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Tanker *Argus*: Re-supply for a LEO Cryogenic Propellant Depot

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ABSTRACT

The *Argus* reusable launch vehicle (RLV) concept is a single-stage-to-orbit (SSTO) conical, winged-bodied vehicle powered by two liquid hydrogen (LH2)/liquid oxygen (LOX) supercharged ejector ramjets (SERJ). The 3rd generation *Argus* launch vehicle utilizes advanced vehicle technologies along with a magnetic levitation (Maglev) launch assist track. A tanker version of the *Argus* RLV is envisioned to provide an economical means of providing liquid fuel and oxidizer to an orbiting low Earth orbit (LEO) propellant depot. This depot could then provide propellant to various spacecraft, including reusable orbital transfer vehicles used to ferry space solar power (SSP) satellites to geo-stationary orbit. Two different tanker *Argus* configurations were analyzed. The first simply places additional propellant tanks inside the payload bay of an existing *Argus* reusable launch vehicle. The second concept is a modified pure tanker version of the *Argus* RLV in which the payload bay is removed and the vehicle propellant tanks are extended to hold additional propellant. An economic analysis was performed for this study that involved the calculation of the design/development and recurring costs of each vehicle. The goal of this analysis was to determine at what flight rate it would be economically beneficial to spend additional development funds to change an existing, sunk cost, payload bay tanker vehicle into a pure tanker design. The results show that for yearly flight rates greater than ~50 flts/yr it is cheaper, on a $/lb basis, to develop and operate a dedicated tanker.

NOMENCLATURE

AATe	Architectural Assessment Tool
CA	contributing analysis
CAD	computer-aided design
CER	cost estimating relationship
DSM	design structure matrix
ETO	Earth-to-orbit
GEO	geostationary Earth orbit
I_{sp}	specific impulse
IOC	initial operating capacity
KSC	Kennedy Space Center
LEO	low Earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
MER	mass estimating relationship
NTR	nuclear thermal rocket
OMS	orbital maneuvering system
OTV	orbital transfer vehicle
q	dynamic pressure
RBCC	rocket-based combined cycle
RLV	reusable launch vehicle
SEP	solar electric propulsion
SERJ	supercharged ejector ramjet
SLS	sea-level static
SSP	space solar power
SSTO	single-stage-to-orbit
STR	solar thermal rocket
T/W	thrust-to-weight
TFU	theoretical first unit
Ti-Al	Titanium-Aluminide
TPS	thermal protection system
UHTCs	Ultra High Temperature Ceramics
WBS	weight breakdown statement

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INTRODUCTION

Space solar power is the concept of collecting, in space, the sun's solar energy and beaming that energy back to Earth for terrestrial use. A representative SSP concept called the geostationary Earth orbit (GEO) Sun Tower would supply 1.2 GW of terrestrial power, but would require an on-orbit mass of 44,090 klbs (20,000 MT).[1] Obviously, a project requiring such a huge mass in orbit will be an epic and expensive undertaking. The transportation phase of the SSP program is broken into two distinct mission areas. The Earth-to-orbit (ETO) portion involves bringing unassembled SSP satellite pieces to LEO, while the in-space portion involves the ferrying of these satellites from LEO to GEO using an orbital transfer vehicle (OTV). A price goal of ~$181/lb ($400/kg) or 2.5¢/kW-hr has been set for the in-space transportation phase.[2] Several candidate OTVs have been proposed for the in-space transfer phase. A limited list of possible propulsion choices for candidate OTVs include nuclear thermal rockets (NTR), solar thermal rockets (STR), solar electric propulsion (SEP), chemical propulsion and dual mode chemical/SEP systems. The high thrust chemical propulsion options have the advantage of shorter trip times between LEO and GEO. Their main disadvantage however is their relatively low specific impulse (I_{sp}). Cheap, readily available propellant in LEO would be required in order to make chemical rocket propulsion a viable option for an OTV. The required propellant could be housed in a LEO propellant storage and processing facility. A representative propellant depot design is shown in Figure 1.

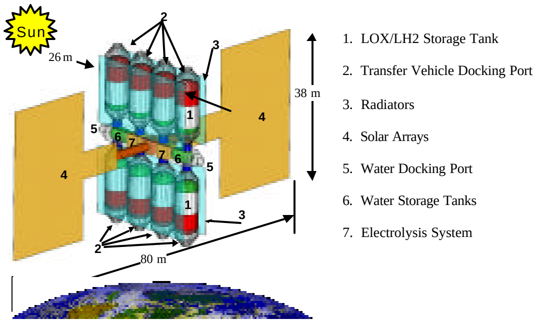


Figure 1 – LEO Propellant Processing Facility[3]

Two different propellant depot designs are envisioned. The more near-term design would receive cryogenic propellants directly from an orbiting spacecraft. A more advanced design like the one shown in Figure 1 would receive ice and process that using solar energy to make LH2 and LOX. Tanker *Argus* is seen as a possible candidate to provide economical delivery of LH2/LOX to a more near-term propellant depot. This would allow easier and cheaper access to GEO and the rest of the inner solar system aiding many programs including SSP.

