AN OPERATIONAL ASSESSMENT
OF
CONCEPTS AND TECHNOLOGIES
FOR
HIGHLY REUSABLE SPACE TRANSPORTATION

EXECUTIVE SUMMARY

Highly Reusable Space Transportation Study
Integration Task Force, Operations

National Aeronautics and Space Administration
Johnson Space Center
Kennedy Space Center
Langley Research Center
Marshall Space Flight Center
Stennis Space Center

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HRST INTEGRATION TASK FORCE OPERATIONS EXECUTIVE SUMMARY REPORT

BACKGROUND

From 1995 through 1997, NASA undertook a study effort to identify future space transportation concepts having significant potential for reducing the cost of access to space. The goal was to define strategies to achieve launch costs cheaper than current systems through addressing the generation of space launch systems after the Reusable Launch Vehicle (RLV.) Teams from Government, academia and industry developed a number of space transportation vehicle concepts intended to drive recurring operations costs $200 or less per pound of payload delivered to low earth orbit (LEO.) An over view of the study results appeared in the March 1998 issue of *Aerospace America* in an article “Lower Costs for Highly Reusable Space Vehicles”, by John C. Mankins, NASA Headquarters.

Five strategic lines of investigation were followed: Combination propulsion systems (CPS); combined cycle propulsion (CCP); Launch assist (use of off-board energy); Revolutionary (on-board) propulsion systems; and highly evolved expendable vehicles (HEELV’s). The various teams also investigated the cross cutting topics of operations, manufacturing, and thrust augmentation and upper stages as applied to the goal of reducing launch costs.

In 1997 at the completion of concept development activities four separate NASA-led Task forces were formed to integrate the results of the study: System Concept Definition, Operations Assessment, Cost Assessment and Technology Assessment. Nine concepts were selected based on (1) which concepts were most likely to have sufficiently detailed data available to support the integration work and (2) which concepts were representative of vehicle “families”, defined as follows:

- All-rocket types (Two Stage to Orbit (TSTO) and highly advanced Single Stage to Orbit (SSTO)).
- Combination Propulsion (Mach 6 and Mach 10) types.
- Combined Cycle Propulsion (Mach 6, Mach 12 and Mach 15) types.

CONCEPTS SELECTED FOR ASSESSMENT

The concepts selected are listed below. For convenience, the concepts will be generally referred to by the common name as indicated **in bold**.

1. Vertical Take-off, Vertical Landing (VTVL) Supercharged Ejector Scramjet (SESJ) Single-Stage-to-Orbit (SSTO).
   - Developer: Kaiser Marquardt (with Georgia Tech.), **Kaiser Marquardt** or **KM**

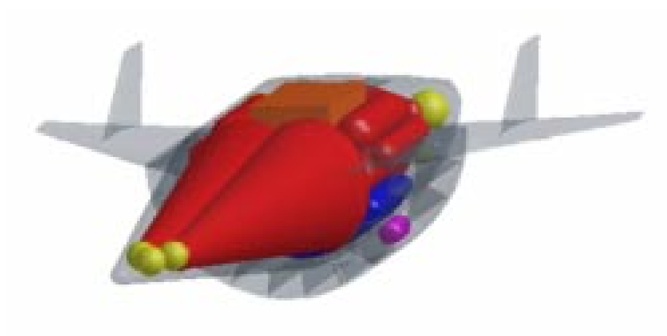
2. Horizontal Take-off, Horizontal Landing (HTHL) Supercharged Ejector Ramjet (SERJ) Non-waverider Type Single-Stage with Launch Assist.
   - Developer: Georgia Tech Aerospace Engineering, **Argus**

3. Horizontal Take-off, Horizontal Landing (HTHL) Rocket Based Combined Cycle (RBCC) Waverider Type Single-Stage with Launch Assist.
   - Developer: Boeing North American (BNA), **Waverider**

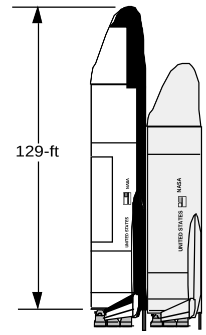
4. Rocket, Baseline Comparative System Update, Using Advanced Chemical Rocket Engine (T/W engine = 92).
   - Developer: Boeing North American (BNA) – Rocketdyne, **ACRE 92**

5. Rocket, Baseline Comparative System Update, using Advanced Chemical Rocket Engine & New Materials (T/W engine = 183).
   - Developer: Boeing North American – Rocketdyne, **ACRE 183**

6. Horizontal Take-off, Horizontal Landing (HTHL) Ejector Scramjet (ESJ) Single-Stage-to-Orbit (SSTO).
   - Developer: Georgia Tech Aerospace Engineering, **Hyperion**



7. Two-Stage to Orbit (TSTO), Vertical Take-off, Horizontal Landing (VTHL) All Rocket (Reusable Booster & Orbiter).
   - Developer: Langley Research Center, Vehicle Analysis Branch, **TSTO**



8. Horizontal Take-off, Horizontal Landing (HTHL) Single Stage-to-Orbit Liquid Air Collection and Enrichment "LACE" Ejector Ramjet/Scramjet
   - Developer: Langley Research Center SSTO,
   - Vehicle Analysis Branch, **LACE**

9. Horizontal Take-off, Horizontal Landing (HTHL) Single Stage-to-Orbit All Rocket with Launch Assist
   - Developer: Space America, Inc. , **SSTO(R) LA**
   - This concept was introduced late in the integration activity and was evaluated only with COMET/OCM and PrOpHET.

