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Stargazer: A TSTO Bantam-X Vehicle Concept Utilizing Rocket-Based Combined-Cycle Propulsion

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ABSTRACT

This paper presents a new conceptual launch vehicle design in the Bantam-X payload class. The new design is called *Stargazer*. *Stargazer* is a two-stage-to-orbit (TSTO) vehicle with a reusable flyback booster and an expendable LOX/RP upper stage. Its payload is 300 lbs. to low earth orbit. The Hankey wedge-shaped booster is powered by four LOX/LH2 ejector scramjet rocket-based combined-cycle engines. Advanced technologies are also used in the booster structures, thermal protection system, and other subsystems.

Details of the concept design are given including external and internal configuration, mass properties, engine performance, trajectory analysis, aeroheating results, and a concept cost assessment. The final design was determined to have a gross mass of 115,450 lb. with a booster length of 99 ft. Recurring price per flight was estimated to be $3.49M. The overall conceptual design process and the individual tools and processes used for each discipline are outlined. A summary of trade study results is also given.

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NOMENCLATURE

C_t	thrust coefficient
I_{sp}	specific impulse (sec.)
q	dynamic pressure (psf)
T/W_e	engine thrust-to-weight ratio

INTRODUCTION

The goal of NASA's Bantam-X program is to identify key vehicle technologies that will enable significantly lower cost launch services for the ultra-lite and small payload community. This 300 lb. – 500 lb. payload class is often associated with University Explorer scientific missions. Budgets for these flights are typically limited (less than $1M - $1.5M for a dedicated flight), but scientific and educational value can be significant. Aggressive new concepts and technologies are needed to address this potential user base. NASA has segregated its program into technologies suited for a near-term launch vehicle solution (initial operational capability before 2005) and those more suited for an IOC around 2008 – 2010. Airbreathing propulsion technologies are included in the latter set.

This paper summarizes part of an 18 month Bantam-X concept study conducted by the Space Systems Design Laboratory at Georgia Tech with the support and collaboration of NASA Marshall Space Flight Center. The study goal was to investigate a promising concept based on rocket-based combined-cycle (RBCC) propulsion for longer range Bantam-class missions. NASA MSFC currently has an ongoing development program in RBCC engines.

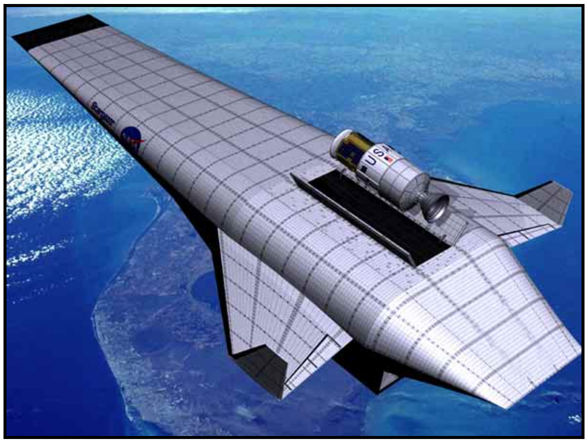

Fig. 1. *Stargazer* Concept.

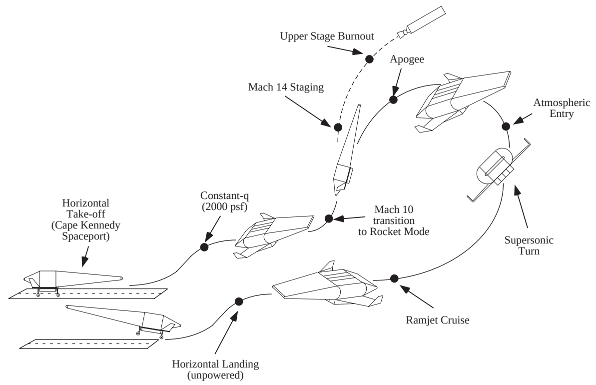

Fig. 2. *Stargazer* Mission Profile.

CONCEPT OVERVIEW

As shown in Fig. 1, the *Stargazer* concept uses a wedge-shaped booster derived from a Hankey wedge forebody configuration. Hankey wedges (a symmetric wedge with rounded shoulders) have been shown to have an attractive compromise between high hypersonic lift-to-drag ratio and volumetric efficiency for internal packaging.[1] Booster propulsion is provided by four LOX/LH2 ejector scramjet RBCC engines mounted under the wedge on the windward side. The booster is fully reusable. *Stargazer* uses a small, low cost expendable LOX/RP-1 upper stage to place a 300 lb. payload into low earth orbit.