CONCEPT OVERVIEW

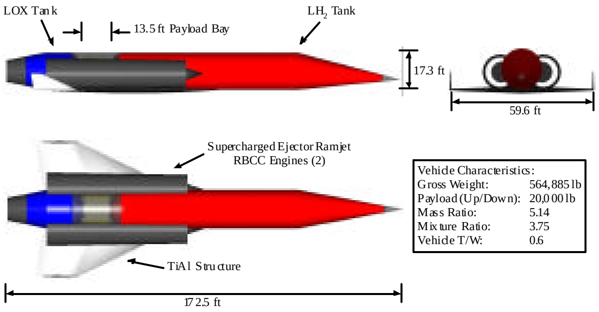
Argus was originally developed by the Space Systems Design Lab (SSDL) at Georgia Tech[4] for NASA's Highly Reusable Space Transportation System (HRST) study[5] in 1996 and 1997. *Argus* is a conical winged body LH2/LOX single-staged-to-orbit vehicle powered by two SERJ engines (Fig. 2).

Figure 2 – Argus Concept

The *Argus* concept utilizes a magnetic levitation track to provide an initial launch assist velocity of 800 fps. This launch assist reduces the total ΔV required to reach orbit but more importantly reduces the required wing size and under carriage weight. *Argus* also uses advanced structural materials including graphite epoxy propellant tanks, along with Titanium-Aluminide (Ti-Al) for the wings, tails, and primary structure. Ultra High Temperature Ceramics (UHTCs) are used to provide a passive thermal protection for the nose cap and wing leading edges. Lightweight avionics and subsystems are used throughout.

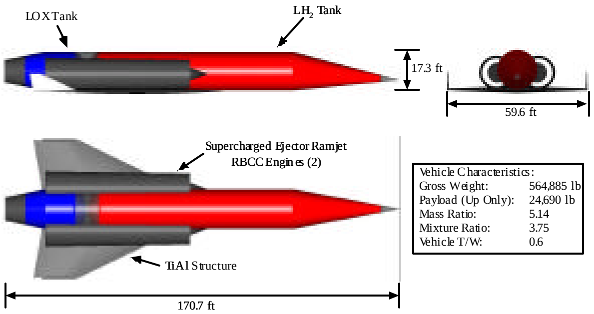
Tanker Designs

The baseline HRST *Argus* vehicle was the starting point for the tanker vehicles designed for this study. The first tanker design is a multi-use vehicle very similar to the original HRST concept. The propellant being delivered to the orbiting depot is housed in tanks that are placed in the payload bay. The vehicle was sized to deliver 20,000 lbs of payload to LEO. The majority of this payload is usable propellant. A small fraction, about 2%-3%, is additional tank weight. The second tanker design is a pure tanker derivative of the first tanker *Argus* concept. The payload bay is removed and the two main propellant tanks are extended to hold additional "payload propellant" for the depot. This changes the vehicle length, but the major subsystems including the engines, wings, and avionics remain the same. This helps reduce the development costs of the derivative. The derivative is able to carry ~23% more useful propellant to the LEO depot for the same gross weight vehicle. Figures 3 & 4 show the internal packaging of the two different designs.



Vehicle Characteristics:	
Gross Weight:	564,885 lb
Payload (Up/Down):	20,000 lb
Mass Ratio:	5.14
Mixture Ratio:	3.75
Vehicle T/W:	0.6

Figure 3 – Baseline Tanker Argus 3-view



Vehicle Characteristics:	
Gross Weight:	564,885 lb
Payload (Up Only):	24,690 lb
Mass Ratio:	5.14
Mixture Ratio:	3.75
Vehicle T/W:	0.6

Figure 4 – Pure Tanker Derivative 3-view

Mission Profile

Both versions of tanker *Argus* follow the same trajectory to LEO. At the time of *Argus'* initial operating capacity (IOC of 2021), it is assumed that there is a futuristic spaceport located at Kennedy Space Center (KSC). *Argus* will be launched from a Maglev track at KSC and accelerate initially using the supercharged ejector mode of its SERJ engines. Ejector mode ends at Mach 2 when fan-ramjet mode begins. A two-step constant dynamic pressure (q) trajectory is followed through fan-ramjet and ramjet modes. The fan-ramjet/ramjet transition occurs at Mach 3. After reaching Mach 6, the ramjet is turned off, and the internal rocket primary of each SERJ engine is reignited to provide the remaining thrust needed to reach orbit. After main engine shutoff the vehicle is in a temporary 50 nmi x 100 nmi x 28.5° orbit. An orbital maneuvering system (OMS) burn is used to provide the remaining ΔV required to reach a circular 100 nmi orbit. Figure 5 shows a notional flight profile.

