

A STUDY OF ARTS: A DUAL-FUEL REUSABLE LAUNCH VEHICLE WITH LAUNCH ASSIST

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ABSTRACT

An independent assessment of the Advanced Reusable Transportation System (ARTS) has been conducted. The ARTS concept is an all-rocket, fully reusable launch vehicle utilizing electromagnetic launch assist. ARTS is fitted with a dual-fuel main propulsion system utilizing flight proven Space Shuttle Main Engines and RD-180s. Nominally, the vehicle is intended to operate without a crew using autonomous guidance and control. Conceptual analysis shows that the vehicle could boost a payload of 48,140 lbs to a 110 nmi circular orbit in its baseline configuration. The DDT&E cost of such a system is estimated to be \$8.8B (FY2003) using existing liquid rocket engines, while the total cost to the first vehicle is \$11B. An alternative design configuration incorporating an additional SSME in the propulsion system is also explored. With this increased thrust, the payload potential is shown to increase to 60,770 lbs, while the cost to first vehicle rises to \$12.1B. A summary of the disciplinary design tools used in this analysis, including mass properties, trajectory simulation, aerodynamics, and non-recurring cost is provided. The implementation of these tools in a collaborative design process is also discussed.

NOMENCLATURE

CAD	Computer Aided Design
c_d	Coefficient of Drag
c_l	Coefficient of Lift
CPS	Coordinate Pattern Search
FY	Fiscal Year
OMS	Orbital Maneuvering System
RCS	Reaction Control System
STS	Space Transportation System
TPS	Thermal Protection System

INTRODUCTION

The road to a viable next generation reusable launch vehicle (RLV) has proven to be fraught with programmatic risk, design failures, and formidable technological challenges. Many evolutionary vehicle concepts fail to gain government or industry support because they do not offer a significant improvement in cost, performance, or operability over the current Space Shuttle. On the other hand, revolutionary concepts often suffer because the level of risk inherent in their technology development programs is unacceptable to potential investors.

PURPOSE

The impetus for the development of the Advanced Reusable Transportation System (ARTS) concept was the desire to incorporate mature RLV technologies in the context of an innovative vehicle concept. Sized as a Shuttle replacement, the ARTS vehicle is a horizontal take-off, horizontal landing (HTHL) concept with all-rocket main propulsion and electromagnetic launch assist. Elements of the ARTS design can be traced to concept studies and general conclusions from the NASA Highly Reusable Space Transportation (HRST) study.^{1,2}

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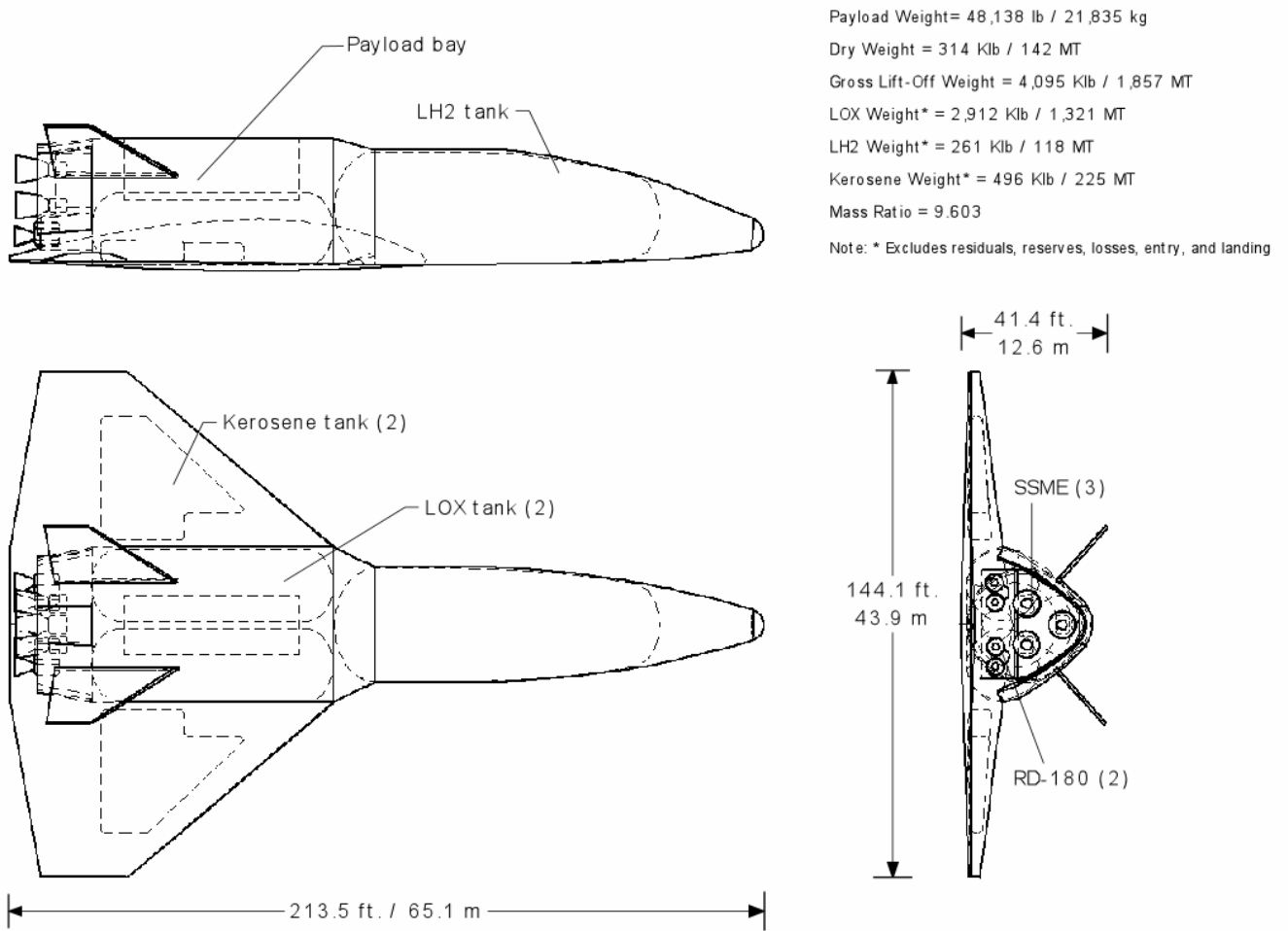


