase of the lunar mission being carried out on commercial systems. This would be a service we could purchase commercially, leaving only the very heavy lift requirement to the government systems, for which it is less likely that there will be commercial applications during this period.” Thus while the current COTS program and its awards does not provide funding towards the aforementioned Spaceliner-class transports, there is optimism that a similar program opportunity will eventually be made available that will target this much needed future spaceflight system.

II. Establishing a Spaceliner-class Transporter Capability

A. Prospective Spaceliner Design Determinants: Generic Case

1. Characterizing the Spaceliner – In this pursuit, directly addressing the question of what a Spaceliner-class transport “ought to be,” an applicable “sequential line of logic” is next introduced. It is formatted as a 10-point characterization of specific vehicle system design points of first-order importance. These points are to be individually addressed in the overall vehicle system definition process. Adhering to the responses to each of these design points, a generic description of an overall vehicle system that fully embraces the aggregate design solution, then follows. An exemplary reference is then cited that documents two past-published specific vehicle/engine configurations that, in integrating all of these design outputs, appear to fit this generic description.
The author’s subject-related earlier paper presents this suggested 10-point characterization of key design determinants for a prospective Spaceliner system. Taken together, the responses to these points serve to define a next-generation ETO space transport vehicle system that meets the above-discussed overarching requirements of safety, dependability and affordability. A summary of the essence of each of the ten points, as extracted from this source, is given below:

2. Summary of Referenced Spaceliner Design Characterization Points:

   i. Fully-reusable vehicle
   ii. Non-staged system, single-stage-to-orbit (SSTO)
   iii. Beyond-rocket propulsion
   iv. Combined airbreathing/rocket propulsion: combination or combined-cycle system
   v. Airbreathing over a wide speed-range: subsonic, supersonic, hypersonic; hydrogen fuel required
   vi. Rocket final in-space mode: maximum Isp, requiring hydrogen/oxygen propellants
   vii. Rocket capability for in-space maneuvers using main propulsion (as throttled)
   viii. Powered descent and landing requires airbreathing modes; powered approach/landing on gas-turbine and/or fan modes (e.g., go-around, vertical let-down)
   ix. Other vital functions require the same low-speed capabilities: e.g., self-taxi, self-ferry, and routine intact abort operations over the mission profile providing assured safe landings
   x. Extremely close physical and functional integration of engine and vehicle is required – e.g., this truism holds: during hypersonic airbreathing flight the vehicle is the engine

3. Narrative Description Based on the Foregoing Design Selection Steps

   The Spaceliner-class transport will be a fully-reusable, non-staged (SSTO) system powered by “beyond rocket” combined airbreathing/rocket propulsion, configured either as a combination or a combined-cycle system. To achieve suitably high orbital insertion inert mass fractions, hydrogen-fueled airbreathing propulsion must be used over a very wide speed range, up to high hypersonic velocities. The final ascent phase speed increment of about 3.0 km/s (~10,000 ft/sec) is to be performed in the in-space rocket mode, at the highest possible levels of Isp, requiring hydrogen/oxygen propellants. Post-entry powered descent and landing, and other vital atmospheric-flight operations, e.g., self-ferry, intact-aborts, descents and safe landings, will use low fuel-consumption gas-turbine/fan modes. Operations over the full mission profile, from takeoff to landing, demand extremely close physical and functional integration of engine and vehicle -- repeating this point: hypersonically, the vehicle is the engine.

   Note that this remains a generalized (or generic) description. But, as such, it establishes a foundational basis for moving on to the delineation of a set of specific vehicle configurations. Two cases in point are next covered.

B. Two Specific Spaceliner-class System Concepts That Fit this “Generic Description”

   Two specific, previously documented Spaceliner-class vehicle system concepts are to be recognized here. While different designs, each of these seemingly meets the key attributes called out in the above generic description. These two concepts are described in the writer’s paper, “Initial Characterization of Airbreathing-Capable Non-Staged Earth-to-Orbit Transportation Systems” and are further referenced therein.