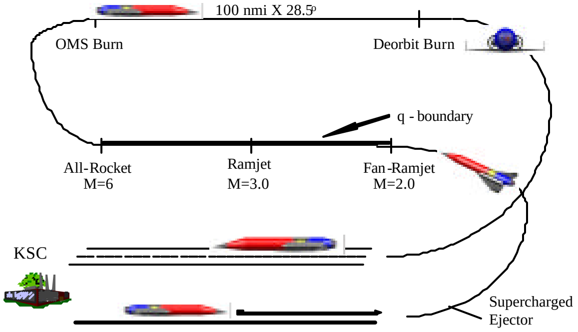


Figure 5 – Mission Profile

DESIGN PROCESS

Both versions of tanker *Argus* were designed using a collaborative, multidisciplinary design process. An integrated design team was used with each team member responsible for a specific discipline. Each team member executed an individual disciplinary analysis tool, and these disciplines were coupled in an iterative conceptual design process in which information about each candidate design was exchanged between the disciplines until the vehicle's design converges. The design process is most conveniently represented by the design structure matrix (DSM) shown in Figure 6. Design structure matrices are useful because they show the coupling between the various disciplines used in the design process. Each box in the DSM represents a specific discipline and is called a contributing analysis (CA). The feed forward links on the top of the CAs show where information must be fed downstream in the design process. The feed back links underneath the CAs show information that must be relayed back upstream in the design process. These feed back loops cause the design process to be iterative. Some CAs are more strongly coupled than others, with the strongest coupling occurring between the propulsion, trajectory and weights & sizing disciplines. Typically 6-8 system level iterations are required to get a converged vehicle design.

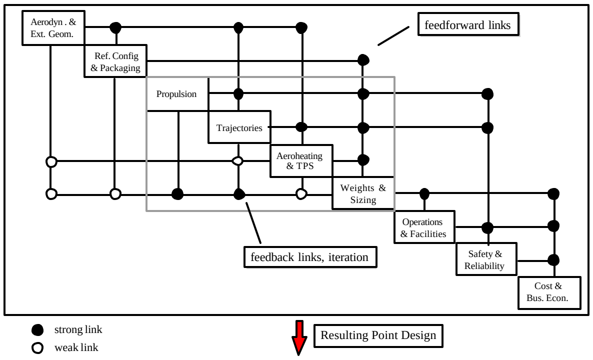


Figure 6 – Argus DSM

The first analyses conducted for the tanker *Argus* designs are the aerodynamic and configuration disciplines. The results from these are used during the main iteration loop between the highly coupled disciplines to determine the converged vehicle design. The vehicle was considered converged when the change between the gross and dry weight of the vehicle did not exceed 0.1% between iterations. The operations and economic analyses were conducted after a converged vehicle design was achieved. No safety or reliability analysis was performed for this study. Following is a more detailed description of the individual disciplines.

DISCIPLINARY ANALYSIS

Aerodynamics

The aerodynamic analysis for tanker *Argus* was completed using a conceptual design tool entitled APAS[6] (Aerodynamic Preliminary Analysis System). APAS, which is written in FORTRAN, was developed by Rockwell International as an aid in the design of the Space Shuttle. APAS couples two subprograms that separately perform the low speed and high speed aerodynamic analysis. UDP (Unified Distributed Panel) was used for Mach numbers up to but not including Mach 2.5. This program uses the geometry created within APAS to perform a vortex lattice method on the body panels. HABP (Hypersonic Arbitrary Body Program) is used to analyze the hypersonic flight regime of the vehicle. APAS requires several data inputs in order to perform the aerodynamic analysis. These inputs include the vehicle's external geometry and parameters such as the reference wing planform area, leading edge sweep angle, and an estimate of the position of the center of gravity of the vehicle. Figure 7 shows the *Argus* geometry file used for the aerodynamic analysis.

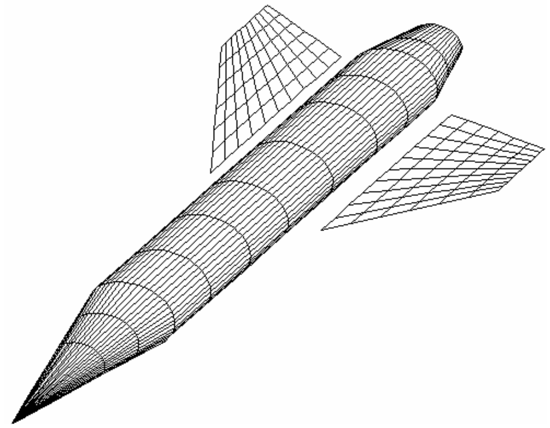


Figure 7 - Argus APAS Geometry

Analysis of the geometry in APAS was performed at several different flight conditions along the expected trajectory. This is done by evaluating several pairs of altitudes and Mach numbers over a range of angle of attack. APAS is thus able to provide the trajectory discipline tables of lift and drag coefficients over a wide range of altitudes, Mach numbers, and angles of attack. During the design process, the *Argus* vehicle is photographically scaled to achieve the proper propellant volume and vehicle mixture ratio. This scaling does not affect the relative external geometry of the vehicle. The aerodynamic coefficients generated by APAS will remain constant during the iteration process, but the actual lift and drag values scale with the vehicle's reference area. Therefore, the aerodynamic analysis only has to be done at the beginning of the design process if the vehicle's outer mold line is not changed.

