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ABSTRACT

This paper summarizes the results of a conceptual design study that was performed in support of NASA's recent Highly Reusable Space Transportation study. The *Argus* concept uses a Maglifter magnetic-levitation sled launch assist system to accelerate it to a takeoff ground speed of 800 fps on its way to delivering a payload of 20,000 lb. to low earth orbit. Main propulsion is provided by two supercharged ejector rocket engines. The vehicle is autonomous and is fully reusable. A conceptual design exercise determined the vehicle gross weight to be approximately 597,250 lb. and the dry weight to be 75,500 lb. Aggressive weight and operations cost assumptions were used throughout the design process consistent with a second-generation reusable system that might be deployed in 10 - 15 years. Drawings, geometry, and weights of the concept are included.

Preliminary development, production, and operations costs along with a business scenario assuming a price-elastic payload market are also included. A fleet of three *Argus* launch vehicles flying a total of 149 flights per year is shown to have a financial internal rate of return of 28%. At \$169/lb., the recurring cost of *Argus* is shown to meet the study goal of \$100/lb. - \$200/lb., but optimum market price results in only a factor of two to five reduction compared to today's launch systems.

NOMENCLATURE

g	acceleration of gravity (32.2 ft/sec^2)
I_{sp}	specific impulse (sec.)
ΔV	velocity change, 'delta V' (ft/sec.)

BACKGROUND

In an effort to identify technologies and vehicle concepts that have the potential to significantly reduce the high cost of access to space, NASA recently conducted the Highly Reusable Space Transportation (HRST) study [1, 2]. The study investigated a number of near-term, far-term, and very far-term launch vehicle concepts with the goal of identifying a technology development path that could reduce the recurring costs of launching 20,000 lb. – 40,000 lb. payloads to low earth orbit (LEO) for under \$200/lb. The HRST study was conducted in two phases from 1995 to 1997. Among the concepts investigated were all-rocket single-stage-to-orbit (SSTO) concepts, concepts with launch assist, rocket-based combined cycle (RBCC) concepts, advanced expendable vehicles, and more far term ground-based laser powered launchers [2]. The *Argus* concept outlined in this paper was one of the concepts proposed.

The notion of an advanced HRST-class launch vehicle using a magnetic-levitation track for launch assist and employing two supercharged ejector ramjet (SERJ) engines and a single LOX/LH2 tail rocket for main propulsion was first suggested to the lead author by Mr. Bill Escher and Mr. John Mankins of NASA Headquarters. At a private meeting at NASA – Langley during the spring of 1995, Escher and Mankins outlined the concept with a simple sketch and an overall notion of how the vehicle would be flown,

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rough propulsion mode transition points, payload mass, etc. A subsequent conceptual performance determination and vehicle sizing exercise was performed by the lead author (then at North Carolina State University) for HRST phase 1. This exercise determined vehicle aerodynamic characteristics, ascent performance, mass properties, heating, propulsion system performance, and final geometric dimensions. Small modifications to the original concept outlined by Escher and Mankins were made as required (e.g. a slight increase in vehicle fineness ratio to reduce drag and a reduction in wing area to save weight).

The resultant concept, simply called *SERJ RBCC with Maglifter*, was presented as a 'thought starter' at the HRST Technical Interchange Meeting in July 1995 and is given in Fig. 1. The vehicle was sized to deliver a 20,000 lb. cargo to LEO after making use of an 800 fps launch assist velocity at the end of a sea level, horizontal mag-lev track. The tail rocket was a generic LOX/LH2 staged combustion rocket with a vacuum I_{sp} of 455 sec. The vehicle had no crew cabin and operated autonomously. Transition from the SERJ RBCC engine to the tail rocket occurred at Mach 6 (peak ramjet speed).

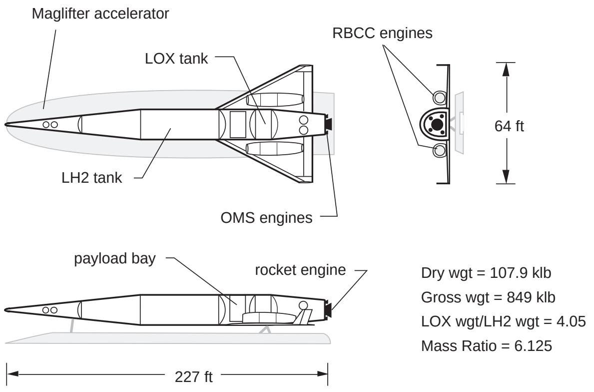


Fig. 1. SERJ RBCC with Maglifter Concept from HRST Phase 1.