These concepts (except for SSTO(R) LA) are described in detail in Appendix B of the HRST Assessment Team Report (Ops Report.)

OBJECTIVES, ISSUES AND APPROACH

The specific objectives of the Operations Assessment Task Force (Ops Team) as tasked by the HRST Study Manager were:

- Define and conduct assessments of operations scenarios and sensitivities required for various HRST concepts.
- Use analysis tools to conduct actual simulations of operations scenarios, including relative operations costs.

In general, the goal of the operations assessment was to determine if there were space transportation vehicle concepts and technologies which had the potential to reduce total recurring operations cost to $100-$200 per pound payload to low Earth orbit (LEO: 100 nautical miles circular orbit at 28.5 degrees inclination.) For the purposes of this assessment, recurring operations costs were defined as all recurring costs except those not technical in nature e.g., cost of financing, etc.

The following issues in assessing the concepts were recognized and considered by the Ops Team:

- There was little detailed data on the concepts at this stage of concept exploration in the area of operations.
- The level of detail in information about concepts varied widely across the concepts. In general all-rocket concepts with relatively little technological advancement in development and operations had more detail and less uncertainty than air-breather concepts with considerable technology development required and practically no operations experience. This disparity gave rise to the formidable problem of avoiding "penalizing" concepts in the assessment because there was much data, some of which might indicate low probability of achieving the HRST study goals or because there was too little data available to support the tools or techniques used in the assessment
- Some of the data was considered proprietary by the developers.
- There are few operational analysis tools suitable for this early phase in concept exploration, especially in view of the level of detail and confidence in the data available.

OPERATIONS INTEGRATION ANALYSIS TOOLS

Six operations analysis tools/techniques were used in assessing the potential of the nine concepts to achieve low cost operations. This varied approach was selected for the following reasons:

- To take maximum advantage of the wide range of skill and experience available in the Ops Team.
- To overcome the variance in the level of detail in concept data described above.

- To cope with the degree of uncertainty inherent in data at this stage of concept development. This aspect is discussed in more detail in the full report.
- By approaching the operations analysis in these different ways, it was anticipated that the concepts most appropriate for further study would manifest themselves through convergence in the five methods.

The operations assessments were conducted using constraints and requirements defined in “Highly Reusable Space Transportation, an Advanced Concepts Study Project Study Guidelines” (September 5, 1995). Those pertinent to operations are included as Appendix A of the Ops Report.

These six operations analysis tools/techniques are introduced here and described in detail in Appendices C through H of the report.

1) Edgar Zapata, KSC, performed a qualitative relative assessment of the HRST concepts based on a volume published by the Space Propulsion Synergy Team (SPST), “A Guide for the Design of Highly Reusable Space Transportation”, in support of the HRST study Edgar Zapata, KSC (For a full description see Appendix C)

2) OSAMS is a systems analysis tool intended to allow program managers and developers to quickly assess the most effective areas to invest scarce resources and evaluate the potential impacts of these investments on the "life-cycle" and per mission cost of the system. An additional model was used in conjunction with OSAMS: The Operations Cost Model (OCM a top level tool for modeling launch and flight operations costs for space transportation systems. (For a full description see Appendix D)

3) Carey McCleskey and Russel Rhodes of KSC developed the “Architectural Assessment Tool” (AAT) a means for scoring and ranking concepts for operational effectiveness as well as assessing the programmatic factors involved with research & technology and commercial acquisition. (For a full description see Appendix E).

4) A maintenance operations analysis tool developed by Doug Morris and Nancy White, LaRC, the Reliability Maintainability Analysis Tool (RMAT), defines Reliability and Maintainability (R&M) characterization of new launch vehicles in the early pre-concept and concept exploration phases. (For a full description see Appendix F.)

5) Richard Brown, MSFC, utilized a hierarchical analysis method, developed by Dr. Thomas L. Saaty, based on pair-wise comparisons of alternatives relative to the criteria that measure success program. (For a full description see Appendix G)

6) An Excel spreadsheet model, the Parametric Operations & Maintenance Hours Estimating Tool (PrOpHET) was developed by John Mankins, HQ and Mike Nix, MSFC, to estimate the Operations and Maintenance (O&M) burden. This burden, expressed as hours of O&M required per pound of subsystem dry mass per flight, could be based on dry weight of subsystems. (For a full description see Appendix H)

DISCUSSION

RBCC and All-Rocket Concepts

RBCC propulsion offers significant <u>near term potential</u> toward achieving HRST objectives of cheap access to space at $100 to $200/lb. of payload. The RBCC concepts, with margin gains considered to have a distinct tie in to potential operability gains, have a notably higher benefit over all-rocket concepts. However, this potential occurs only for concepts that are more focused on operations as a driver.