Figure 1. Baseline ARTS Vehicle Configuration.

The original design study that produced the ARTS concept was conducted at Gray Research by Gordon Woodcock. Gray Research has worked in conjunction with researchers from NASA MSFC and PRT Advanced Maglev Systems Inc. who are developing and testing a subscale electromagnetic accelerator track system at NASA Marshall.

SpaceWorks Engineering, Inc. (SEI) was tasked by NASA MSFC to conduct an independent assessment of the performance and cost of the ARTS vehicle. SEI's design analysis process included trajectory simulation, component weight estimation, aerodynamics, CAD, and non-recurring cost analysis. SEI conducted this analysis without knowledge of the results of prior ARTS sizing and performance studies. An assessment of the design, operation, and cost of the electromagnetic accelerator track was beyond the scope of this task.

CONCEPT DESCRIPTION

The ARTS concept, shown in Figure 1, is an all-rocket, fully reusable launch vehicle with launch assist. As a baseline design, the ARTS system is able to carry a 48,140 lb payload to a 110 nmi circular orbit at an inclination of 28.5°.

An electromagnetic launch assist track is used to impart a portion of the required delta-V to orbit. The ground-based launch assist approach provides additional design benefits, namely reduced landing gear and wing weights.

The fuselage geometry consists of an ogive nose with circular cross section, followed by mid and aft fuselage segments with rounded triangular cross sections. A delta wing is used as the primary lifting surface, and

two outward-canted vertical stabilizers are mounted on the aft end of the fuselage.

Retractable main and nose landing gear are located in the wings and forward fuselage, respectively. Five liquid rocket engines comprising the main propulsion system are installed on the back face of the fuselage. For the baseline design there are three SSMEs and two RD-180s arranged as seen in Figure 1.

One of the principle design features of the ARTS concept is its dual-fuel configuration. To accommodate both liquid hydrogen (LH2) and Kerosene, fuel tanks are located both within the forward fuselage and in the wing. In particular, one semi-integral LH2 tank is positioned within the nose and two Kerosene tanks are located in the delta wing. The liquid oxygen (LOX) oxidizer is stored in two cylindrical tanks located beneath the payload bay in the mid to aft fuselage.

KEY TECHNOLOGIES

Airframe / Tank Structure

ARTS uses advanced graphite epoxy composites for both airframe and tank structures. Graphite epoxy materials have a high strength to weight ratio and offer a promising alternative to conventional metallic structures.