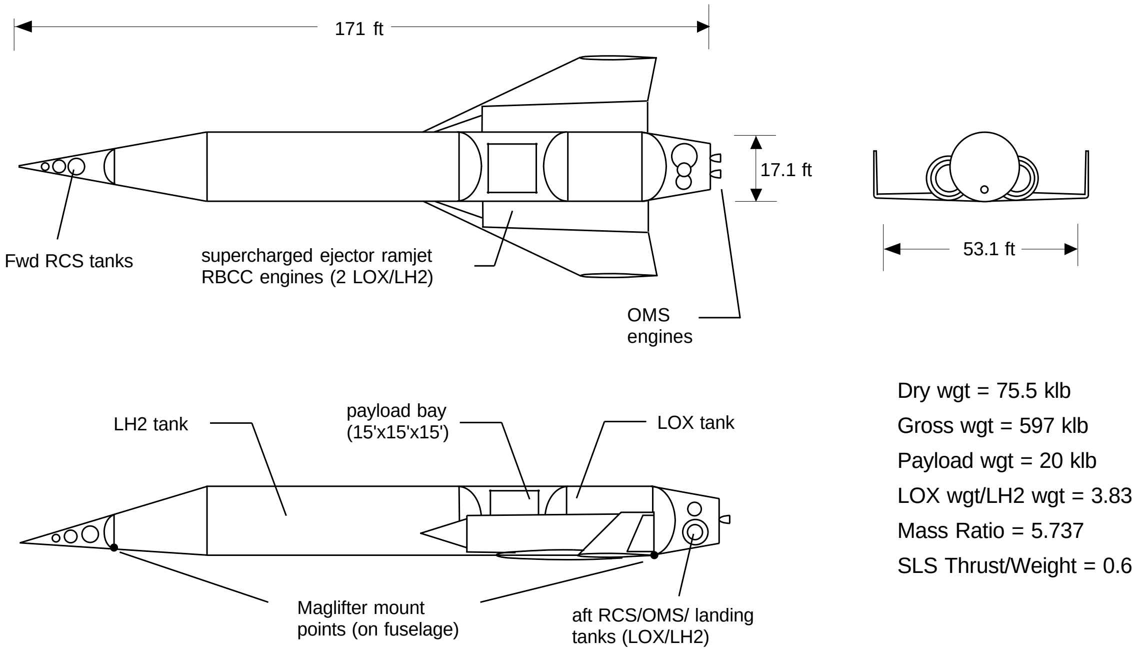
Among the recommendations from the phase 1 concept definition was to eliminate the redundant tail rocket and instead rely solely on the built-in rocket mode of the SERJ engine. Along with several specific trade studies on the vehicle ascent profile, a full life cycle cost and economic analysis on the modified concept was also recommended. These changes were implemented during a HRST phase 2 study by the lead author (now at Georgia Tech) and a team of graduate students in the Aerospace Engineering school lead by the second author. This modified concept has been named *Argus*. *Argus* has subsequently been evaluated as one of the more promising concepts to emerge from the HRST study [2].

BASELINE ARGUS CONCEPT

Argus System Overview

Argus is designed to be a low cost cargo delivery system to LEO. A magnetically-levitated sled (Maglifter) is used to provide an initial ground-based launch assist. LOX/LH2 supercharged ejector ramjet engines provide the main motive power to the vehicle. These engines operate in supercharged ejector, fan-ramjet, ramjet, and pure rocket modes during ascent and can provide several minutes of powered loiter time during landing. The baseline configuration can deliver a 20,000 lb. payload to a 100 nmi. circular, 28.5 deg. inclination orbit from Kennedy Space Center and approximately 11,100 lb. to the International Space Station (ISS). For additional revenue, a 'passenger module' can replace the payload in the payload bay to transport up to six passengers to orbit and back. In an operational system, a fleet of three vehicles can fly 149 flights/yr. and achieve a favorable return on investment of 28%. Aggressive weight and cost assumptions were used throughout the analysis.

As sized to deliver a 20,000 lb. payload to LEO, the baseline *Argus* is 171 ft. long along the fuselage with a fuselage fineness ratio of 10. The wingspan is 53.1 ft. with a wing sweep of 65 deg. and theoretical wing planform area of 2,825 ft^2. The wing is only 4% thick, has a taper ratio of 0.35 and a theoretical aspect ratio of 1.0. A combination of vertical winglets and reaction control thrusters are used for lateral control throughout the mission. Each SERJ engine has an inlet area of 60.6 ft^2 and is sized to deliver a sea-level static thrust in ejector mode of approximately 180,000 lbs. with an initial secondary-to-primary flow ratio of 3.44. The engines were assumed to have a length-to-diameter ratio of 5.5. The payload bay volume is 3,375 ft^3 (a payload density of about 6 lb/ft^3).



Dry wgt = 75.5 klb
Gross wgt = 597 klb
Payload wgt = 20 klb
LOX wgt/LH2 wgt = 3.83
Mass Ratio = 5.737
SLS Thrust/Weight = 0.6

Fig. 2. Current *Argus* Concept.

Using a launch assist velocity of 800 fps (velocity at the start at of angle-of-attack rotation), *Argus* has a gross liftoff weight of approximately 597,250 lb. and a payload mass fraction of 3.35% for LEO cargo delivery missions. Without payload or propellants, the vehicle dry weight is approximately 75,500 lb. The ratio of payload to payload plus dry weight is 0.201. The required mass ratio was determined to be 5.737 (initial mass/burnout mass) for an equivalent propellant mass fraction of 0.826. The tanked mixture ratio of LOX/LH2 is 3.83 by weight. A three-view drawing of the *Argus* concept (orbital vehicle) is shown in Fig. 2. Artist Pat Rawlings' rendition of the vehicle at a future spaceport is shown in Fig. 3 [2].

Fig. 3. *Argus* Artist's Rendition.

Maglifter Track

Recent research has indicated that a magnetically-levitated sled operating along a concrete guideway with embedded superconducting magnets can accelerate a launch vehicle to speeds several times faster than those achievable with a steel wheels and rails approach. Mag-lev launch assist speeds as high as 600 mph – 1,200 mph and launch velocity angles from 0 deg. to 45 deg. have been suggested [3]. The power to drive a large mag-lev system could be supplied by underground superconducting magnetic energy storage devices or underground pneumatic storage chambers [4]. Such a system can benefit a launch vehicle in a number of ways to be discussed later. While the system is not yet mature for launch applications, research and even some development of 350 mph mag-lev trains is actively being conducted in Germany, Japan, and the United States.