Margin

Margin that does not translate into operability does not offer significant improvement over current systems regarding lower cost operations. Margin as evidenced by required mass fractions two or three times lower (better) than a rocket single-stage-to-orbit may be considered relevant only if translated into operability *and* payload with operability as more crucial. The potential of airbreathers is not likely to be demonstrated immediately in any attempt to gain significant payload combined with test and demonstration. It is more likely that as the technology evolves, if properly focused on recurring costs, capabilities beyond rocket reusable launch vehicles will be achieved in payload cost per pound and payload per year in the long term due to recurring cost improvements.

Flight Rate Capability

Actual flight rate capability for any of the concepts considered is a crucial determinant in overall affordability. It is believed basic concept decisions deterministically constrain flight rate capability and associated infrastructure. This determines productivity. Predicting what this capability is, based on conceptual information has multiple uncertainties. The capability is mostly determined by these up front design decisions, but not necessarily known (and may be unknowable until deployment.) However, methods used in this assessment attempted to determine the actual likelihood for a concept of avoiding the Shuttle scenario, a low single vehicle capability with high infrastructure requirements per vehicle. The Architectural Assessment Tool and the design criteria assessment used inherent design features *unrelated* to weight to assess probable productive capability such as flight rate at a given manpower and operating cost. It is stressed here that this actual flight rate can make or break the ability of a concept to even approximate HRST goals. For this reason further definition on the few concepts considered most likely to achieve HRST goals is required to fully develop any research and technology portfolio**. Many of the concepts can be discarded immediately as having flaws not likely to allow attainment of HRST goals.** Certainty on the remaining concepts requires further iteration.

Reliability

Reliability is a major factor in the ability of concepts to achieve HRST goals. Technology maturity to a level that is similar to commercial off the shelf items such as in aircraft can only come about with large production capabilities. R&T that neglects proper feed through of requirements into the design, test and certification processes, such as when driven solely by up-front cost and schedule, is essentially creating downstream costs in operations which seriously jeopardize attainment of HRST goals. Furthermore, approaches in development such as emphasis on sub-system levels when actual problem causes are at higher system levels can negatively affect technology maturity.

Launch Assist

The recurring cost impacts of launch assist require further understanding and quantification. The concept ranked with the most benefit (benefit criteria relate to the issues of recurring cost, the operation of the system, it's dependability, environmental compatibility, public support, responsiveness and safety) is the Horizontal-take-off-horizontal-landing (HTHL) single-stage Supercharged Ejector Ramjet (SERJ) with launch assist (Argus). This estimate is more uncertain given the lack of an operational database or group of expertise related to magnetic-levitation launch assist systems; this uncertainty is in addition to and larger than uncertainties in RBCC propulsion. Studies on similar systems can assist in definition at the component level of similarity. Existing and planned magnetic passenger rail systems are not applicable in the following areas of experience:

1) cryogenic fluid interfaces to or through a sled (versus just electrical power distribution)
2) dynamics of separation (versus transient fixed systems)
3) speeds at the high end for these concepts
4) load distributions
5) complexities of the sled itself (pitch up actuators, interfaces, fluid, electrical and structural)

Complexities in launch assist are more similar to those in staged space transportation systems.

Launch assist where used to simplify a system, especially the vehicle, meant greater benefit moving toward HRST goals. Where launch assist was used to reduce mass fraction or in combination with more systems, it resulted in little benefit over rocket systems. Of the two concepts incorporating launch assist, Argus ranked significantly better than Waverider on benefit and slightly better on R&D programmatics.

Design Optimization

Optimizing launch vehicle concepts at the system level rather than optimizing components is more likely to result in recurring costs in the range of HRST goals. There are technologies that reduce the operations and maintenance (O&M) burden that are common to both all-rocket and airbreather type concepts. For the HRST concepts examined in detail using RMAT (Figure 4), the major driver of maintenance burden was the TPS system, representing from 55 to 83 percent of the total burden. Structures, Main

Engines, and MPS are generally the next major contributors, the order depending on the concept. The potentially large recurring economic impact of closed compartments on cryogenic vehicles should not be underestimated. Future system features such as purged aeroshells, TPS purges, multiple separate tanks in order to conform to certain moldline approaches, and multiple engine modules should not be underestimated in the degree to which the resulting required infrastructure can be non-responsive to lower operations cost goals. Numbers of interfaces, numbers of active systems required to operate safely, numbers of strict requirements on flow rates and temperatures, numbers of detection systems and measurements, and numbers of failure modes or opportunities for failure are all negatively affected by these types of approaches.