OMS / RCS Propulsion

Cryogenic propellants are used for OMS and RCS propulsion in the ARTS design. Although hypergolic propellants tend to be more storable, the performance advantage offered by a LOX/LH2 system means more OMS delta-V per unit propellant weight.

Electromagnetic Launch Assist System

The payload capacity of the ARTS vehicle is increased by the use of a ground-based launch assist system. Specifically, the concept calls for a launch assist track equipped with linear induction motors to electromagnetically accelerate the RLV to launch velocity.

Autonomous Guidance, Navigation, and Control

The ARTS RLV is designed to operate without a crew onboard. The guidance, navigation, and control (GNC), and landing functions are therefore carried out autonomously by flight computers. Future studies may

examine the possibility of carrying passengers in a crew cabin mounted in the payload bay.

MISSION PROFILE

A typical mission for the ARTS vehicle begins at a future launch site situated at Kennedy Space Center (KSC) on the Florida coast. The unmanned vehicle is accelerated from rest along a track by electromagnetic linear induction motors (LIM) to a takeoff speed of approximately 650 ft/s.

The flight profile continues with a pull-up maneuver, during which the wing loading is constrained to no more than 1.2 times the vehicle gross weight. After exiting the initial pull-up, the vehicle continues to climb and accelerate until about Mach 10. At this optimized point, the Kerosene burning RD-180 engines are shut down, and the SSMEs alone carry the vehicle to orbit insertion.

After insertion into a 65 nmi x 110 nmi orbit, a pair of orbital maneuvering engines circularize the orbit at 110 nmi. Upon completion of the on-orbit activities, the vehicle performs a deorbit burn, reenters the atmosphere, and conducts an unpowered, autonomous landing at KSC.

DISCIPLINARY TOOL OVERVIEW

Aerodynamics

Aerodynamic analysis was conducted using a tool called the Aerodynamic Preliminary Analysis System (APAS).³ For subsonic prediction, APAS employs a panel code algorithm called UDP, and for supersonic and hypersonic flight the program uses the Supersonic/Hypersonic Arbitrary Body computer Program (S/HABP).

The APAS tool was used to obtain lift and drag coefficients as functions of Mach number. Although these results were obtained for a baseline vehicle, it was assumed that photographically scaling the system would not alter the aerodynamic coefficients.

Mass Properties / Weight Estimation

Weight estimation for the systems, subsystems, and structures of the ARTS vehicle was accomplished using both standard and custom mass estimating relationships (MERS) encapsulated in a Microsoft Excel workbook. Most of these MERS can trace their roots to NASA

Langley Research Center, and all were suited to a wing-body spaceplane.

A 15% growth margin was placed on all weight breakdown items except for the main propulsion system and the orbital maneuvering system (OMS). These latter two items were considered off-the-shelf systems for which no margin was necessary.

The mass properties spreadsheet was designed to accept a mass ratio output from the trajectory analysis. The scaled length, ascent propellant masses, and payload mass were adjusted by an Excel Solver routine until the mass ratio and mixture ratio from the worksheet matched the corresponding ratios from the trajectory code. In this way, the design was converged or 'closed' for a given gross weight.

Trajectory Simulation

Trajectory analysis was conducted using the Program to Optimize Simulated Trajectories (POST).⁴ POST is a widely used trajectory simulation and optimization code developed by NASA and Lockheed Martin. The code accepts propulsion and aerodynamic inputs in tabular form, and outputs a wide variety of vehicle state variables.

POST allows the user to constrain numerous problem variables to ensure an accurate, optimally flown trajectory. For the purposes of this analysis, it was necessary to constrain the magnitude of the wing loading, the maximum dynamic pressure, and the

characteristics of the final orbit.

Non-recurring Cost

For the analysis, the non-recurring cost was considered to be the sum of the design, development, test, and engineering (DDT&E), theoretical first unit (TFU), and engine acquisition costs. Cost estimating relationships (CERs) were obtained or formulated for each item in the system weight breakdown. These CERs were based largely on the NASA-Air Force Cost Model (NAFCOM).⁵

Due to the fact that both engine types used in the main propulsion system are already in production, the DDT&E cost to the ARTS program for these items was assumed to be zero. Also, the cost for System Test Hardware (STH) was determined assuming half-scale prototyping during the vehicle development. Finally, a 20% cost margin was used since the 15% weight margin was excluded from the cost analysis.