MISSION PROFILE

Stargazer is a horizontal takeoff, horizontal landing vehicle. It operates from a notional airfield at Kennedy Space Center. Initial acceleration occurs in ejector mode. From about Mach 3 dual mode LH2 ramjet/scramjets are used to accelerate the booster and enclosed upper stage to Mach 10 along a 2,000 psf dynamic pressure boundary (Fig. 2). At Mach 10, the booster uses its internal rocket mode to accelerate off of the q boundary to a high altitude Mach 14 staging point. The upper stage is jettisoned as the dynamic pressure falls to below 2 psf. The booster then performs a descending turnaround and initiates a ramjet powered flyback to KSC while the upper stage ignites and accelerates the payload into a 200 nmi. circular low earth orbit with a 2-burn trajectory.

DESIGN PROCESS & DISCIPLINARY ANALYSIS

Stargazer was designed using a collaborative, multidisciplinary integrated design team approach. Team members executed individual disciplinary analysis tools in an iterative conceptual design process, exchanging information and data files, for each candidate configuration until the propellant mass fractions for each mission segment were converged. The overall Design Structure Matrix (DSM) for the *Stargazer* design process can be seen in Fig. 3. The bolded box represents the main disciplinary iteration loop, the details of which are shown in Fig. 4.

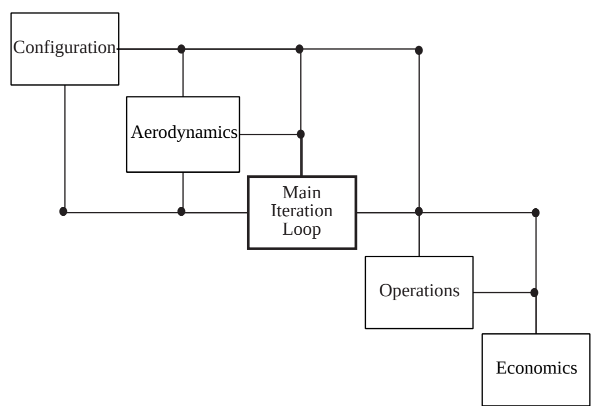

Fig. 3. *Stargazer* DSM.

Design structure matrices are a useful mechanism for showing the data interdependencies in a multidisciplinary design process. In the diagrams, lines above the disciplines on the diagonal represent data that must flow "downhill" from one discipline to a subsequent discipline. Lines below the diagonal represent data that is fed back "uphill" to a previous discipline, therefore requiring iteration between the disciplines. The main iteration loop exhibits strong coupling among the propulsion, performance (trajectory optimization) and weights & sizing disciplines. The aeroheating (thermal protection system) discipline is rather weakly coupled with the other three beyond the first iteration.

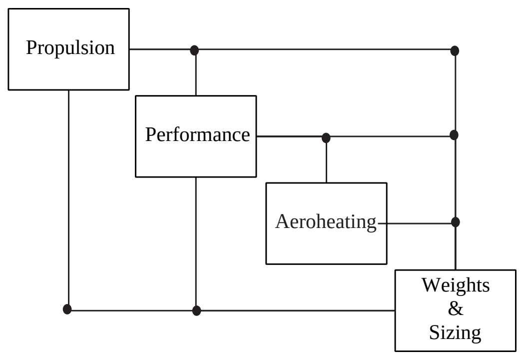

Fig. 4. Main Iteration Loop.

At the beginning of the design exercise, a brainstorming session occurred in order to create an initial configuration. During this session, all analysts had a chance to give inputs. Next, the first two disciplines in Fig. 3 iterated to find a feasible packaging and aerodynamic configuration. Once a feasible configuration was determined, the analyses in Fig. 4 iterated to find a converged, properly scaled design to deliver the 300 lb. payload. Vehicle convergence was based on a relative tolerance of 0.1% applied to both the dry and gross weights. The operations and economics disciplines in Fig. 3 were analyzed after a converged design was created. Additional details on the assumptions that went into discipline and selected results from each discipline are given in the following sections.

Configuration

For most conceptual designs performed at the Space Systems Design Laboratory, the process of defining the external and internal geometry is an iterative one between the aerodynamics engineer and the configuration (CAD) engineer. For an estimated vehicle length, the configuration engineer lays out the propellant tanks and payload bay within the available fuselage volume according to the required mixture ratio between LOX and LH2. Reference propellant tank volumes, fuselage surface areas, and other key geometric variables are subsequently determined. Ordinarily, a matrix of two or three estimated lengths and two or three mixture ratios are performed to allow rapid interpolation during the subsequent scaling and sizing process.