   1. First Qualifying Concept -- The first of these, treated in the appendix of this referenced paper, is a horizontal takeoff and landing (HTHL) SSTO system using a spatulated-nose lifting-body configuration, one powered by a combination propulsion system. Its propulsion elements are gas turbines, dual-mode ramjets and a tail rocket. This concept was developed and refined by systems analysts and designers of the NASA Langley Research Center over a number of years, with its origins in the agency’s Access to Space study of 1993. A comprehensive system description of the concept is referenced. Its hypersonic airbreathing termination speed is Mach 15.

   Based on the ten-step concept selection process cited above, the following brief system descriptive statement covering this Langley-originated concept is quoted, as follows. The numbers in brackets refer to the individual selection-step sequence covered above (see Section A-2).
The selected fully reusable [1] advanced aerospace transportation vehicle/propulsion system comprises a
class propulsion [4], and specifically a combination propulsion system [4] consisting of separately installed
and operated gas-turbine, dual-mode ramjet/scramjet and linear aerospike tail rocket engines [6,7],
arranged and integrated as separately installed engine modules [8], that power a spatulated-nose lifting-
body vehicle [9], one which takes off and lands horizontally [10].

2. Second Qualifying Concept -- The second specifically described Spaceliner-class system concept to be covered
is a vertical takeoff and landing (VTVL) SSTO system. It is configured with an axisymmetric (conical) body and
powered by a set of ten combined-cycle airbreathing/rocket engines. This concept was developed beginning with
studies going back to the mid-1960s by researchers at The Marquardt Corporation. Since that time, several
government, industry and university study teams have extensively expanded the technical coverage of these
earlier assessments, as reported in concept-summary papers by the author.6,7 Its nominal hypersonic airbreathing
termination speed is Mach 12.

Again, as characterized in the 10-step selection process discussed, this second Spaceliner concept is described as
follows:

The selected fully reusable [1] advanced aerospace transportation vehicle/ propulsion system comprises a
propulsion [4] of the combined-cycle type [5], and specifically, Supercharged Ejector Scramjet (SESJ) [7]
“R+T/BCC” class combined-cycle engines [6], arranged and vehicle-integrated as separate engine modules
[8], that power an axisymmetric (conical) vehicle [9], one which takes off and lands vertically [10].

C. Why the Stipulation of a Hypersonic System?

The title of this paper calls out a “Hypersonic ETO Space Transporter.” While the importance (and the
engineering challenges) of the basic Earth-to-orbit and return mission steps has been pointedly covered in the
preceding text, the stated need for a hypersonic vehicle system may not have been adequately explained to the
reader’s satisfaction at this point in the paper. The following sections are responsive to this possible shortcoming.

1. Revisiting the system characterization guideline points provided (Section A-2) -- With reference to the Third
Point of “the sequential line of logic,” non-staged (SSTO) vehicle systems using all-rocket propulsion (no
airbreathing), are found to be “not generally accepted” because they have “too small a working mass fraction
delivered to orbit.” This is a consequence of the specific impulse limitations inherent with rocket propulsion. It
follows that “beyond-rocket propulsion” is called for, the governing metric being I*, equivalent effective specific
impulse (see Appendix A of this paper for related terminology and definitions). A discussion of the high
significance to the system design, of achieving a high orbital insertion mass fraction, is provided later in the text.

The Fourth Point states that it is necessary to “incorporate airbreathing propulsion” if Ieff (and I*) are to be
substantially increased above attainable rocket levels. Combined airbreathing/rocket propulsion systems are then
uniquely specified since, as noted, an all-airbreathing (no rocket) propulsion system for SSTO service is judged
non-feasible. For, the rocket element is critically needed for that final post-airbreathing push into space and
acceleration to orbital speed. It may also contribute to the lower-speed ascent phase of flight.