Collaborative Design Process

In a collaborative design process, increased communication between disciplinary design tools and processes facilitates a thorough understanding of the interdependencies among these entities. For the ARTS concept analysis, collaborative design was achieved using Analysis Server© and ModelCenter© software from Phoenix Integration, Inc.⁶

The ModelCenter© design environment enables a user

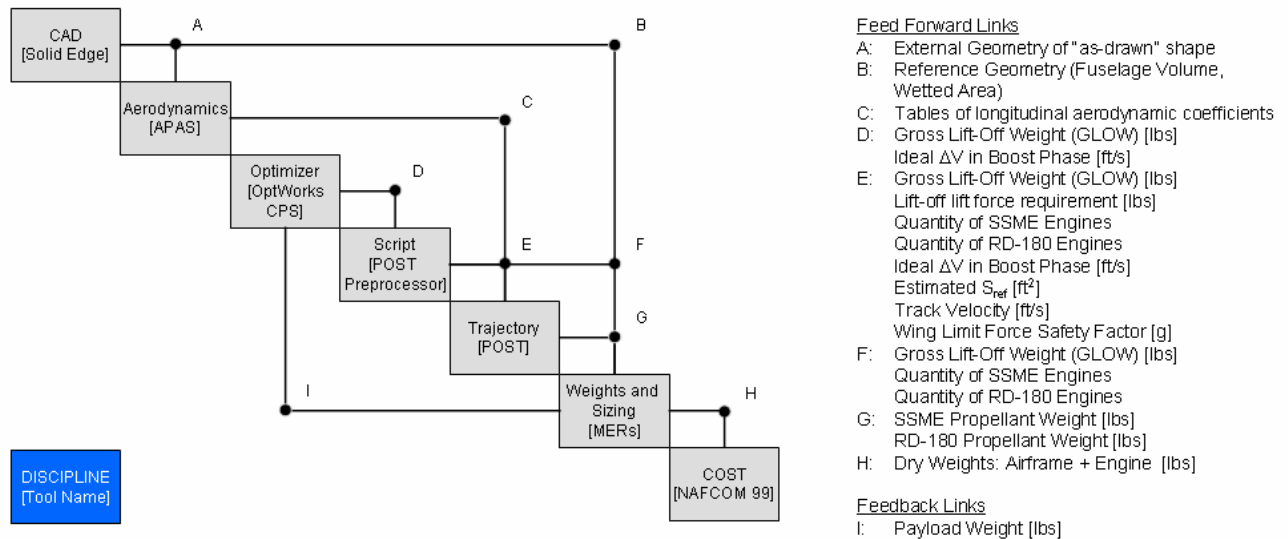


Figure 2. ARTS Design Structure Matrix.

to establish links between multiple design codes and other types of components located on a single computer or distributed across several networked computers. In addition to linking engineering design tools in a common environment, ModelCenter© also allows for the introduction of optimization components and custom script components to a design model.

Each of these capabilities was utilized in the ARTS analysis, including linking mass properties, trajectory, and non-recurring cost codes, adding a pre-processing script for the trajectory inputs, and driving the entire process with an optimization component. Figure 2 represents the design structure matrix (DSM) for the ARTS design process. Feed forward and feedback links for design variables are listed as well. Meanwhile, the OptWorks Coordinate Pattern Search optimizer is shown in Figure 3, along with the script and disciplinary components as they appear in the ModelCenter© environment. OptWorks is a suite of non-gradient based optimization components developed by SpaceWorks Engineering, Inc. (SEI) and available for purchase through the company website.

Execution time for the automated ModelCenter© model file from initial guess to converged design was on the order of 2 to 3 hours. The optimizer, mass properties, and cost components were run on a Windows XP equipped PC (1 GHz, Pentium 3), while POST was executed on an SGI Octane (250 MHz, R10000 CPU).

SUMMARY OF RESULTS

Aerodynamics

Aerodynamic coefficients obtained from the APAS analysis were verified by comparison with similar wing-body RLV concepts. The theoretical wing planform area was chosen as the reference area (S_{ref}). Since an untrimmed trajectory was flown in POST, only the lift and drag coefficients were required as aerodynamic inputs. A perspective view of the APAS wireframe model can be seen in Figure 4. Figure 5 shows the drag polar results for the ARTS test model at various Mach numbers between 0.3 and 30.

Internal Layout / CAD

A CAD model representing the outer mold line of the ARTS vehicle as well as the internal packaging of the propellant tanks and payload bay was created using Solid Edge software. Calculations conducted within Solid Edge yielded reference surface areas, volumes, and packaging efficiencies required for the mass

properties and aerodynamic analyses. Figures 6 and 7 show external and internal configuration views, respectively.