For the *Stargazer* design, an initial propellant packaging configuration was created in the SDRC I-DEAS solid modeling software system. However, given that *Stargazer* is constructed of simple shapes (wedges, cylinders, elliptical domes), it was determined that *analytical* models of the fuselage volume and individual tank volumes could be created from geometry relationships. Therefore, subsequent configuration analysis for *Stargazer* was evaluated analytically using geometric relations in a Microsoft Excel© spreadsheet. The analytical spreadsheet was verified using SDRC I-DEAS. This analytical model results in a more exact estimate of volumetric packaging efficiency than the baseline interpolated results from the CAD program. Given a required propellant mixture ratio, required LOX propellant load, forebody wedge angle, and engine length, the spreadsheet determined all tank and vehicle lengths, surface areas, and volumes. To expedite data exchange with the weights & sizing discipline, the new configuration spreadsheet was directly integrated with the weights & sizing spreadsheet.

The internal fuselage volume of the *Stargazer* booster is occupied by seven propellant tanks and the internal cargo bay that holds the upper stage. Integral LH2 tanks follow the forward and aft fuselage mold lines. A center longitudinal LH2 tank is mounted below the payload bay. The relative lengths of the four propellant tanks in the main fuselage section (one LOX and one LH2 on each side) can be changed to accommodate a required LOX/LH2 mixture ratio. A three-view for the final booster configuration is shown in Fig. 5. The final configuration was recreated in I-DEAS. Fig. 6. gives a cutaway view of the CAD model showing the internal tank layout.

Aerodynamics

The aerodynamic analysis for *Stargazer* was performed using the conceptual design tool called Aerodynamic Preliminary Analysis System (APAS).[2] APAS was developed by Rockwell International as an aid in the design of the Space Shuttle. Coupled with two other codes, Uniform Distributed Panel (UDP) for

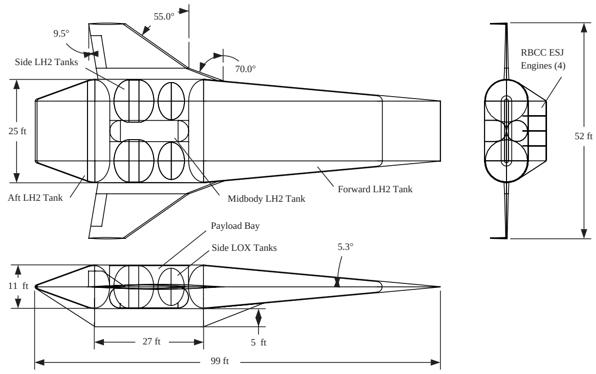

Fig. 5. 3-View of Baseline *Stargazer*.

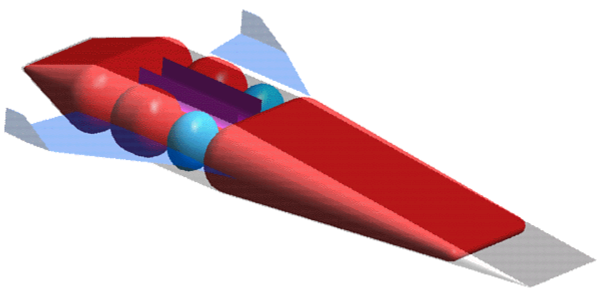

Fig. 6. *Stargazer* Tank Layout.

low speed analysis and Hypersonic Arbitrary Body Program (HABP) for high speed analysis, APAS provides a quick and effective tool for calculating the aerodynamic force coefficients of a given launch vehicle.

The *Stargazer* booster fuselage is derived from a Hankey wedge forebody. The Hankey wedge, a symmetric wedge with rounded shoulders, has been shown to yield an attractive compromise between a high hypersonic lift-to-drag ratio and a high internal volumetric efficiency for propellant. A 5.25° wedge half-angle was somewhat arbitrarily chosen to balance the competing needs of a low drag profile and adequate forebody compression for the propulsion system. Trade studies could be performed to determine a more optimum wedge half-angle.

Wings swept at 55° provide primary lift at takeoff and landing. Vertical wingtip controllers are used for active lateral control (but are not sized for static lateral stability). The subsonic analysis module of APAS (UDP) is not well suited to low speed analysis of winged wedges, so required wing planform area was determined by estimating the maximum wing loading at takeoff. Takeoff weight divided by theoretical wing planform area (extended into the fuselage) was taken to be 86 lb/ft^2. The resulting wing planform area for the final configuration is 1,325 ft^2. Wingtip controller planform area was 2.5% of wing area for each controller.