Finally, in this revisiting of Point Five, above, it states that “airbreathing operation must be performed over a very
wide speed range – well into the hypersonic speed range (>Mach 5).” It is here concluded: “thus a hypersonic
airbreathing propulsion system capability . . . stands as a firm need.”2

2. Introducing a Key Descriptive Graphic -- In order to assist the reader in grasping the basic rationale of this point-
by-point invocation of hypersonics as a “necessary attribute” of a Spaceliner class ETO transporter, a clear-cut, if
abbreviated “benefits of hypersonics story” needs to be told. This will be attempted using a simplified graphical
portrayal (Figure 1) published earlier.8 This chart shows several SSTO flight systems’ diminishing mass history with
their flight speed to achieve orbit. The following interpretation of this graphic, by intention at least, will be seen to
support each of the three design determination steps called out above (viz., Points 3 – 5).
What is reflected in this figure is the vehicle system mass history for the SSTO mission from launch to orbital insertion in LEO. The instantaneous values of system mass are normalized to the system’s initial mass value, i.e., its takeoff gross weight (TOGW). The “in flight” values are seen to progressively decreases from unity, through a continuum of descending fractional values. This is as the vehicle’s propellant mass is depleted in producing thrust to accelerate and lift the vehicle into space. Several trend lines are exhibited on this figure, each of which will be explained.

First, two main points need to be made: 1) The area of the chart to the right of the Mach 5 vertical reference line represents the hypersonic flight regime, that is, to the extent the ascending vehicle remains within the atmosphere (hypersonics is undefined in space). 2) The slope of the several vehicle trend lines is a direct reflection of the vehicle’s (unit) propellant usage per (unit) flight-speed gain. The steeper the slope, the higher is the speed-related specific propellant consumption. The slope actually denotes the system effective specific impulse, leff. Again, the steeper the slope, the lower the leff value at that point in the ascent flight (see Appendix A for a definition of leff).

3. Interpreting the Vehicle Trend Lines (Figure1)

All-Rocket Vehicle – The lower heavy line represents an all-rocket powered SSTO vehicle system. It has the steepest slope (highest specific propellant consumption) as governed by this system’s relatively low specific impulse (and leff) level across the full speed range. Its consumption rate improves slightly as it departs the atmosphere in the high supersonic speed range (but usually short of hypersonic speeds). This is due to the favorable effect on engine specific impulse of the lowering nozzle atmospheric back-pressure, going eventually to a vacuum level in space (thus maximizing Isp, but as still restrained to limited rocket levels).

As shown by the terminal end of the all-rocket trend line, this system’s inert mass fraction upon reaching orbit, with its usable propellant load now expended, is about 0.1, or some ten-percent of its takeoff mass. Reference can be made again to Point Three, above, judging this to be “too small a working mass fraction delivered to orbit” to support a true Spaceliner-class system design. For instance, it is unlikely that descent-phase airbreathing propulsion can be accommodated in the all-rocket powered system due to related hardware and fuel added-weight prohibitions, those consistent with the small inert mass fraction delivered to orbit.

Combined Airbreathing/Rocket Vehicle – This upper trend line initially has a lower slope than the all-rocket one, denoting the much higher leff levels of the several airbreathing modes conducted in the initial phases of flight. These airbreathing modes lead to a lower specific propellant consumption as reflected in the lower mass depletion-with-speed slope exhibited. But subsequently, at much higher speeds, the vehicle’s operating mode shifts from airbreathing ramjet/scramjet operation to the in-space rocket mode (“airbreathing termination speed”), performed here at Mach 15 flight speed. As the vehicle now begins its pull-up into the space environment, the slope of the trend line steepens, reflecting the accompanying drop in leff. Note that this new slope is about the same as that of the all-rocket system. That is, the two lines now become parallel since the rocket-mode leff levels now attained by both systems are essentially the same.

But, as a consequence of the airbreathing-modes’ lower-slope section depicted earlier along the trend line, the end-point orbital insertion inert mass fraction value is substantially higher than that of the all-rocket system. This fact carries high significance toward the achievement of an acceptable Spaceliner design, as will be discussed. For the combined-propulsion powered vehicle the orbital inert mass fraction is shown to be 0.3. This means that, for the same takeoff mass, the airbreathing-capable system delivers three-times the orbital insertion mass as does the all-rocket system.