Configuration

The configuration discipline is responsible for the internal packaging of the vehicle and for developing a baseline reference configuration which serves as an initial guess for the vehicle design. The aerodynamic and configuration disciplines will work together to deliver a vehicle that has good aerodynamic performance as well as a high packaging efficiency. The packaging efficiency is defined as the ratio of total ascent propellant volume to total internal fuselage volume. Typically a 3-D computer-aided design (CAD) program is used to draw a reference configuration and determine the internal layout of the vehicle. For a given reference vehicle length, vehicle mixture ratio (O/F), and mass ratio ($M_{initial}/M_{final}$), the configuration engineer draws the locations of the propellant tanks, payload bay and RCS tanks. From this drawing, reference surface areas and other key geometric features are determined. The reference values are then incorporated into the weights & sizing spreadsheet tool. The vehicle is then photographically scaled as needed throughout the iterative design process. The two tanker *Argus* configurations are very similar. The baseline design has a forward integral LH2 tank, a payload bay located near the middle of the vehicle and a rear integral LOX tank (see Figure 3). The overall converged vehicle length for the baseline configuration is 172.5 ft. For the pure tanker design the payload bay was removed and both the LH2 and LOX propellant tanks were extended to hold the additional propellant to be delivered to LEO. The additional propellant was added at a mixture ratio of 5.5. The mixture ratio was chosen because it represents a typical O/F ratio of an in-space LOX/LH2 engine. The pure tanker converged vehicle length was 170.7 ft (see Figure 4). The vehicle length changed because of the removal of the payload bay and the extension of the main tanks, but the remaining dimensions are the same as the baseline payload bay tanker *Argus* design. This was done to limit the additional development costs associated with the pure tanker derivative.

Weights & Sizing

The weights & sizing discipline for tanker *Argus* uses a photographic scaling set of parametric mass estimating relationships (MERs) that have a NASA Langley heritage. These relationships are used in an in-house Georgia Tech, Microsoft Excel© based, weights & sizing tool called GT-Sizer. GT-Sizer receives required vehicle mass and mixture ratios from the trajectory discipline and uses the MERs along with the reference vehicle input values to photographically scale the vehicle to meet the trajectory requirements. Since changing the vehicle scale changes the gross weight, capture area, sea-level static (SLS) thrust requirements, and other vehicle parameters; the weights & sizing, trajectory and propulsion disciplines form an iteration loop. As mentioned earlier it usually takes around 6 to 8 iterations to get a converged vehicle design, depending on the initial guesses used for the various vehicle parameters. As a reminder, during the iteration process the vehicle is photographically scaled so the aerodynamics and internal packaging do not have to be computed every iteration. They can just be scaled from their initial reference values.

The baseline MERs used for the tanker *Argus* analysis are based on near-term materials and construction techniques. Therefore, these relations were adjusted downward by a linear scaling factor to allow their use for the advanced materials and technologies used on *Argus*. Titanium-aluminide is used as the prime structure for *Argus'* wings, nose cap, payload bay structure, and tail cone. Graphite epoxy tanks with liners are used to construct both the integral LOX and LH2 tanks. Several other advanced subsystems were assumed for *Argus*. They include an autonomous flight control system, lightweight avionics, and a vehicle health monitoring system.

Many vehicle parameters are supplied by the weights & sizing disciplines to other analyses. The trajectory analysis uses the vehicle's gross weight, wing aerodynamic reference area, and the maximum design wing loading. The propulsion discipline needs the required sea-level static thrust and the operations and cost disciplines need the vehicle weight breakdown statement. Graphical breakdowns of both the dry and gross weight of both tanker *Argus* designs are shown in Figures 8 through 11.