The primary focus of the *Argus* conceptual design assessment has been placed on the orbital vehicle design rather than the Maglifter launch assist system.

However, some assumptions were made about the launch system. The baseline vehicle assumes a subsonic launch assist speed of 800 fps (545 mph) which avoids problems associated with supersonic travel on the ground (shock reflection, sonic booms, etc.). The track is assumed to be located in the vicinity of Kennedy Space Center (KSC) oriented for an easterly launch. KSC was chosen both for its traditional role as America's spaceport and its favorable geographic location for water overflight. Due to the topography of the site and the necessity to minimize construction costs, the track was assumed to be flat with no incline at the end. This configuration also avoids a possible negative g arc over maneuver required during an aborted launch attempt. Assuming an acceleration of 0.6 g during a baseline 800 fps launch and allowing for 1.2 g's during a launch abort, the combined launch/abort track will be approximately 5 miles long.

A preliminary sensitivity analysis on launch velocity considered a lower track velocity of 600 fps (410 mph). For the baseline *Argus* airframe, the payload was reduced by 13.4% when the track velocity was reduced to 600 fps. Alternately, if the payload was to be kept constant at 20,000 lbs. to LEO and the vehicle resized to meet that constraint, the dry weight of the launch vehicle increased by 4.4% when the track velocity was reduced to 600 fps. Clearly, the higher track speed is more desirable.

Argus Airframe Structure

Argus is a second-generation reusable launch system with an expected deployment date of 2010 - 2015. As such, it uses aggressive materials and subsystems technology assumptions throughout it's airframe. Compared to nearer-term materials such as those used on the shuttle or even the X-34, these advanced materials offer significant weight reductions.

As shown in Table 1, the exposed wing is constructed of Titanium-Aluminide (Ti-Al), an advanced lightweight, high temperature alloy on which preliminary research was conducted during the NASP program. In highly loaded areas such as the wing carry through structure, the metal matrix composite version of this material reinforced with Silicon-Carbide (SiC) fibers is used. Ti-Al was assumed to have a multi-use temperature of 1,500 deg. F and was assumed to be 35% lighter than conventional aluminum wing structures (40% in the carry through).

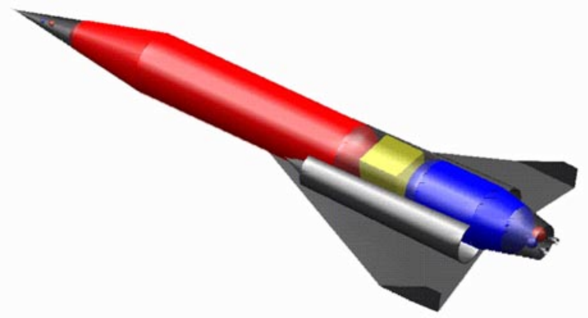


Fig. 4. *Argus* Internal Configuration.

Table 1 - Argus Structural Materials

Structure	Material	Notes
wing	Ti-Al	w/SiC carry through
LOX/LH2 tanks	graphite/PEEK	integral load paths
non-tank struct.	Ti-Al	some hot structure
payload bay	graphite/epoxy	intern. support struct.

The main propellant tanks are cylindrical in shape and integral to the load paths of the vehicle. The LOX tank is aft and the LH2 tank is forward (Fig. 4). The cargo bay is located between the two tanks. The tanks are assumed to be honeycomb graphite/polyether-etherketone (PEEK) or alternately graphite/epoxy. The cylindrical shapes reduce the manufacturing complexity by enabling filament winding of the tanks. In addition, the circular tank cross sections simplify hoop stress load paths and reduce tank weight. Integral tanks have been shown to be lighter than equivalent non-integral tank plus aeroshell construction, and do not share the latter's difficult purge requirements. These honeycomb tanks are assumed to save 30% - 35% relative to conventional aluminum materials and isogrid tank construction.

Non-tank primary structure is Ti-Al (at 2.21 lb/ft^2). Because of this material's high temperature use limit, some locations along the leeward side of the vehicle are designed to be 'hot structure' with no protective thermal protection covering. Payload bay internal structure is a lightweight graphite/epoxy (15%

lighter than equivalent aluminum). In addition to main structure, lightweight avionics, power, wiring, electromechanical actuators, landing gear, thermal control, and electrical distribution subsystems are assumed for *Argus*. Weight reductions ranging from 10% - 25% were assumed for these subsystems relative to current state of practice. A 15% dry weight growth margin was added to all dry weight line items.

A top level summary of the multi-line weight breakdown structure (WBS) produced for the baseline *Argus* concept is shown in Table 2. Values in Table 2 are rounded to the nearest 50 lb. The full mass properties statement for *Argus* consists of over 100 line items at three different levels of WBS. This data was determined using historical mass estimating relationships adjusted for weight reductions as outlined above. The sizing process was iterative between engine performance, launch trajectory optimization, engine weights, and airframe weight.