APAS requires input of the vehicle external geometry and parameters such as the reference wing planform area, leading edge sweep angle, wing thickness ratio (4%), and an estimate of the center of gravity (54% back from the nose). While rudimentary techniques exist to transfer the external geometry surface data from I-DEAS to APAS, in this case, the geometry was recreated directly within APAS using its geometry editing tools. Analysis was performed at several flight conditions along the expected flight path. The analysis points are input via 8 - 10 ordered pairs of Mach number and altitude and a range of angles-of-attack for each. Sideslip angles were not considered.

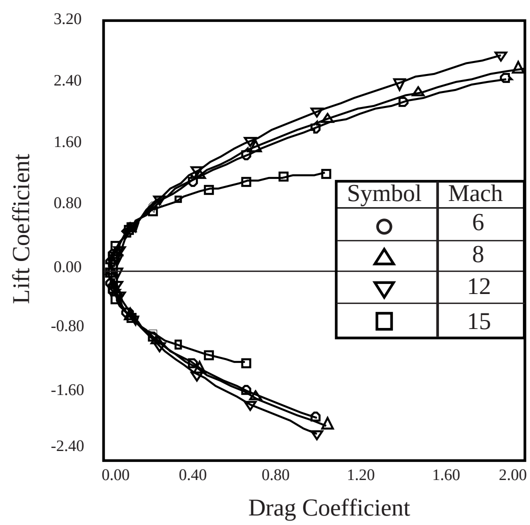

Fig. 7. *Stargazer* Drag Polar.

Using APAS, tables of lift and drag coefficients for each angle-of-attack at each Mach number were produced. A sample drag polar from APAS can be seen in Fig. 7. Pitching moment coefficients were also generated, but the subsequent trajectory analysis did not consider trim. The entire aerodynamic database of approximately 500 aerodynamic coefficients was thus created and provided to the trajectory analyst. The *Stargazer* design process used a photographic scaling approach to match internal propellant load to the required propellant. Therefore, the relative external geometry did not change as the vehicle was resized. The aerodynamic coefficients remained constant while actual values of lift and drag forces depended only on the rescaled wing area. Thus the aerodynamic analysis was only necessary at the beginning of the entire convergence process.

Propulsion

The propulsion system analysis was performed using the 'Simulated Combined Cycle Rocket Engine Analysis Module' (SCCREAM).[3] SCCREAM is a one-dimensional analysis code that is capable of analyzing all modes of RBCC engine operation. The final output from SCCREAM is an engine deck preformatted for use in a trajectory simulation program. This engine deck includes engine thrust, thrust coefficient, and I_{sp} for a range of altitudes and Mach numbers for each operating mode.

The *Stargazer* booster stage uses four liquid oxygen and hydrogen ejector scramjet (ESJ) engines to accelerate the vehicle to the staging point at Mach 14. The RBCC engines also provide the return to launch site capability when cruising under ramjet mode power. Fig. 8 shows the engine layout and station identifications used by SCCREAM. The engines were mounted on the lower side of the vehicle, which provided 5.25° of forebody compression.

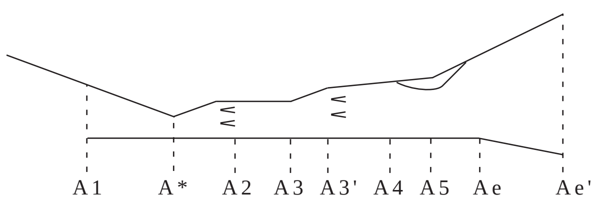

Fig. 8. *Stargazer* ESJ Engine Configuration.

An engine cowl height of 3.0 feet for the final scaled booster was determined based on a Mach 10 shock-on-lip condition. Each engine width of 5.4 feet was dictated by the final scaled booster width. A variable inlet geometry and exit nozzle were assumed. For the final scaled booster, the total engine length, including a Mach 10 inlet, was estimated to be 27 ft.

A LOX/H2 rocket primary with a chamber pressure of 2,000 psi and an ejector mode mixture ratio of 8.0 was selected. The engines were sized at sea-level-static (SLS) conditions to meet the vehicles' overall takeoff thrust-to-weight ratio of 0.7. Each engine is thus capable of producing 20,200 lbs. of thrust at SLS, with an I_{sp} of 421 seconds. Using this process of specifying an inlet area and a required thrust takeoff, the initial secondary-to-primary bypass flow ratio is an output of the propulsion analysis. For the *Stargazer*, the secondary-to-primary flow ratio at SLS was 3.5.