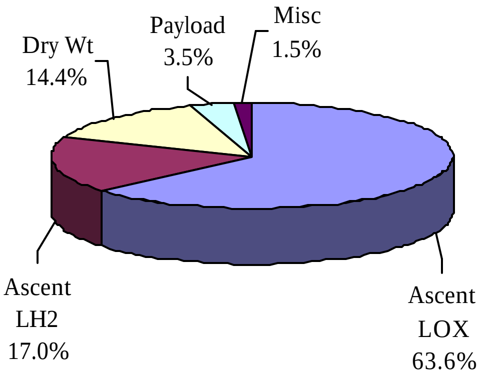


Figure 8 – Baseline Tanker Gross Weight Breakdown

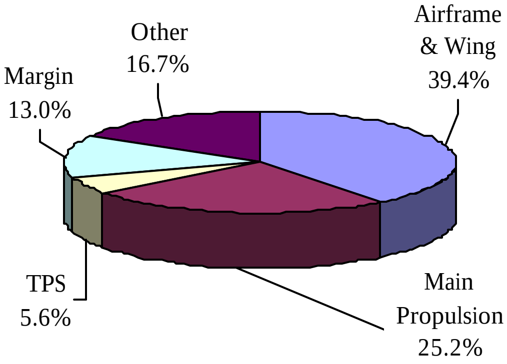


Figure 9 – Baseline Tanker Dry Weight Breakdown

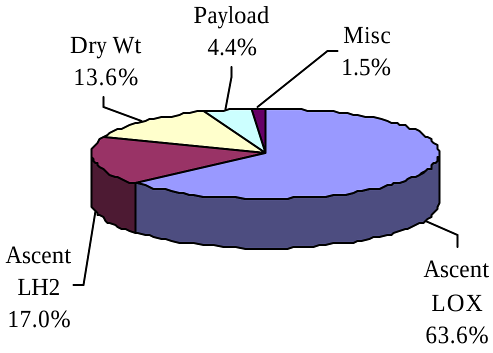


Figure 10 – Pure Tanker Gross Weight Breakdown

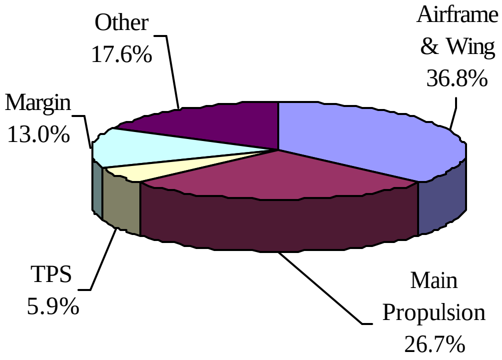


Figure 11 – Pure Tanker Dry Weight Breakdown

Propulsion

Tanker *Argus* is powered by two supercharged ejector ramjet engines (Figure 12). These engines are capable of operating in several different engine modes. The vehicle is first accelerated using the supercharged ejector mode of the SERJ engines. In this mode the engine thrust is provide by the rocket primaries located inside the engine. The ejectors are sized to provide a sea-level static vehicle thrust-to-weight (T/W) ratio of 0.6. Ejector mode powers *Argus* until Mach 2 when the transition to fan-ramjet mode occurs. The rocket-based combined cycle (RBCC) rocket primaries are ramped down while ramjet combustion begins. The supercharging fan is still used during fan-ramjet mode to raise the internal pressure inside the engine to help with ramjet combustion. At Mach 3 the fan stops performing as a supercharger and *Argus* operates in pure ramjet mode until Mach 6. At Mach 6 the transition to all-rocket mode is made. This involves the closing of the SERJ inlets and the re-ignition of the internal rocket primaries while simultaneously shutting down the ramjet combustion. *Argus* continues in this all-rocket mode until reaching the desired parking orbit.

Tanker *Argus'* SERJ engines were analyzed using SCCREAM.[7] SCCREAM, the Simulated Combined Cycle Rocket Engine Analysis Module, is a quasi one-dimensional in-house Georgia Tech code that models many different types of RBCC propulsion systems. This code was used to determine the performance characteristics of the two supercharged ejector ramjet engines.

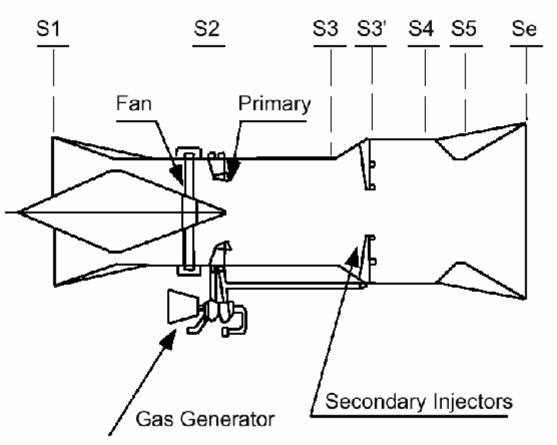


Figure 12 – Representative SERJ Engine

The output obtained from SCCREAM is an engine performance deck that is pre-formatted to be used in the trajectory program. This deck contains engine thrust, thrust coefficient, and specific impulse (I_{sp}) for a range of altitudes and Mach numbers for each operating mode of the engines. It should be noted that the propulsion force accounting system used for this engine analysis is cowl-to-tail. Therefore, all forebody pressures are included in the aerodynamic calculations done in APAS. Figures 13 and 14 show the thrust and I_{sp} profiles for the tanker *Argus* trajectory.

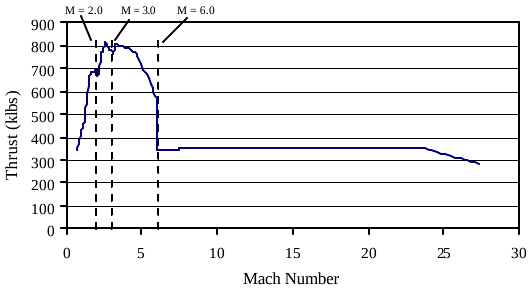


Figure 13 – Tanker Argus Thrust Profile

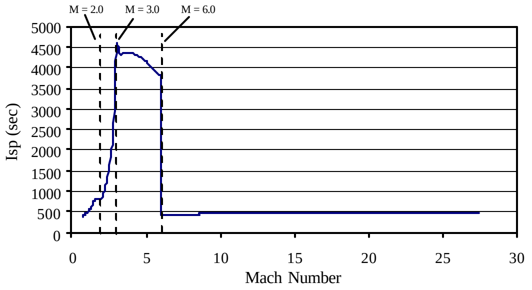


Figure 14 – Tanker Argus I_{sp} Profile

Performance

The Earth-to-orbit trajectories for the tanker *Argus* designs were modeled using POST.[8] POST, the Program to Optimize Simulated Trajectories is a three degree-of-freedom code that was written by Lockheed Martin and NASA. It is a generalized event oriented trajectory optimization code that numerically integrates the equations of motion given the aerodynamic and propulsive characteristics of the vehicle. The program minimizes the given objective function, usually propellant consumed, while meeting the given trajectory constraints. The target orbit for tanker *Argus* is a 100 nmi circular orbit at an inclination of 28.5°. POST is used to simulate the trajectory needed to reach a 50 nmi x 100 nmi x 28.5° parking orbit. Other trajectory constraints, besides the final orbit, include a maximum dynamic pressure boundary, a 3g maximum acceleration in rocket mode, and a maximum wing normal force load during the pull-up maneuver at the beginning of the all-rocket mode. The value of the maximum dynamic pressure allowed during the trajectory was 2000 psf. This constraint limits the internal engine pressure and vehicle heat loads. The wing normal force limit represents a compromise between wing structural concerns and the more fuel-efficient, sharp pull-up maneuver at the beginning of rocket mode.