This is the case for a Mach 15 airbreathing termination speed, an arguably ambitious (high speed) presumption, one implying effective scramjet-mode operation up to that speed, as yet an unverified experience factor. Generally, it can be seen that the selection of reduced airbreathing termination speeds will have a distinct effect on the end-point delivered inert mass fraction, the lower the termination speed, the lower that mass value.

The effect of terminating the airbreathing mode at as low a speed as the hypersonic-onset speed, Mach 5, and not entering the hypersonic regime in airbreathing operation makes this point. This is represented by the light, supplementary combination-propulsion system vehicle trend line. It terminates with a 0.15 inert mass fraction. This is 50-percent above the all-rocket system value, but only half that of the Mach 15 hypersonic airbreathing termination case.
Another way to look at this intermediatedly positioned, non-hypersonic airbreathing case is that at 0.15, falling between the two reference cases of 0.10 and 0.30, it offers but 25-percent of the beneficial 0.20 mass-fraction difference between these “base cases.” In other words, it gains only a quarter of the potential added inert mass fraction benefit. Important to observe, the remaining three-quarters of the increment gained derives from the “full use” of hypersonic airbreathing propulsion. The message to the system designer is clear: If airbreathing propulsion is to be selected, it should be hypersonically capable, as well as being operable at lower ascent-phase speeds, and to support a power-on descent and landing phase of flight, in addition.

D. Significance of a High Orbital Inert Mass Fraction

1. Basic Rationale and Mass Fraction Elements -- What, then, is the telling benefit of achieving a high vehicle orbital insertion inert mass fraction? The overall vehicle mass arriving at its orbital destination is made up of a number of residual elements of the original vehicle mass at launch. This includes the vehicle physical hardware, some propellants and the payload to be delivered. Considering each of these classes separately leads to insights as to the important gains made available as this on-orbit mass fraction is increased. As will be seen, this is the key payoff of going to hypersonic-airbreathing flight.

Propellants – At orbital insertion, with the main mission propellants consumed, there will be a combination of propellant residuals from the ascent propulsion phase, plus post-insertion-maneuvering propellants, and, finally, reserves, providing an operational margin of safety. The residuals may result from propellants trapped in various feed lines and manifolds, and in-tank propellants not fed to the engines upon ascent. Means of collecting some of these residuals and repositioning them for later active use would likely be worth pursuing. Looking ahead, additional propellants will be required for the vehicle’s on orbit attitude-control reaction control system (RCS) operation, for general maneuvering during the payload delivery and/or pickup operation, and for the orbit-departure retro-thrust function. RCS operation is also typically used in the early entry phase and – in true Spaceliner cases – significant quantities of fuel will be needed for conducting the airbreathing-powered flyback, final approach and landing phases, for routinely and safely concluding the mission.

Vehicle Physical Hardware – The payload-transporting vehicle itself is obviously the dominant portion of the inert mass fraction aggregate arriving on orbit, with its contained payload and residual and remaining mission propellants, and reserves. This comprises the vehicle’s propellant containers and basic structure, with its thermal protection system (TPS), and all of its various functional subsystems, including payload accommodations and propulsion. An important distinction in the physical hardware mass accounting is made between all-rocket, and combined airbreathing/rocket powered vehicle systems. As graphically demonstrated earlier (with Figure 1), the former yields the smallest orbital mass fraction, and the latter the largest. A factor of three difference between the two cases has been expressed in the examples illustrated in Figure 1.

But, matching this pattern, the all-rocket case actually requires the least inert mass for its propulsion and thermal protection system. This is because rocket engines are relatively lightweight; their thrust/weight ratios are typically five-to-seven times that of leading combined-cycle engines, for instance. Further their TPS is designed just for reentry, and not the more stringent ascent aeroheating conditions experienced by airbreathing systems. This signifies a lower TPS weight than that required for hypersonic airbreathing capable systems. As suggested, the latter systems’ TPS design is sized on the basis of the increased thermal severity experienced during their extended atmospheric ascent flight, particularly so in the hypersonic speed regime.