Technologies

The following technology areas were identified by the operations team as having higher priority for development because they offer the potential for most significant reductions in the O&M burden, both taken individually and in combination at the systems level. In order of most significant impact on operations:

> **Packaging and Integration:** The concepts reviewed, although integrating the rocket and airbreather in RBCC type concepts, did not integrate the secondary and main propulsion systems. Rocket systems with orbital maneuvering, reaction control and main propulsion systems are highly non-integrated. Future developments must more readily address propulsion technology integration that reduces interfaces, separate tanks, etc.
>
> **TPS development without aeroshells & purges**: Development of passive, robust, zero-coating, zero-waterproof, zero-purge TPS is a top priority for reducing recurring costs.
>
> **Number of Engines**: Engine count is a key, simple measure of potential benefit. Development focus should be on fewer engines: Objectives should be between 2 and 4 main engines or engine modules. Fewer engines relates to multiple measures of benefit such as reducing confined spaces, which inherently require purges, servicing and interfaces to the ground as well as additional complex systems for leak detection and isolation. Engine count also relates to key issues of additional flight and ground interfaces, fluid and electrical, basic issues of reliability and dependability (more parts, more opportunities for failure, more maintenance), active systems, and flight and ground functional complexity.
>
> **Reliability & Dependability**: Hardware and system reliability and dependability are keys to low cost operations. In order for a space transportation system to meet the HRST goals of hundreds rather than thousands of dollars per pound, very high degrees of dependability must be achieved. Hardware replacement costs must be a small fraction of a percent per flight, keeping the vehicle out of the hangar, increasing its commercial utilization, i.e., flight rate, which is an absolutely critical parameter for commercially viable space transportation.

Commercial-Off-The-Shelf (COTS): A key to reducing recurring costs is maximum use of COTS products. Many subsystems currently used in space transportation systems will require intensive research and development and DDT&E programs in order for the majority of components and software to become commercially available. Yet this is a must for attaining the order-of-magnitude operations cost reduction. (For a detailed discussion, see Appendix E.)

Vehicle Health Monitoring (VHM): Also required to enable achievement of lower operations costs is the continued development of VHM technologies. Critical in this area is the non-intrusive detection of fluid leakage and other techniques to overcome the tremendous amount of unplanned maintenance that occurs between flights of functionally complex vehicles, such as a reusable launch vehicle-particularly a highly reusable launch vehicle.

Horizontal vs. Vertical take-off: The benefit of reduced infrastructure for vertical landing may represent a far term capability that is desirable for operating within infrastructure or location constraints. Aircraft, for example, have evolved both large passenger jets as well as urban centered helicopter services. For the near term, however, the ability to simplify space transportation as far as relates to engine count will be assisted uniquely by horizontal take-off. Assuming engine out requirements, the horizontal take-off/landing uniquely allows both low engine count as well as ease of recovery and return to the spaceport. This is an area in which little or no improvements can be made with all rocket systems, high engine counts being required for engine out capabilities. Further, horizontal take-off rockets, especially single stages, are practically constrained leaving vertical take-off options as most viable, which again entails high engine counts.

Environmentally benign technologies: Ground-rules for future system development should include no hypergols (propulsion or power) and avoid multiple toxic freons and ammonia. These relate directly to high operating costs, hazards, and complex servicing and turnaround requirements as evidenced with Shuttle experience.

Avoidance of slush hydrogen: Slush hydrogen introduces unfavorable programmatic (non-recurring cost) impacts as well as unfavorable benefit (recurring cost) impacts. Use of slush hydrogen is not conducive to the use of facilities and infrastructure that are simple and responsive to high flight rates.

Hydrogen as common fuel: Advances in non-rocket areas may benefit the ability to use hydrogen as a common fuel in systems such as the Hyperion HTHL SSTO turbofans (used for loiter and self ferry). This would eliminate separate JP fuel, possibly simplifying servicing, basic design and operation. This represents an avenue of future study to determine synergy potential with other work in Hydrogen energy applications.

Complexity

Additions of complexity must be further quantified as to benefits. The addition of systems such as fans, liquid air collection and enrichment (LACE), slush hydrogen and launch assist did not always mean greater recurring benefit in the Ops Team analyses. Neither did additions of complexity, adding capabilities such as loiter, thus eliminating a dead-stick glide-in landing, necessarily result in less recurring benefit As an example of this, Argus uses a fan / supercharging approach. The benefits to be accrued from these additions were highly dependent on overall system configurations, how they are integrated into the whole concept and against what they trade. It is highly possible to have increasing complexity coupled with increasing economic viability as witnessed in today's aircraft and airport infrastructures many orders of magnitude more complex than early aircraft in the pre-DC-3 era. That there is also a threshold at which increasing complexity ceases to provide commercially effective benefit is clear from the example of the Concorde airliner. Heretofore space transportation systems, having to operate at the edge of performance by their very nature, had to be very complex without commensurate operational effectiveness. The concept that integrates increasing complexity toward low cost operations is crucial to basic airbreather economic viability.