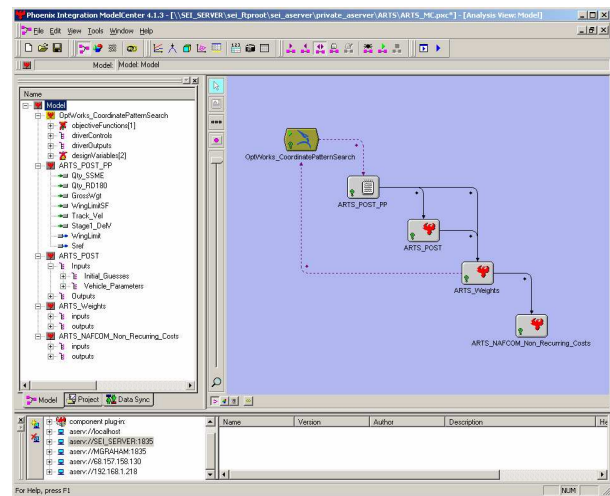


Figure 3. ARTS Design Process in ModelCenter©.

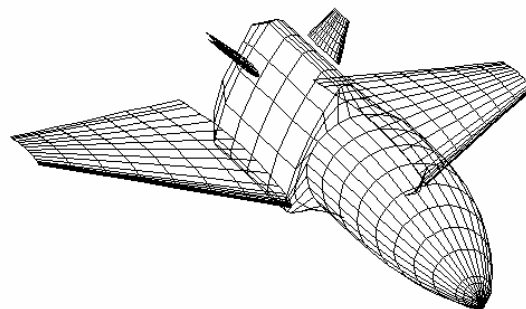


Figure 4. APAS Aerodynamic Model.

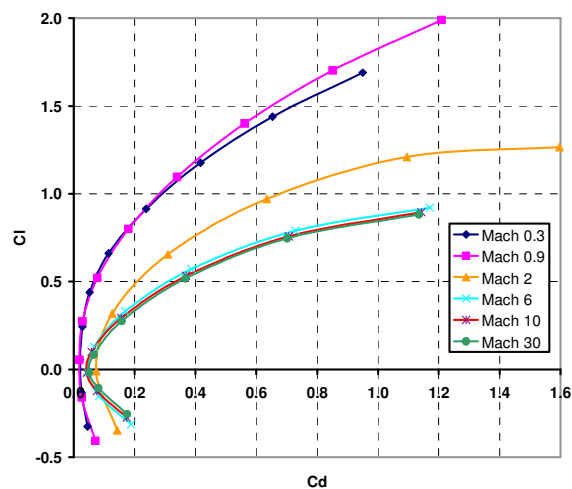


Figure 5. Drag Polar Results for ARTS Baseline.

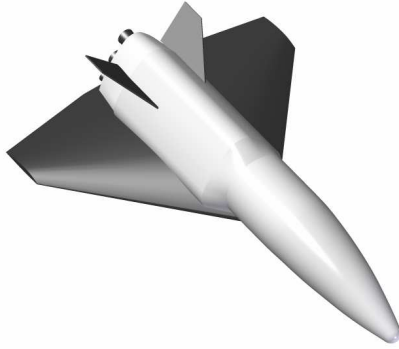


Figure 6. External CAD View.

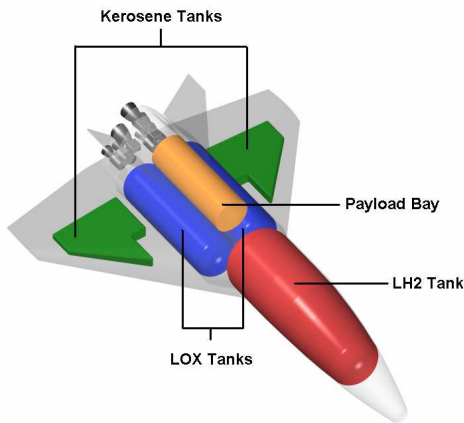


Figure 7. Internal CAD View.

Trajectory Optimization

Several key constraints were used to obtain the simulated trajectory of the ARTS vehicle. Starting at time $t = 0$ seconds, the launch assist track is simulated by a horizontal ground hold until the lift force on the spacecraft becomes equal to the weight. Results show that this event takes place at about $t = 10$ seconds.