Payload – Payload mass delivered to the orbital destination, along with any on-orbit mass to be returned to Earth, constitutes the fundamental system’s “mission metric,” one that characterizes the overall transportation function being performed. Generally, the upper limit of payload mass is as stipulated for the particular manifest being served. However, an opportunity to increase payload capacity would be welcomed to enhance future flight operations.

2. With the Hypersonic Airbreathing System, Mass to Spare -- Nonetheless, when the combined airbreathing/rocket powered vehicle’s heavier engines and TPS are assessed in the light of available system studies and the remaining vehicle structures, subsystem and propellant weights are fully tallied, the “factor of three” gain in orbital mass fraction is found to readily accommodate these increased propulsion and TPS weights (over the all-rocket case). This results in having a discretionary mass surplus. Initially, this constitutes a still unassigned, to-be-distributed mass resource to be
judiciously allocated by the designer. This mass surfeit can, in principle, be advantageously assigned to any number of
vehicle elements as suggested above: 1) to structures by way of local reinforcements and increased safety margins; 2) to
subsystems in increasing their number, and/or doubling up to provide redundancy, thereby increasing reliability; 3) to
add to propellants resources, e.g., increased descent-phase fuel and reserves, 4) to installing needed mission-abort
success-assurance measures, and, possibly, crew-escape means, and finally, 5) for increasing payload capacities (with
any remaining allocatable mass increment).

E.  Key Findings: Orbital Mass Fraction Comparisons Leading to the Hypersonics Payoff

1. Orbital Mass Fraction Comparisons
   1. The hypersonic-airbreathing capable combined-propulsion powered SSTO system delivers a ~0.30 orbital
      inert mass fraction (normalized to takeoff mass).
   2. The all-rocket SSTO delivers a ~0.10 mass fraction, one third of the above case.
   3. The non-hypersonic-airbreathing capable SSTO delivers a ~0.15 mass fraction (50% above the all-rocket
      case, but only 25% of the ~0.20 hypersonic/all-rocket increment.
   4. While the ~3:1 gain of the hypersonic system, over the all-rocket case, more than covers its heavier engines and
      TPS, this coverage may be questionable in the case of the ~1.5 increment of the non-hypersonic airbreather, i.e.,
      the choice between the two airbreathing systems is clearly in favor of the fully hypersonic system.
   5. For the hypersonic-airbreathing system, the orbital fraction “extra mass” (with its heavier propulsion and TPS
      being previously accommodated) can be advantageously applied to a number of areas, singly or in
      combination:
      a. Structural reinforcements, increased safety factors
      b. Increasing numbers of subsystems (added services), or installed subsystem redundancies for
         reliability enhancements
      c. Added propellants, e.g., descent-phase fuel and reserves
      d. Augmenting crew escape means, if used, or mechanizing assured broader-ranging mission-abort
         capabilities
      e. Increasing payload capacities.

2. Attainment of an Aircraft-Like Space Transporter: Payoff of a Hypersonic Design
   The high-speed airbreathing/rocket powered non-staged vehicle types described earlier, both yield the largest orbital
   mass fraction available, while readily including airbreathing power-on descent and landing capabilities. The former
   gain provides a discretionary-mass addition benefit that enables significant design upgrades; the latter ensures safe
   vehicle and payload recoveries, during routine flight operations, as well as during emergency conditions. These gains
   are distinctly in the direction of attaining an aircraft-like orbital transport system.

III. SUMMARY OF KEY POINTS
   The initiating and concluding steps of all human space-access journeys will continue to be the energetic ascent flight
   from the Earth to low Earth orbit, and – following the wide range of mission operations to be pursued – the return
   flight home to a safe landing. The salient question posed is: what human-qualified vehicle(s) are to perform these vital
   transportation services? Order-of-magnitude advances in flight safety, operational dependability and overall
   affordability, over existing transport systems, will almost certainly be demanded by the future commercial and military
   spaceflight-service using communities.