Table 2 - Argus Top-Level Weight Statement

WBS Item	Weight
Wing & Tail Group	10,250 lb.
Body Group (includes tanks)	18,000 lb.
Thermal Protection System	4,450 lb.
Main Propulsion (includes SERJ)	19,750 lb.
OMS/RCS Propulsion	1,400 lb.
Subsystems & Other Dry Weights	11,800 lb.
Dry Weight Margin (15%)	9,850 lb.
Dry Weight	75,500 lb.
Payload to LEO	20,000 lb.
Other Inert Weights (residuals)	8,600 lb.
Insertion Weight	104,100 lb.
LH2 Ascent Propellant	102,150 lb.
LOX Ascent Propellant	391,000 lb.
Gross Weight	597,250 lb.

Argus Propulsion

Argus is powered by two LOX/LH2 supercharged ejector ramjet engines [5,6]. The engines operate progressively in supercharged ejector, fan-ramjet, ramjet, and pure rocket modes throughout the ascent. A representative picture of a SERJ engine is shown in Fig. 5 [6]. Unlike the layout shown in Fig. 5, the SERJ engine used in this study does not have a fan disposal mechanism. Instead, the fan is assumed to be windmilled in place during high Mach number airbreathing flight. This capability will require technology advances over today's state of practice.

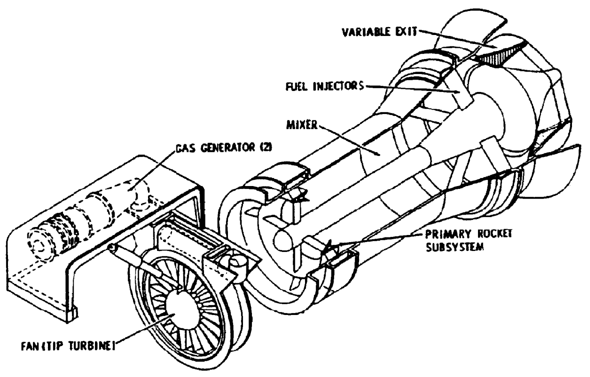


Fig. 5. SERJ RBCC Engine.

From the end of the Maglifter track, the vehicle is accelerated to Mach 2 under supercharged ejector ramjet power. Between Mach 2 and Mach 3, *Argus* transitions to fan-ramjet mode and intercepts a constant dynamic pressure boundary of 1,500 psf. Fan-ramjet mode assumes some flow compression benefit from the supercharging fan. *Argus* flies along this constant dynamic pressure path until Mach 6 (transitioning to conventional ramjet mode after Mach 3). Transition to internal RBCC rocket mode occurs at Mach 6 and the vehicle accelerates to a 50 nmi. x 100 nmi. parking orbit. Orbital maneuvering system (OMS) thrusters are used to circularize the orbit at apogee and deorbit the vehicle at the end of the mission. Five minutes of low thrust, fan-only operation is available at landing to provide runway area operational flexibility and safety. This same fan-only mode can be used to subsonically self-ferry the (almost empty) *Argus* from point-to-point after landing. Alternately, ramjet self-ferry is possible.

The rocket primaries in the SERJ engine are assumed to operate stoichiometrically in the airbreathing modes and therefore a diffusion-afterburning cycle is used. SERJ engine performance (thrust and I_{sp} vs. Mach number and altitude) in the airbreathing modes was determined using Georgia Tech's SCCREAM engine analysis tool for RBCC engines [7]. No forebody precompression was assumed to be derived from the *Argus* nose.

The rocket primaries are assumed to shift to a 7:1 LOX/LH2 mixture ratio during pure-rocket operation above Mach 6. The vacuum I_{sp} of this mode is assumed to be 462 sec. (representative of a high expansion ratio rocket). This I_{sp} assumption has a significant effect on the vehicle performance and additional research is recommended to determine if such an aggressive value can be achieved with proper development. For the engine geometry, secondary-to-primary flow ratio, and primary mass flow rate required, the SERJ engine installed thrust-to-weight ratio was estimated to be 20.03 using Georgia Tech's WATES RBCC engine weight estimation tool [8].

The OMS thrusters on the vehicle base and the smaller reaction control system (RCS) thrusters located at the nose and aft end of the vehicle use cryogenic LOX/LH2 (actually pressure fed gaseous O2/H2 for the nose RCS). The aft RCS system is integrated with the OMS thrusters and they share a common set of propellant and Helium pressurant tanks. The use of cryogenic propellants increases system performance (vacuum I_{sp} for the OMS of 462 sec. and 420 sec. for the RCS) and results in a common set of propellants with the main engines. Toxic hypergolic propellants are avoided.

Argus Thermal Protection System

Argus uses a passive thermal protection system (TPS) to protect the airframe from aeroheating extremes during ascent and entry (active regeneratively cooled panels are still required inside the engine). Maximum heating typically occurs at Mach 6 prior to rocket-mode transition during ascent. Hafnium-diboride SHARP TPS materials are used in the highest heating regions at the nose and along the wing and winglet leading edges. This material has a multi-use temperature near 4,250 deg. F and enables extremely small, low drag radii (on the order of 0.5 in. for the nose) to be used without active cooling complexities.