Upon lift-off, a generalized acceleration steering (GAS) algorithm is activated to constrain the wing loading during the pull-up maneuver to 1.2 times the gross weight.

At approximately $t = 38$ seconds, the pull-up maneuver is completed and control of the trajectory is shifted to a table of relative pitch angles versus time. Pitch angle control continues until orbit insertion and ensures a flight path angle of 0° at the end of the simulated trajectory at $t = 578$ seconds. Figure 8 illustrates the profile of the ARTS trajectory.

In the midst of the pitch angle controlled ascent, an engine transition event takes place. The timing of this event, in which the RD-180 Kerosene burning engines are shut off, is controlled by the OptWorks optimizer in the ModelCenter© model. This coordinate pattern search algorithm varies the engine shut off point and the gross weight of the vehicle in an attempt to maximize the payload weight. For the baseline vehicle, the optimized RD-180 shut off was at time $t = 334$ seconds and speed about Mach 10, as seen in Figure 9. Figure 10 tracks the change in net Isp throughout the flight, and also indicates the RD-180 shut off.

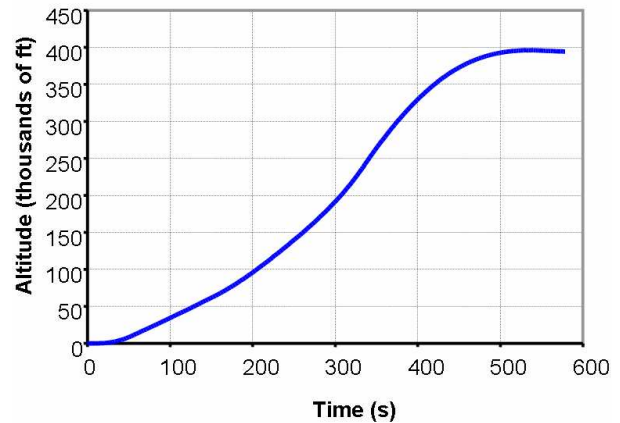


Figure 8. Altitude Versus Flight Time for Baseline ARTS Trajectory.

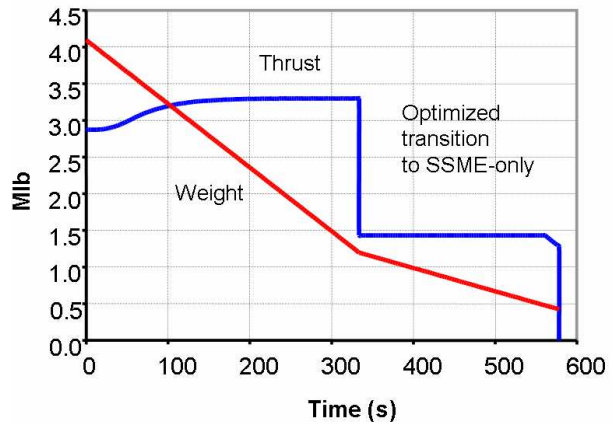


Figure 9. Weight and Thrust Versus Flight Time.

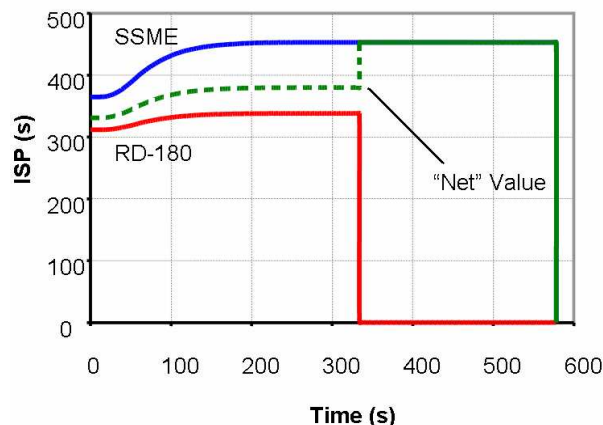


Figure 10. Net Isp vs. Flight Time.

Mass Properties

The converged ARTS vehicle outfitted with the baseline 3 SSME / 2 RD-180 main propulsion system resulted in a gross lift-off weight (GLOW) of 4,095,010 lbs. The dry weight for this vehicle was 313,610 lbs and the mass ratio (MR) for closure was 9.6. External dimensions for this vehicle include a nose-to-tail length of 214 ft and a wingspan of 144 ft. A more detailed summary of the weight breakdown for the baseline ARTS vehicle can be seen in Table 1 below.