RESULTS

Room for improvement exists. The Ops Team developed a conceptual vehicle that embodies the systems optimization approach for operational effectiveness. An ideal spaceliner, Horizon Mission, described in Appendix C of the Ops Report, and appearing on some of the Figures below, is an even more dramatic improvement over the systems conceptualized for this study. Iteration toward this vehicle is possible with existing concepts.

Figure 1 shows how the concepts were ranked in order of preference by each analytical approach. As discussed above, the approaches were deliberately varied in measures of merit and procedure to compensate for the uncertainty inherent in operations data in this early phase of concept exploration. There was general agreement in the results. Argus, an SSTO HTHL RBCC vehicle with Launch Assist, appears eight times in the top three ranks, six times as the top ranked concept. The all-rocket SSTO HTHL ACRE 183 appears five times. While Hyperion (HTHL SSTO RBCC) appears four times, this overall rating was discounted because of the low payload capability (20K). Kaiser Marquardt's VTVL SSTO RBCC appears 3 times while the HTHL RBCC SSTO Waverider, also with Launch Assist appears twice. ACRE 92 and the TSTO VTHL all-rocket appear once each. From these rankings, it seems clear that RBCC type vehicles can offer operational advantages. That not all do may be traced to additional system complexity that does not increase operability proportionally. Rockets with advanced materials (lightweight, low maintenance) have some potential of achieving HRST low operations cost goals. Launch assist does not appear to confer a particularly decisive advantage, as witnessed by the difference between Argus and Waverider rankings.

Figure 1: Number of Times Concepts Were Ranked Among Top 3 by the Analytical Measures)

Concept Name	Number of Times Ranked in Top 3 by Analysis
Argus	8
ACRE 183	5
Hyperion	4
KM	3
Waverider	2
ACRE 92	1
TSTO	1
ANSER	0
LACE	0
SSTO(R) LA	0

Figure 2 (below) is derived from the AAT assessment and indicates that RBCC type vehicles (in general, but not all) offer greater operational effectiveness than all-rocket concepts. Note that ACRE 183 competes well with RBCC's in this analysis. The horizontal scale of Commercial Acquisition places the concepts in terms of relative commercial viability. The figure further indicates that operational effectiveness can be increased for all concepts by applying Design Principles from the "Guide and Rules of Thumb (for applying margin to enhance operability) developed by the Ops Team.

Figure 2:Operational Effectiveness vs. Non-Recurring Investment Commitment (from AAT)