The bulk of the airframe is covered with an advanced 1,800 deg. F metallic panel TPS (about 35% of the surface area) and high temperature 1,200 deg. F flexible blankets (about 50% of the surface area). As discussed above, some of the fuselage and most of the wing leeward side is not protected by a surface TPS. Relative to today's state of practice in TPS design, the materials used on *Argus* are assumed to be significantly lighter weight. TPS unit weights of 1.06 lb/ft^2 and 0.50 lb/ft^2 for the metallic panels and blankets respectively, reflect a predicted weight savings of 30% - 50% relative to current Inconel metallic panels and TABI blanket insulation. To reduce the high number of TPS tile maintenance actions required on current space vehicles, large conformal TPS sections are employed on *Argus*. An inventory of approximately 50 - 100 separate tile sections (metallic or alternately a more robust TUFI-style ceramic) could replace the 1,000's of different tiles required for current vehicles.

DESIGN OBSERVATIONS

Argus was designed and optimized by the authors and a team of graduate students at Georgia Tech's Space Systems Design Lab. The process is highly coupled and iterative between several different engineering disciplines — aerodynamics, trajectory optimization, propulsion, vehicle sizing and mass properties, aeroheating, and engine mass properties. In addition to the Georgia Tech conceptual design tools discussed above, APAS [9] and POST [10] were used to perform the aerodynamic and trajectory optimization analyses, respectively. Once the contributing analysis models had been setup, a typical point design took from 4 – 6 hours to converge with most of the time consumed by repeated iteration between trajectory optimization (providing required mass ratio, mixture ratio, and maximum wing loading), vehicle sizing (resizing the vehicle photographically to meet the required propellant mass fraction and mixture ratio), and SERJ engine performance (providing new thrust and I_{sp} data for the resized engine geometry and new takeoff thrust requirements). This iteration was performed 'manually' among the different disciplines rather than via an automated design framework.

Benefit of Maglifter Launch Assist

The obvious benefit to the 800 fps launch assist for *Argus* is the reduction in total ΔV required to reach orbit. However, given *Argus*' total propulsive ΔV requirement of more than 32,000 fps required to reach

LEO, this relatively small percentage of the total does not account for the size advantage the *Argus* concept enjoys compared to non-launch assist systems. In addition to providing an initial velocity, the Maglifter provides the following important synergistic benefits to the *Argus* system.

1. Landing Gear vs. 'Takeoff' Gear. *Argus* rides on a mag-lev sled as it accelerates to 800 fps. Its internal main and nose gear are stowed until landing and are therefore not required to bear the full gross weight of the vehicle on takeoff. The result is that the gear weight on *Argus* is roughly 25% of the weight of conventional horizontal takeoff launch vehicles and this weight savings cascades throughout the design (smaller overall vehicle, fewer engines, etc.). It should be noted however, that this design decision creates a significant abort problem should the abort occur just after the vehicle leaves the track. In that case, nearly all of the propellants would have to be quickly dumped before a landing could be attempted.

2. Smaller Wing Size. With a takeoff rotation speed of 800 fps, *Argus* is able to generate considerable lift on relatively smaller wings than wings of conventional horizontal takeoff vehicles. This situation is very compatible with a single-stage launch vehicle because of the very large difference in takeoff and landing weight. That is, *Argus* is not penalized for having small wings on landing because the landed weight is only 16% of the liftoff weight. In addition, smaller wingspan wings are able to bear the load of takeoff somewhat easier than larger wings due to reduced bending moments at the wing root.

3. Better SERJ Performance. Unlike conventional rocket engines, the thrust and I_{sp} produced by a SERJ engine significantly improves with flight velocity for a given altitude. This augmentation can be as high as 25% - 30% near Mach 1. The use of the Maglifter puts the SERJ engine at a better point in its performance map at the start of the trajectory. In addition, *Argus* flies a relatively gentle pullout from the Maglifter as it accelerates toward a 1,500 psf dynamic pressure trajectory point at Mach 3. This avoids significant wing loads for a high g pullout common for a rocket-powered vehicle and is a more 'natural' launch condition for an airbreather. This shallow pullout also favors a more level track for *Argus* as opposed to a highly inclined track for an all-rocket craft.

Argus Operability

A key goal of the HRST study was to identify vehicle concepts with extremely low recurring cost. The *Argus* operational scenario assumes that future airframes, structures, and engines can be made highly reusable. Unlike shuttle-like systems which must be thoroughly inspected and often replaced after each flight, major *Argus* systems are assumed to have more aircraft-like lifetimes of 1,000 flights before replacement (500 for engines). Simple inspection and verification is all that is required between flights, and major scheduled maintenance occurs only every 250 flights. *Argus* relies heavily on advanced automated vehicle health monitoring (VHM) and built-in test (BIT) systems assumed to be available when the vehicle is deployed. The results are smaller spares requirements, minimal replacement hardware between flights, faster turnaround times (less than one week per vehicle), fewer airframes and engine sets required, and smaller ground operations crew sizes (approximately 50 cross-trained 'touch labor' personnel for the track and flight vehicle and a total of only 400 other personnel in the baseline *Argus* 'company').

The path toward achieving these aggressive operations goals has been the subject of some debate within the conceptual design community. It has often been suggested that more generous operating margins and factors of safety on engines, structures, and subsystems will lead to longer life, more robust components. However, this philosophy often leads to increased component mass, which when cascaded through the design process, leads to a larger vehicle, more or bigger engines, more TPS surface area, and more difficult ground handling problems. Thus the use of heavier and more robust 'over-designed' components helps one measure of operations while hurting others. The challenge to future system designers will be to design robust, operable structures and components that do not significantly increase system mass. The baseline *Argus* system uses standard aerospace margins on components (e.g. 1.5 on wing loads, 1.4 on allowable stresses, 4.0 on high pressure bottles), but assumes that future advances in these components will produce a robust aircraft-like operations environment.