   This paper has responsively argued for a true “Spaceliner Class” vehicle system to fill this role, named here as “The
   Hypersonic ETO Transporter.” Such a system has been defined using a set of stated design determinants for
   conducting a progressive, step-by-step system definition process. A generalized (or generic) system description first
   resulted. Then, two previously documented vehicle system examples that generally fulfill this description were
   identified, and found to be consistent with this generic description. Notably, both of these systems engaged extensively
   in hypersonic airbreathing flight – to airbreathing-termination speeds of Mach 12 to 15.

   Special explanatory emphasis was given to the hypersonic stipulation for these selected systems. This discussion
   focused on the decisive payoffs of achieving a high value of orbital insertion mass fraction (of takeoff mass). This
   achievement, leading to true “aircraft like” qualities in space transport system, is uniquely the decisive consequence of
performing extended hypersonic airbreathing flight. This propulsion approach is innately consistent with like-contributing subsonic and supersonic ascent-phase airbreathing operation, as well as being compatible with fuel-thrifty airbreathing power-on descent and landing operations. These combined design contributions, as potentially ensconced in future Spaceliners, should well serve tomorrow’s human spaceflight transportation needs.

IV. CONCLUSION

True Spaceliner-class ETO transporters will be powered by combined airbreathing/rocket propulsion systems capable of extensive ascent-phase hypersonic airbreathing operation, e.g., to Mach 12 to 15 flight speeds.

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References


Appendix A.

Definitions of Effective Specific Impulse, $I_{eff}$, and Equivalent Effective Specific Impulse, $I^*$

**Effective Specific Impulse, $I_{eff}$**

$$I_{eff} = I_{sp} \left[ 1 - \frac{W \sin \Theta}{T} - \frac{D}{T} \right]$$

[Effective Specific Impulse, $I_{eff}$] Applicable to *accelerating* systems, $I_{eff}$ is the instantaneous vehicle systems-level measure of specific propellant consumption based on the net accelerative force being applied to the vehicle. The vehicle’s weight and drag forces are subtracted from its propulsion-system developed thrust, all co-linear with its velocity vector, to yield this net force.

[Specific Impulse, $I_{sp}$] Commonly used propulsion subsystem-level measure of specific propellant consumption based on engine-developed thrust divided through by the relevant propellant consumption rate. Applicable directly to non-accelerating atmospheric flight (cruise conditions). For accelerating systems operating in drag-free space with near-horizontal flight paths, such as the final phases of an ascent to low orbit, $I_{sp}$ closely approximates $I_{eff}$. But for systems accelerating and climbing through the atmosphere, $I_{eff}$, having a significantly lower numerical value than $I_{sp}$, is the governing performance parameter.

[Weight, $W$] The instantaneous vehicle system weight component aligned with the vehicle velocity vector.

[Flight-path Angle, $\Theta$] The angle of the vehicle velocity vector expressed in degrees measured with respect to the local horizontal.

[Drag, $D$] The opposing aerodynamic forces acting on the vehicle that are aligned with the velocity vector.

[Thrust, $T$] The instantaneous level of vehicle propulsive thrust applied co-linearly with the vehicle velocity vector.

**Equivalent Effective Specific Impulse, $I^*$**

$$\Delta V_f = g I^* \ln \frac{M_0}{M_1} \quad I^* = \frac{\Delta V_f}{\int \frac{dv}{I_{eff}}}$$

[Equivalent Effective Specific Impulse, $I^*$] The single-value parameter relating to $I_{eff}$ that, when inserted into the ideal rocket equation, yields the actual flight velocity, rather than the numerically larger “ideal” velocity, which includes so-called drag and gravity velocity losses. Numerically, $I^*$ equals the flight-speed increment (delta-v) of interest divided by the integral of the inverse of $I_{eff}$, with respect to flight velocity. Graphically represented, this quantity ($I^*$) is inversely related to the area under the curve plotted of $1/I_{eff}$ vs. flight velocity.

[Incremental Flight Velocity, $\Delta V_f$] Vehicle final velocity less its initial velocity; characteristic mission “Delta-V.”

[Gravitational constant, $g$] Standard conversion constant with a numerical value of 32.2.

[Vehicle system mass, $M_0$ and $M_1$] The initial and final mass of the vehicle, respectively, following the completion of the acceleration phase of the mission in question.