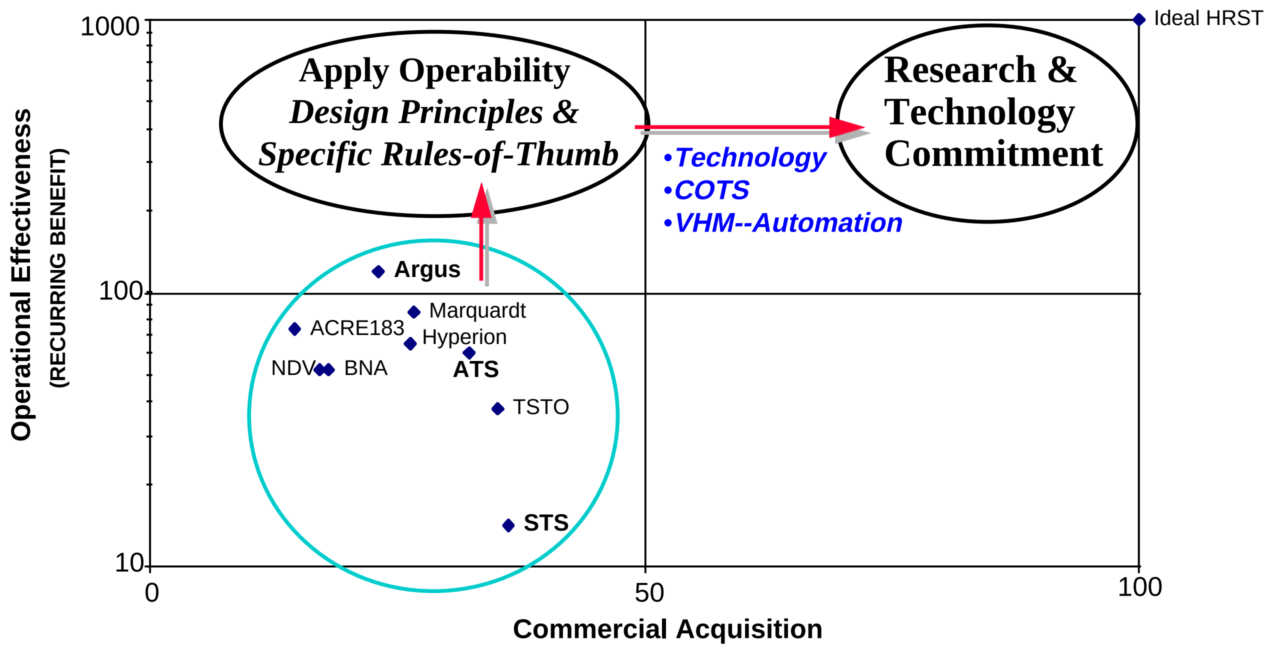


Figure 3 indicates the AAT scores for the concepts (relative ranking) as well as the potential flight rates (per year per vehicle) enabled by the concept architectures. Figure 4 also indicates the relative number of O&M hours per flight per lb. of dry mass, which were used in the PrOpHET analysis.

Figure 3: Single Vehicle Utilization Assessment (from AAT)

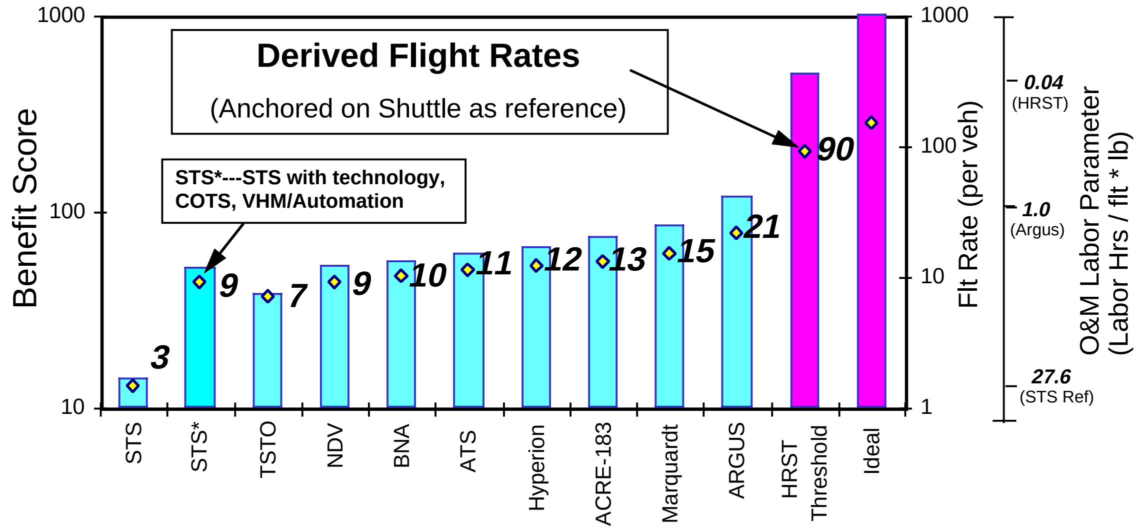
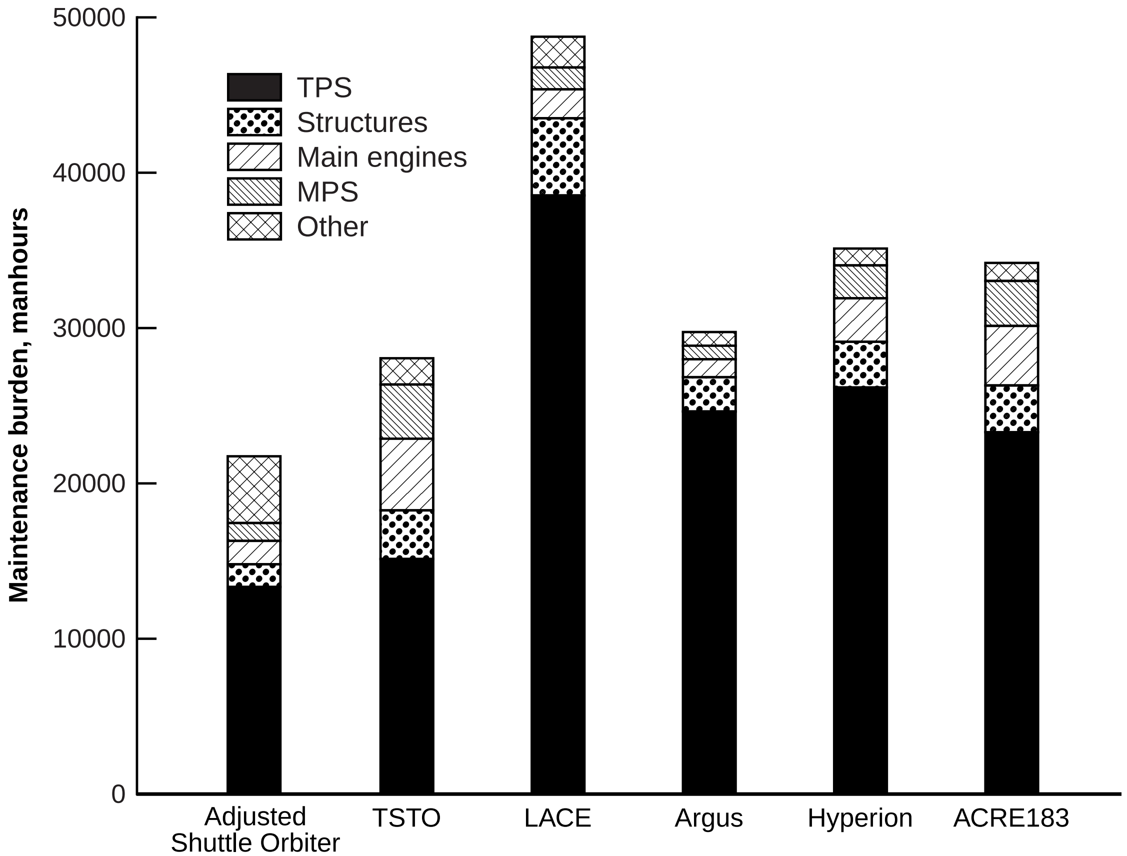