Non-recurring Cost

The non-recurring costs associated with the ARTS vehicle were estimated using NAFCOM based CERs. Inputs to the CERs include various airframe component weights, propulsion system weights, and appropriate complexity factors. It is also necessary to provide a rate of inflation and a fiscal year for the output values.

Given this information, the NAFCOM CERs will determine DDT&E and TFU costs for the vehicle airframe and propulsion system. For the ARTS analysis, the DDT&E cost for the main propulsion system was assumed to be zero since the engines used on the design are currently in production. The baseline ARTS cost results are listed in Table 2.

Note that only the non-recurring costs associated with the vehicle were considered in this study. The DDT&E and construction costs for the electromagnetic launch assist track were not estimated for the present study.

Table 1. Baseline ARTS Weight Breakdown.

Item	Weight (lbs)
Wing Group	55,100
Tail Group	6,970
Body Group	112,000
TPS Group	32,700
Landing Gear	10,350
RCS Propulsion	4,040
OMS Propulsion	4,210
Primary Power	1,260
Electrical Conversion & Dist.	1,560
Hydraulic Systems	0
Surface Control Actuation	1,850
Avionics	1,600
Environmental Control	2,390
Personal Equipment	0
Main Propulsion: SSME (3)	21,010
Main Propulsion: RD-180 (2)	23,780
Total Propulsion Weight	44,790
Dry Weight Margin (15%)	34,790
Total Dry Weight	313,610
Total Payload Weight	48,140
Total LOX Weight (Ascent)	2,912,270
Total LH2 Weight (Ascent)	260,720
Total Kerosene Weight (Ascent)	495,580
Total residuals, reserves, losses, entry, and landing propellants	64,690
Total Propellant Weight	3,733,260
Total Gross Lift-Off Weight (GLOW)	4,095,010

Table 2. Baseline ARTS Cost Estimates.

Item	Value (FY2003\$)
DDT&E (Airframe)	\$8,800 M
DDT&E (Engines)	\$0 M
First Unit (Airframe)	\$2,084 M
First Unit (All Engines)	\$130 M
Cost to First Vehicle	\$11,014 M

4 SSME / 2 RD-180 ALTERNATIVE CONFIGURATION

Introduction

Evaluation of the baseline ARTS concept begs the question of whether adding more propulsive thrust to the vehicle offers any significant benefits to the overall design. In order to find an answer, the ARTS vehicle was closed for a second time with 4 SSMEs and 2 RD-180s. The addition of one SSME to the baseline necessitated new trajectory optimization, geometric rescaling, and cost analysis.

Summary of Results

The impact of the additional SSME was apparent in several ways. In terms of weight outcomes, the 4 SSME configuration closed at a GLOW of 4,725,000 lbs with a dry weight of 367,980 lbs. The payload capacity increased by 26% to 60,770 lbs when flown to the identical baseline orbit of 110 nmi circular x 28.5°. A summarized weight breakdown is provided in Table 3.

Table 3. Abbreviated Weight Breakdown – 4 SSME Variant.

Item	Weight (lbs)
Body, Wings, Tails	206,610
TPS	37,390
Landing Gear	12,250
MPS, OMS, RCS	61,560
Subsystems	9,260
Dry Weight Margin (15%)	40,190
Dry Weight	367,980
Payload	60,770
Ascent Propellant	4,220,920
Reserves, Residuals	75,330
GLOW	4,725,000

The shut down point for the RD-180 engines occurred at Mach 11, a slightly higher value than the optimized point in the baseline case.

In terms of cost figures, the extra engine and corresponding larger vehicle led to increases in airframe and engine acquisition costs. A brief summary

of these costs is included in Table 4 below.

Table 4. Cost Summary – 4 SSME Variant.

Item	Value (FY2003\$)
DDT&E (Airframe)	\$9,641 M
DDT&E (Engines)	\$0 M
First Unit (Airframe)	\$2,318 M
First Unit (All Engines)	\$166 M
Cost to First Vehicle	\$12,1254 M

The differences in gross weight values and cost between the baseline and 4 SSME ARTS variants are shown in Figure 11. Meanwhile, Figure 12 contains a scale comparison of each of the ARTS variants with the current Space Shuttle.