The SCCREAM engine output deck is formatted in a way that allows POST to treat each operating mode of the SERJ engines as a different individual engine. Therefore, the transitions from one engine operating mode to another are done by varying the throttle parameter in POST for each mode. For example, for the transition from ejector to fan-ramjet mode, the ejector throttle control is linearly throttled down over the ½ Mach number range from Mach 2-2.5 while the fan-ramjet throttle is linearly throttled up over the same range.

Until Mach 6 the trajectory follows a two-step constant dynamic pressure path. The first q-boundary followed is 1500 psf. The vehicle reaches this boundary just before the transition to fan-ramjet mode. After transitioning to ramjet mode the q-boundary value is increased to 2000 psf. Plots of both altitude and dynamic pressure versus Mach number are shown in Figures 15 and 16.

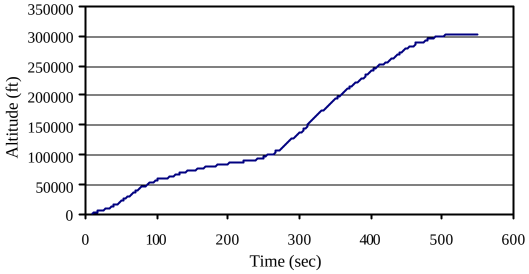


Figure 15 – Altitude vs. Mach Number

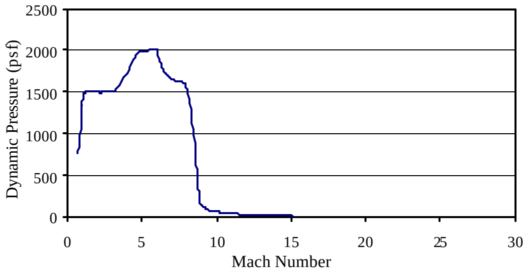


Figure 16 – Dynamic Pressure vs. Mach Number

After the trajectory analysis is complete, the required vehicle mass ratio and mixture ratio are used in the weights & sizing discipline to determine the vehicle's weight and overall size. The ascent trajectory is also sent to the aeroheating analysis to determine the thermal protection system (TPS) requirements for the vehicle.

Aeroheating

The aeroheating analysis for tanker *Argus* was performed using two separate tools. The first tool, MINIVER[9], is a thermal analysis code that was written by NASA and performs a 2-D flow analysis over the vehicle. Trajectory information, including angle of attack, altitude, velocity, and sideslip angle as a function of time are input into MINIVER along with the vehicle geometry. MINIVER then models the vehicle using simple geometric shapes and calculates the centerline temperature distributions, convective heat rates, and total heat loads for the simplified vehicle.

Once the MINIVER analysis is complete, an in-house Georgia Tech tool, TCAT[10] (Thermal Calculation Analysis Tool) is used to determine the type and thickness of thermal protection needed for each section of the vehicle. TCAT allows the analysis of TPS materials from the NASA Ames' TPS-X[11] database and has an internal optimization routine that allows for the calculation of the minimum TPS material thickness required to protect the vehicle substructure.

As mentioned earlier, *Argus*' wings, tail and primary structure are made of Ti-Al and therefore most of these components do not need TPS. Metallic TPS (i.e. large block Inconel tiles) are used on the windward side of the vehicle's composite tanks. TABI blankets are used on the leeward side of the tanks. Ultra High Temperature Ceramics are used to provide a passive thermal protection for the nose cap and wing leading edges. UHTCs are under development at NASA Ames as an alternative technology to actively cooled leading edges.[10]

Operations

The operations analysis was completed using the enhanced Architectural Assessment Tool (AATe).[12] This spreadsheet based, ground processing operations model was created by NASA KSC. The inputs to AATe are qualitative and quantitative answers to questions regarding the vehicle's attributes. These questions cover the number and type of propellant tanks, TPS material, vehicle size, engine type, etc. The vehicle is then judged using the Space Shuttle as the baseline concept. The results are then compiled into a final quantitative measure of the vehicle operability.

Using the results from the operations analysis, AATe is able to predict the ground operations cost associated with the reusable parts of the vehicle. For the operational cost analysis, it is assumed that the company operating the tanker *Argus* vehicles is using a large fictitious spaceport at KSC and is therefore able to share common facilities with other companies.

Economic Analysis

The tool used for the economic analysis of the tanker *Argus* vehicles was CABAM.[13] CABAM (Cost and Business Analysis Module) is a spreadsheet tool developed at Georgia Tech that uses parametric cost estimating relationships (CERs) to determine the cost of the launch system. The inputs to CABAM include a weight breakdown of the vehicle, technology and complexity factors, and the operations cost results.