Figure 4: Maintenance Burden (Work hours) by Subsystem (from RMAT)



Although these reductions in Shuttle support requirements may appear large, they may not be that difficult to achieve. Current Shuttle support represents support for systems that lack maturity, at least relative to aircraft systems. Therefore the maintenance required, both in frequency and in repair time reflect the relative lack of experience in dealing with these technologies in this environment. As this prudent approach matures, experience will contribute to these required reductions by better being able to judge when maintenance is required and by increased confidence in the repair process. New technologies such as the use of vehicle health monitoring will help to reduce the time required to detect and isolate problems before repair. Also, all new technologies will have an extensive test program to assure that these R&M characteristics are achievable, before inclusions on the concept.

The differences in results illustrated here are due only to the size, number of systems, and system requirements. Differences in specific technology choices are not reflected in these results, however, the R&M characteristics defined apply to all the HRST concepts. All will require system technologies that have been developed, tested and proven to have support requirements orders of magnitude less than that currently in use. This will both reduce the personnel involved and shorten the time required for maintenance so as to better utilize the vehicles in productive service

Of interest here is not only how the concepts ranked relative to one another, but which subsystems were the drivers - TPS and main engines, which result was incorporated into the OCM/COMET and PrOpHET models. Here LACE fares poorly by comparison due to the extensive cooling requirements, through both active and passive subsystems requiring high maintenance. In this approach TSTO competed well with the other concepts, due at least in part to the relative simplicity of both the first stage and the orbiter. RMAT did not consider processing requirements outside of the VPF, such as the integration of the stages. Argus and ACRE 183 were very close, with ACRE 183 losing the advantage due to main engine and MPS maintenance burdens (six engines on the first stage and three on the second.)

RECOMMENDATIONS

The HRST Integration Task Force, Operations, believes that the following recommendations will enable continued advancement toward the goals of the HRST study, routine and highly affordable access to space.

RECOMMENDATION 1. Architectural, global optimization of designs is required to achieve HRST goals. Optimization at component or sub-system levels must be only one part of a broader improvement strategy focused on affordable architectures. Large-scale optimizations that rethink major design decisions must be improved upon across the board to achieve HRST goals.

The Ops Team developed a set of "Architectural Guidelines" which expand on the need to optimize designs and technology around broad, global features. The Guidelines are derived from the work of the Space Propulsion Synergy Team (SPST), a multi-industry-NASA-academia and government-entrepreneur group. This work by the SPST was in support of the HRST project. These Guidelines are outlined ahead in the section "Architectural Guidelines." Further, the Team developed more specific recommendations, or "Rules of Thumb", for applying system margin (See Guideline 1.2,"Fielded Margin") to vehicle design for the purpose of enhancing operability. This particular objective, margin - the ability to field a system that is not operating near the edge of it's design limit, can be one enabling factor for the incorporation of multiple other features which make a space transportation system more affordable to acquire and to operate. The improvement, or not, in all of these major areas outlined below is crucial to achieving a total system, flight and ground, capable of one day meeting HRST costs goals. These specific recommendations are listed ahead in the section "Rules of Thumb."

RECOMMENDATION 2. Demonstrators are required that prove the proper flight regime and the more complex systems that may associate with rocket based combined cycle (RBCC) concepts.

Anchoring the benefits of airbreather propulsion through demonstration will allow quantified understanding of the proximity to achieving the HRST operational objectives. Basic R&D, component, system and integrated testing focused on advanced propulsion development is required to sidestep inherent all rocket limitations.

RECOMMENDATION 3. Margin Benefits: Future concept definition for airbreather space transportation systems must provide links to margin benefits.

Realistic estimates are required of resulting margins from airbreather approaches correctly accounting for additional systems unique to airbreathers such as active cooling, active geometries and associated actuation mechanisms, fans, etc. The effect of this margin on other systems such as TPS, structures, power, and flight and ground subsystems must be further understood (Ref. Recommendation 2).