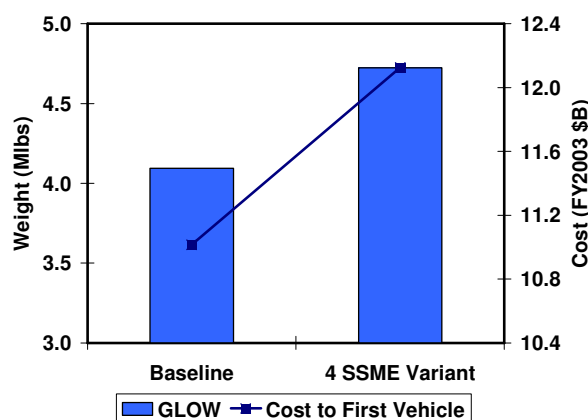


Figure 11. Weight and Cost Comparison of ARTS Variants.

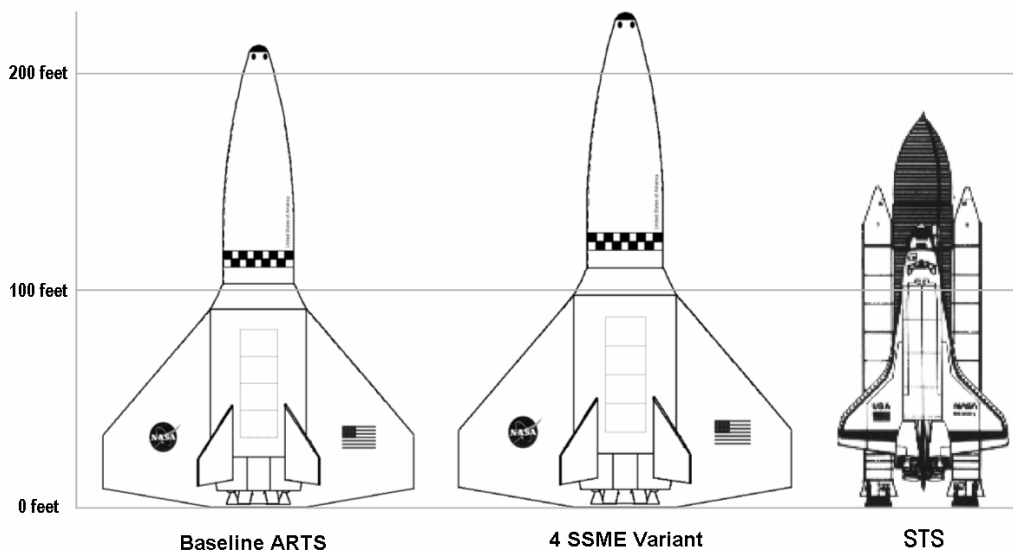


Figure 12. Size Comparison of ARTS with Space Shuttle.

SUMMARY

SpaceWorks Engineering, Inc. (SEI) was tasked by NASA MSFC to conduct an independent assessment of the dual-fuel, launch assisted ARTS RLV concept. A multidisciplinary, collaborative design process was executed to converge a vehicle in the 50,000 lb payload class, without knowledge of prior sizing data.

The results of the SEI design process indicate that an ARTS vehicle with a dry weight of 313,610 lbs and a gross weight of 4,095,000 lbs could lift a payload of about 48,140 lbs. Analysis predicts that the cost to obtain this vehicle, including DDT&E and acquisition, would be about \$11B (FY2003).

An additional study of an ARTS variant with 4 SSMEs instead of the baseline 3 revealed that a payload weight of up to 60,770 lbs could be carried in such a configuration. However, the dry weight in this case rose to 367,980 lbs with a gross weight of 4,725,000 lbs. The cost to first vehicle figure increased to \$12.1B.

The ARTS concept illustrates the advantages offered by the use of existing propulsion technology and ground-based launch assist to a next generation RLV. Employing off-the-shelf rocket engines not only lowers non-recurring costs by eliminating propulsion DDT&E, but also acts to reduce the development risk for the complete system.

Likewise, as demonstrated in other studies, the electromagnetic launch assist component does more than contribute delta-V, it reduces landing gear and wing weight while increasing payload potential.

Future work could include additional operations, safety, and economic assessment of the ARTS system. Quantifying metrics such as turnaround time, casualty rates, and market price per unit payload would allow a more comprehensive comparison of ARTS with other RLV concepts.

Continued studies might also examine the performance and economic impacts of scaling the ARTS vehicle to a smaller payload class. A smaller RLV would ease requirements for the electromagnetic launch track, and could encourage a higher flight rate compared with the baseline system. Both of these possibilities should strengthen the economic outlook of the ARTS concept.

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