Enabling Technologies for Argus

In addition to the dominate requirements for a high speed Maglifter launch assist track and a Mach 6 capable LOX/LH2 SERJ RBCC engine, the *Argus* concept depends on several key technologies that must be mature 3 – 5 years before the concept is deployed.

1. Advanced Structural Materials. *Argus* derives significant weight savings from the use of Ti-Al, Ti-Al/SiC, and graphite/PEEK or epoxy structures. Small Ti-Al components and test articles had been manufactured under the NASP program before it was cancelled, but additional research is needed. Large-scale cryogenic graphite tanks for reusable launch vehicles will be tested on the X-34 and X-33.

2. Thermal Protection Systems. High temperature hafnium-diboride has the potential to eliminate active panel cooling complexity from an entire class of airbreathing launch vehicles while retaining low drag wing and nose configurations. While this material is heavy, the operational advantages are the real reason to adopt it. Lighter weight TPS blankets and large-block metallic (or alternately a TUFI-style ceramic) conformal TPS sections for windward heat protection are equally critical to achieving predicted operations and weight reduction payoffs. NASA – Ames is leading valuable research in these areas.

3. Subsystems. *Argus* assumes a number of advances in vehicle subsystems. Cryogenic OMS/RCS systems increase performance, eliminate toxic fluids, and use common fuels with the main propulsion system. An integrated aft OMS/RCS system (with common tanks) can reduced system complexity. Hydraulics were eliminated on *Argus* in favor of electromechanical actuators to improve ground operations. Lightweight avionics, batteries, power distribution, wiring, and thermal control are critical for reducing overall vehicle weight to the aggressive levels shown. VHM and BIT are important for reducing ground crew size and vehicle turnaround times.

The technologies and weight reduction assumptions to achieve a desired vehicle size and configuration are perhaps the easiest to identify. Using that vehicle to achieve significant launch cost reductions is a more difficult exercise. Achieving significant reductions in cost will require a cultural change in the space launch community. Vehicle designers must understand the business impact of their decisions, and business managers must optimize their entry into the commercial space launch market.

COST AND ECONOMICS

After the *Argus* vehicle configuration was determined, a conceptual assessment of its development cost, production costs, fleet size, operational costs, and even its potential revenue stream was determined. This assessment was made using Georgia Tech's CABAM cost and business modeling spreadsheet [11]. This model includes NASA-developed cost estimating relationships for determining non-recurring costs associated with a given launch vehicle. Vehicle flight rates are determined as a function of payload size (or number of passengers per flight) and the size of the available market. CABAM uses data from NASA Commercial Space Transportation Study (CSTS) [12] and user entered competition models to approximate the price elastic behavior of four potential LEO markets — government cargo, government passengers, commercial cargo, and commercial passengers. The 'medium' market growth models from the CSTS study was used for the baseline, but the nuclear waste disposal market was not included. For conservatism, all cargo traffic from the CSTS model was assumed to be destined for ISS orbit. In addition, a 15% penalty for incompatibilities between multiple manifested payloads was assumed. Therefore, for the economic study, *Argus* was assumed to deliver an average of only 9,435 lb. of CSTS payload in a single flight.

Within this dynamic economic simulation, changing *Argus* market entry prices for each of the four markets results in an increase or decrease in potential traffic in each market, a change in the number of flights per year required to capture the markets, a change in annual revenue from each market, and a possible change in fleet size required (due to minimum turnaround time or more often the requirement to replace airframe or engine hardware that has exceed its 1,000 or 500 flight limit). While the objective of the HRST study was to examine vehicle concepts that could reduce recurring operating costs to below \$100/lb. - \$200/lb. of payload delivered, the goal of the present research was to identify the optimum pricing strategy that results in maximum internal rate of return (IRR). IRR is defined as the discount rate for a certain project that results in a \$0 net present value. Neglecting risk, higher IRR's are better.

Argus Business Model

Argus will be operated by a private business, but the government was assumed to have a significant financial interest in the success of the venture. The U.S. government is a very heavy user of launch services and launch cost reductions will ultimately benefit the taxpayers. Therefore, in the following financial data, the government was assumed to pay for 100% of the SERJ RBCC engine non-recurring development cost (DDT&E), the two Maglifter launch assist systems, and 20% of the *Argus* airframe DDT&E. As an added contribution, the government also was assumed to guarantee commercial debt loans made to the *Argus* company so that financing could be obtained at a reasonable interest rate (12%). All airframe and engine production costs as well as all operations and financing costs are borne by the *Argus* company. While these government contributions may seem excessive to some, analyses performed without early government contributions or loan guarantees were shown to provide unacceptably low IRR's.

Table 3 - Optimized CSTS Market Prices for Argus

Market	Price	Traffic
Comm. Cargo	\$800/lb.	1,000 klb/yr.
Comm. Pass.	\$0.72M/pass.	33 pass./yr.
Gov't Cargo	\$1,640/lb.	297 klb/yr.
Gov't Pass.	\$9.42M/pass.	33 pass./yr.

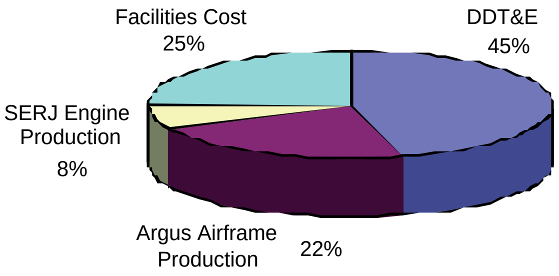


Fig. 6. Non-Recurring Cost Breakdown.