RECOMMENDATION 4. Two major systems areas require technology development, propulsion and thermal protection (highly linked for airbreather concepts.)

For commonality with multiple avenues, and with enabling benefit they become priorities:

- **Ejector ramjet (ERJ) R&D and demonstration.**
- **Ejector scramjet (ESJ) R&D and demonstration, build on previous.**
- **Thermal protection systems (TPS) - passive, zero waterproof, robust against damage.**
- **Thin leading edge passive TPS.**
- **Thermal protection systems (TPS) - active, robust, low maintenance (as fallback).**

Active and Passive Cooling: Active cooling should compete in this priority in so far as it is requisite; passive cooling developments should focus on the potential elimination of any active cooling requirement at leading edges, inlets and at other structures as required. Active cooling should be considered a backup or fallback technology. Key technologies that enable low cost operations are as follows:

- **Reusable propellant tankage and feeds (cryogenic service) - composites.**
- **Integral, conformal propellant tankage (for all propellants).**
- **Robust, maintenance-free thermal protection systems.**
- **Electric actuation, high horsepower - eliminate hydraulics, applies to propulsion geometry and aerosurfaces.**
- **Power systems, simplified, non-toxic, low and high horsepower - eliminate hypergols, eliminate multiple different types of power systems to service and maintain.**
- **Common propellant systems (propellant grade fuel cells, orbital maneuvering systems (OMS) and reaction control systems (RCS) using propellants common with main propulsion).**
- **Vehicle and ground health management systems (VHM/HM).**

RECOMMENDATION 5. Operations Cost Modeling: The conceptual phase of any study activity is characterized by broad characterization and less specific information. By it's nature the intent is to avoid allocating into a program before preliminary study has been undertaken. Cost modeling with an ability to work on limited types of information is required.

Models based on more specific information have also been noted as an area for agency improvement since even operational systems such as Shuttle do not adequately account for and explain costs of operations with any traceability that allows decision making focused on improvement. It should be re-iterated here that a major factor, if not the major factor, in cost modeling for space transportation systems is the launch rate capability of the concept, the effect of which was discussed in "Discussions and Conclusions" (above).

RECOMMENDATION 6. Operations Cost Measure Of Merit: A measure "useful payload per year to LEO per vehicle" is proposed as an equalizer that allows the benefit of systems with less payload but more response (flight rate at a given resource expenditure or cost) to be measured against systems with less response and higher payload.

The ideal is more payload as well as higher flight rate. Less payload per flight should not be assumed to be undesirable except as applies to particular markets.

RECOMMENDATION 7. Building an Earth-to-Orbit (ETO) Technology Roadmap (Ground & Flight Demonstrators —"Pathfinders" & "Trailblazers"): The next step beyond HRST efforts should be to build a technology roadmap that defines a phasing plan for ground and flight demonstrations.

However, the concepts, as provided, are not yet to a level of maturity for clearly determining which will achieve HRST goals. That being the case, a roadmap that leads to architectures achieving operating costs below $1,000 per pound is likewise premature. It is recommended that an iteration process be initiated on the provided concepts. The iteration process should be guided through the use of the suggested design "rules of thumb" (see below.) Once the concepts have reached maturity, or the HRST goals are assessed as having been met, then the nation will be ready to construct an ETO roadmap that leads to a portfolio of promising architectural concepts that are capable of achieving $100-$200 per pound cost. In the context of these promising architectures, the technology requirements could then be formulated.

RECOMMENDATION 8. Concept Programmatic Information Needs to be Better Identified and Clearly Separated Between R&T and Commercial Acquisition Commitment Phases.

As the iterative process unfolds, better definition of cost and schedule should be made available. Particularly needed, however, is clear discrimination between which are incurred during the research and technology phase, and which are incurred during the commercial acquisition phase. This clear discrimination is required to build an effective research and technology program that reduces high cost and risk investments associated with commercial acquisition.

RECOMMENDATION 9. Final Recommendation to HRST Study Team: Avoid Presenting Premature Architectural Selection.

Premature architectural concept selection at this point will lead to a programmatic commitment that would fall well short of the Civil Space Transportation Study goal of engendering space market growth.

ARCHITECTURAL GUIDELINES AND RULES OF THUMBS

As discussed in Recommendation 1 (prior), HRST goals will not be realized without architectural, global optimization of designs. A broader improvement strategy focused on affordable architectures must be implemented. The Ops team developed a set of Guidelines and Rules of Thumb, applicable to space transportation system design at the architectural level, intended to provide both general design principles and specific examples that, if followed, should result in a more operable and less costly launch system. These are derived from the work of the SPST and the Ops Team. Attached to this Summary is an abbreviated version of the complete Guidelines and Rules to be found in the Ops Report, “Space Vehicle Operability Quick Reference Guide.”