Several assumptions where made during the economic analysis. They include the following:

- Program Years
    - Initial operational capability in 2021
    - Program termination in 2040
- Market is only the launching of propellant to LEO fuel depot
- Government cost contributions
    - Airframe (DDT&E only): 20%
    - Propulsion (DDT&E only): 100%
    - Facilities & MagLev (DDT&E and Construction): 100%
    - All cost figures in 2001 dollars

For the pure tanker derivative economic analysis it is assumed that the baseline payload bay tanker version already exists and therefore can be purchased without any design, development, testing and evaluation costs (DDT&E). The only DDT&E costs for the pure tanker derivative are the costs associated with changing the payload bay baseline into a pure tanker. The majority of the baseline vehicle remains unchanged (wings, engines, tooling…), which helps limit the development costs. The theoretical first unit (TFU) cost breakdown for the baseline vehicle and DDT&E cost breakdown for the pure tanker derivative are shown in Figures 17 and 18.

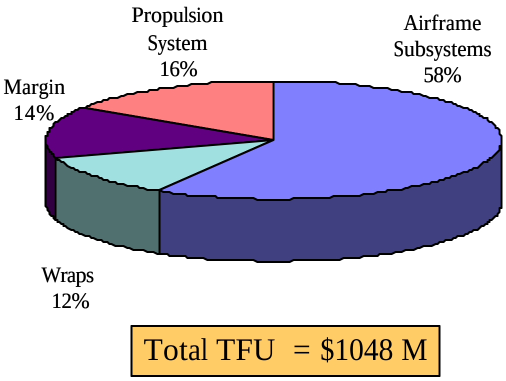


Figure 17 – Baseline Tanker Argus TFU

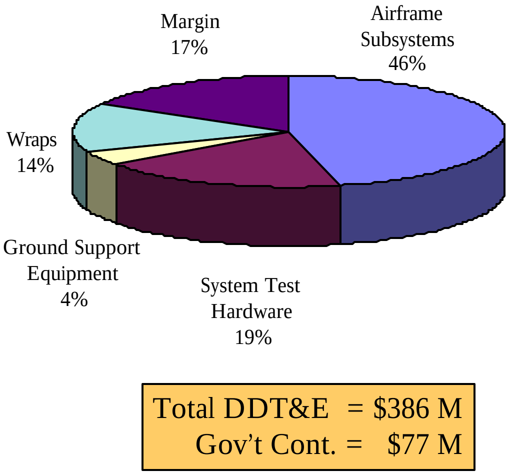


Figure 18 – Pure Tanker Derivative DDT&E

The TFU costs for both versions of tanker *Argus* are just above one billion dollars. These costs are very similar because the vehicles share many common components. The TFU cost is the cost to build the first vehicle from a new production line. The vehicle unit cost will decrease over time because of the learning curve effect associated with the assembly process. The recurring costs for each vehicle were modeled by the operations analysis using AATe and used as inputs for the economic discipline. These direct recurring costs include the costs for cargo processing, launch, landing, turnaround, operations and management, and propellant. Also a third-party liability insurance cost of $100K/flight is added to the AATe results. Figure 19 shows the recurring cost in $M verses flight rate for both vehicle designs.

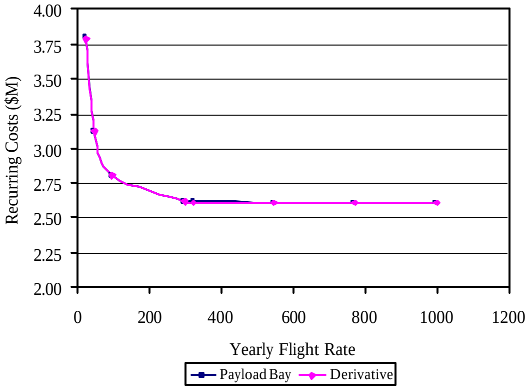


Figure 19 – Recurring Cost ($M) vs. Flight Rate

As can be seen the recurring cost difference between the baseline payload bay tanker and the pure tanker derivative is negligible. This is because both vehicles have almost the same weight and length and share many common components. The recurring cost difference can be seen in Figure 20 which gives the recurring cost in $/lb verses flight rate. Here the distinct advantage of the pure tanker derivative can be seen. Its $/lb cost is cheaper because it is able to carry more propellant to LEO per launch.

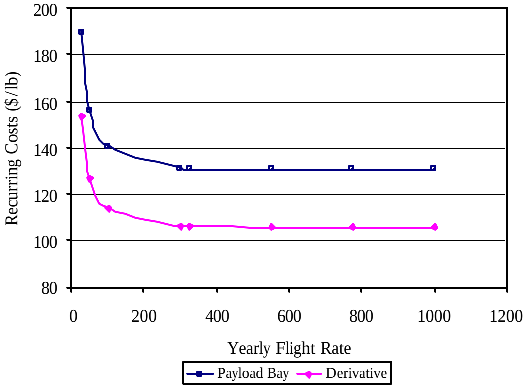


Figure 20 – Recurring Cost ($/lb) vs. Flight Rate

RESULTS

For each tanker design a complete weight breakdown statement (WBS) was developed during the weights & sizing analysis. An abbreviated version of this WBS is shown in Table 1. The baseline tanker design referred to in Table 1 is the tanker version of *Argus* with a payload bay. This vehicle is designed to carry 20,000 lbs to LEO and its gross liftoff weight is 565 klbs. The pure tanker design in Table 1 is the tanker *Argus* derivative in which the payload bay was removed and the main propellant tanks were extended to hold the additional "payload propellant" to be delivered in LEO. The amount of "payload propellant" in the pure tanker design was constrained by the fact that it must have the same gross weight as the baseline payload bay tanker. This condition allows the use of the same engines, wings and other subsystems for both tanker vehicles. By matching the gross weight the pure tanker derivative is able to carry 24,690 lbs of "payload propellant" to the LEO propellant depot.