The optimized business scenario resulted an IRR of 28.1% with a fleet size of three *Argus* vehicles, two tracks, 450 personnel in the company, and a total steady state flight rate of 149 flights per year (106 commercial cargo, 31 government cargo, and 6 passenger/astronaut flights to each market). The company operates *Argus* for 15 steady state years after a two year ramp up and flies a total of about 2,500 flights. The venture is predicted to break even two years after initial operations begin. Non-recurring costs (DDT&E, engine and airframe production, facilities construction, but not financing costs) of the entire venture is estimated to be \$8.9B (96\$) of which the U.S. government is expected to contribute \$3.3B (96\$). See Fig. 6 for a distribution.

Specific market price results are given in Table 3 in 1996 constant year dollars. Recall that the prices per pound of cargo reflect an ISS destination. A commercial cargo price of \$800/lb. would therefore generate about \$7.55M in revenue (accounting for the reduced average *Argus* payload capacity to ISS of 9,435 lb.). Note that the less price elastic government traffic models result in a higher optimized market price for government missions compared to commercial missions. That is, the size of the government launch market is relatively constant over a wide range of prices, so the IRR optimization tends toward a higher price.

Relative to current expendable launch vehicle prices in this class, the optimized market prices represent only about a factor of five decrease in price for commercial payloads and a factor of two decrease in price for government payloads. The reductions are more significant with respect to the Space Shuttle, but dramatic multiple orders of magnitude decreases in access to space costs do not appear likely given the current models and assumptions if the proposed company is to achieve an attractive rate of return for its investors. It should also be noted that an IRR of 28.1% initially appears attractive, but it must be compared in light of the perceived risk associated with a new launch venture. Investors and company decision makers might demand a return as high as 35% or more for a program such as this with significant risk and uncertainty.

Argus Recurring Costs Per Flight

For *Argus*, very aggressive assumptions were made to determine recurring costs. For this study, recurring costs were assumed to be the sum of the following four items (1996 dollars). Other contributors (track power, etc.) are assumed to be small.

1. Labor costs at a $150,000/yr. encumbered rate per employee. Converted to a per launch cost.
2. Line replaceable unit spares at 0.15% of airframe weight replaced per flight times an average cost of $10,000/lb. of hardware.
3. Airframe replacement insurance at 0.03% of airframe value per flight based on expected high reliability of 0.9997. Note that this type of insurance is not currently available and unless backed by government guarantees, premiums will be prohibitive.
4. Propellant costs at $0.10/lb of LOX and $0.25/lb of LH2 based on the assumption of an on-site propellant production facility. Converted to a per flight propellant cost.

Based on these assumptions, each flight of *Argus* is estimated to cost $1.6M (96$). A recurring cost breakdown is given in Fig. 7. For a typical Space Station cargo delivery mission with an average actual payload delivered of 9,435 lb., the recurring cost per pound of payload is therefore $169/lb. The cost per pound for delivering payloads to a 100 nmi. due east orbit is potentially lower. It is important to note that this is a somewhat artificial value. *Argus* customers pay the optimized launch price in Table 3, not the recurring cost. The price includes recurring costs, amortized hardware and design costs, financing costs, and company profit and thus is several times higher.

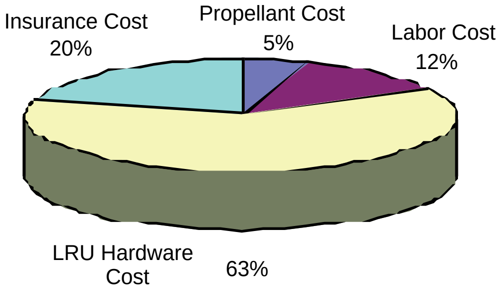


Fig. 7. Recurring Cost Breakdown.

TRADE STUDIES

Several one-variable-at-a-time trade studies were performed on the baseline *Argus* concept to determine key sensitivities and alternate configurations. The following sections give results from three such trade studies.

Payload Mass

The HRST study guidelines specify a payload range of 20,000 lb. (Atlas-class) to 40,000 lb. (Titan-class) for delivery to LEO. The baseline *Argus* concept delivers a 20,000 lb. payload. Fig. 8 gives the change in the baseline *Argus* concept's dry weight and gross weight as the payload is changed to 40,000 lb.

While the payload mass fraction of the 40,000 lb. payload configuration is more efficient than the baseline case (4.73% vs. 3.35%), the lower flight rates

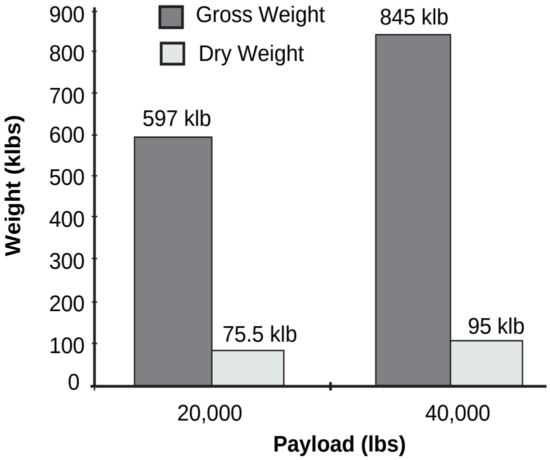


Fig. 8. Argus Sensitivity to 40 klb Payload.

and higher initial design and development cost of the larger vehicle tend to reduce the IRR for business models built on the larger version. Therefore, for a business perspective, the smaller vehicle is preferred. In fact, trends indicate that payload ranges of 10,000 lb. – 15,000 lb. might be the most financially attractive, but these configurations have not been explored.

Target Orbital Destination

Figure 9 shows the performance of the baseline *Argus* concept when flown to the International Space Station orbit (220 nmi. x 51.6 deg. inclination) rather than the baseline LEO (100 nmi. x 28.5 deg.) destination. The vehicle mold line and propellant loading were kept constant. Both missions entered an intermediate parking orbit with a perigee of 50 nmi. before using OMS propulsion to circularize into the final orbit. The baseline *Argus* can deliver a maximum of 11,100 lbs. to the Space Station orbit. As discussed above an average actual delivery mass of 9,435 lb. was used in the cost analysis as the conservative destination of all CSTS cargo traffic to account for packaging losses when manifesting multiple payloads on a single flight.

Operability Margin

During the discussion of vehicle operability, it was suggested that one mechanism to reduce maintenance problems, reduce inspections, etc. was to design excess 'robustness' into key structural, subsystem, and engine components. These extra factors of safety or high design limits relative to the operating conditions are typically manifested in additional dry weight. Fig. 10 shows the effect of adding an 'operability margin' to the baseline Argus dry weight.

This operability margin is in addition to the standard 15% dry weight growth margin that is present on the baseline design, but differs in that it is only added to components that could benefit from additional weight (wing, tail, structure, tanks, engine, TPS, and landing gear). As discussed above, the baseline *Argus* uses standard factors of safety in its design and has no additional operability margin specifically added. For a 10% operability margin, there is approximately a 13% increase in vehicle dry weight. Whether this additional weight, size, and the associated non-recurring cost increase is balanced by expected operations costs savings remains to be determined.

CONCLUSIONS

This paper presents a summary of the *Argus* conceptual design assessment performed in support of NASA's Highly Reusable Space Transportation study. A summary of the vehicle technical design features, a conceptual cost and economic study, and several trade study results were presented. The following points are among the specific conclusions reached in this paper.

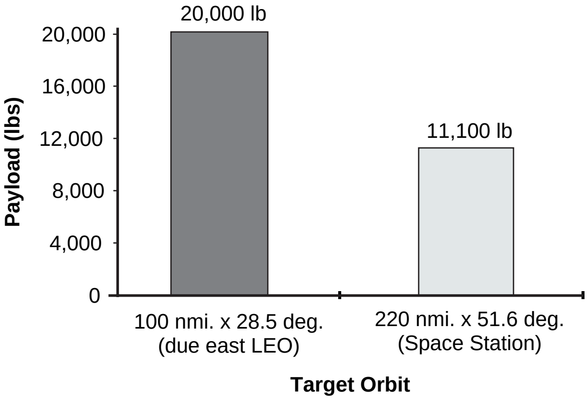


Fig. 9. Space Station Payload Delivery Mission.

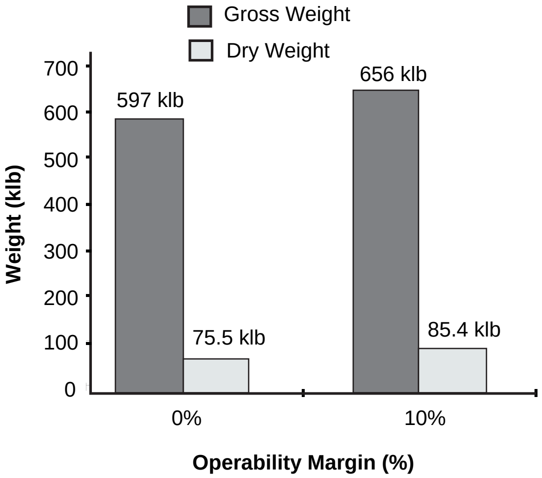


Fig. 10. Argus Sensitivity to Operability Margin.

1. The *Argus* flight vehicle is an attractive size and weight for delivering cargo and even passengers to LEO. It offers a relatively large payload mass fraction of 3.35% and avoids the use of scramjet propulsion. However, it does make aggressive weight reducing technology assumptions in structure, TPS, and subsystem weights, so should not be considered a *near-term* launch vehicle candidate. However, a target deployment date of 2010 - 2015 seems reasonable.

2. The Maglifter ground-based launch assist system offers some particularly synergistic benefits for the SERJ-powered *Argus*. When coupled with the Maglifter, *Argus* has lighter landing gear, smaller wing, and better engine performance. Due to its more shallow trajectory, steep track release angles are not necessary and a 0 deg. departure angle was baselined.

3. A conceptual cost and business model assessment of the *Argus* system shows an optimized IRR of 28.1% for a fleet of three vehicles serving commercial and government cargo and passenger markets to LEO and the Space Station. The recurring cost per pound of payload was estimated to be $169/lb. for the ISS mission— meeting the HRST target of $100/lb. - $200/lb. However, given the risk and uncertainty involved, a 28.1% IRR might still be insufficient for investors. Also, the optimized market prices (not costs) show only a moderate advantage over current expendable launch vehicles and so significant reductions in the cost of access to space were not realized with the current analysis models.

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