Table 1 – WBS for Tanker Argus Designs

	Baseline Tanker	Pure Tanker
Wing and Tail	15,195	15,195
Body	16,900	13,100
Thermal Protection	4,575	4,530
Main Propulsion	20,535	20,570
OMS/RCS	1,510	1,510
Subsystems/Other Dry Wgts	12,065	12,050
Margin (15%)	10,620	10,045
Dry Weight	81,400	77,000
Payload	20,000	24,690
Residuals, OMS prop, etc.	8,530	8,240
Insertion Weight	109,930	109,930
Ascent Propellant	454,955	454,955
Gross Liftoff Weight	564,885	564,885
** All Weight in lbs*		

The main objective of this study was to determine when it would be economically beneficial to spend additional development money to transform an existing *Argus* vehicle with a payload bay into a dedicated tanker vehicle. The advantage of the dedicated tanker is that for the same gross weight it would be able to carry more "payload propellant" to LEO. Four different economic scenarios where studied to answer this question. The baseline payload bay design was analyzed twice. First including all the development costs in the analysis and then assuming the development costs where already sunk. Then the pure tanker derivative design was studied with and without its additional development costs ($ 386M) included in the analysis. Figure 21 shows the results for this analysis.

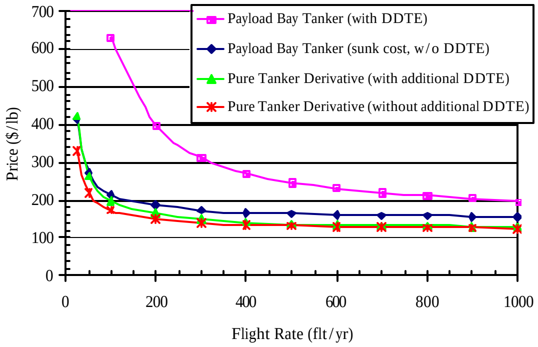


Figure 21 - Price ($/lb) vs. Flight Rate for 30% IRR (Four Scenarios)

Figure 21 is a graph of $/lb versus annual propellant delivery flight rates for a business scenario with an internal rate of return (IRR) of 30%. IRR is a measure of the economic attractiveness of an investment. It is defined as the discount rate required to get a net present value of zero. An IRR around 30% would be needed to attract investors to this project.

Two of the four economic scenarios analyzed are the most relevant to this study. They are the analysis of the sunk cost baseline payload bay tanker and the pure tanker development scenario including all of its DDT&E costs. This represents the most likely scenario in which an existing vehicle, with a payload bay, is available to bring propellant to LEO. Since it is assumed that this vehicle has been in service for a long period of time, its develop costs would already have been paid and the vehicle could simply be purchased for some percentage of its TFU cost. To develop a pure tanker version of this vehicle would require additional DDT&E funds in order to modify the existing design. This is similar to the situation with the Boeing 707 and KC-135. Figure 22 shows the comparison of these two tanker *Argus* economic scenarios.

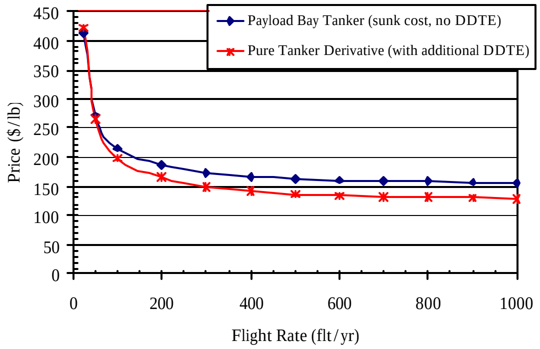


Figure 22 - Price ($/lb) vs. Flight Rate for 30% IRR (Two Scenarios)

CONCLUSIONS

From Figure 22 it can be seen that a sunk cost payload bay version of tanker *Argus* is worth modifying into a pure tanker craft if the expected propellant delivery flight rate exceeds 50 flts/yr. At this flight rate and with a 30% IRR, the sunk cost payload bay tanker has a propellant delivery cost of $270/lb. The cost for the pure tanker derivative at the same flight rate and IRR is $264/lb, even when including the additional $386M DDT&E costs. Both *Argus* tanker designs have approximately the same recurring cost per flight, but their $/lb cost is different. For the pure tanker derivative, its DDT&E costs are included along with its recurring costs in the $/lb calculations. However, at flight rates greater the 50 flts/yr, this additional cost is offset by the increased "payload propellant" capacity of the pure tanker. Therefore, if the market demand for propellant in LEO exceeds 50 flts/yr it is financially beneficial to spend additional development money to design and operate a pure tanker version of *Argus*.

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