Table 1 provides the internal engine geometry values and fuel injection properties for a single *Stargazer* engine. With a minimum internal contraction ratio of 1.95, the lowest possible Mach number at which the inlet could start for ramjet operation was Mach 2.9. The inlet is never able to start during ejector mode operation because the inlet throat must be closed down to limit the secondary flow rate, which drives the Mach number at the exit of the mixer section. A maximum mixer exit Mach number of 0.8 was specified in SCCREAM. At Mach numbers greater than this, experimental work has shown the flow can trip and become supersonic upon entering the combustor, generating excessive performance losses.[4]

Table 1. *Stargazer* ESJ Engine Data.

inlet area, A_1	16.23 ft^2
primary throat, A_t	0.412 ft^2
mixer area, A_3	9.02 ft^2
combustor break, $A_{3'}$	12.62 ft^2
combustor exit, A_4	16.42 ft^2
maximum exit area, $A_{e'}$	52.75 ft^2
combustor efficiency, η_c	95.0%
nozzle efficiency, η_{nozz}	98.5%
friction coefficient, f	0.001
fuel inlet temperature, T_f	500.0 R
fuel injection velocity, V_f	4,000 ft/s
fuel injection angle, θ_i	0.0 deg

Fig. 9 shows the net specific impulse versus Mach number during ejector mode operation. Between Mach 3.0 and 3.5, transition to ramjet mode is modeled by linearly throttling the ejector mode down while the ramjet mode is ramped up. Fig. 10 shows the net thrust coefficient (C_t) versus Mach number for ramjet and scramjet mode operation for a single engine. To obtain the thrust coefficient, the thrust was normalized by the dynamic pressure (q) and inlet area of 16.23 ft^2. Note that the propulsion force accounting system in

SCCREAM is cowl-to-tail. All forebody pressures are included in aerodynamic drag calculated by APAS. Forebody calculations are performed in SCCREAM to determine mass capture at various flight conditions, but the pre-compression effects are not used to reduce the cowl-to-tail thrust coefficients and I_{sp}'s.

Evident in Fig. 10 is the significant increase in performance due to the inlet starting at Mach 2.9. Additionally, an equivalence ratio of 1.0 is obtained at Mach 3.5 without unstarting the inlet, further increasing the thrust of the engine. Fig. 11 shows the net specific impulse in ramjet and scramjet modes.

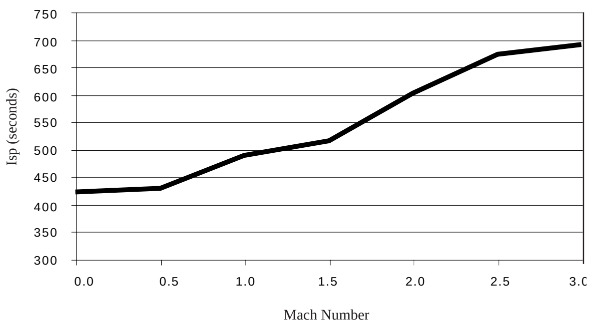

Fig. 9. Ejector Mode Net Specific Impulse.

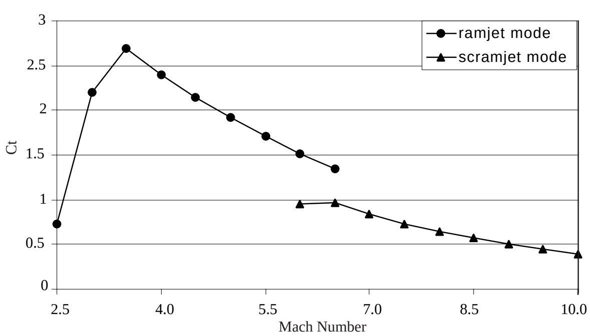

Fig. 10. Thrust Coefficient vs. Mach Number.

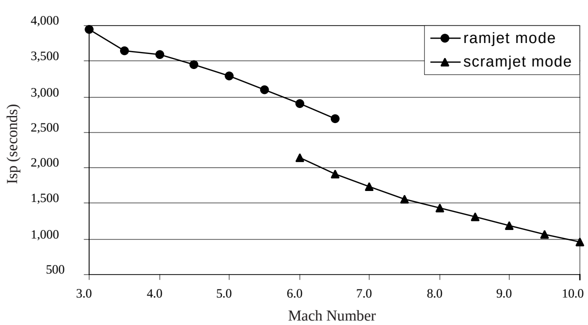

Fig. 11. Net I_{sp} vs. Mach Number.

When operating in the all-rocket mode between Mach 10 and Mach 14, *Stargazer* generates a maximum of 76,700 lbs. of vacuum thrust, at a vacuum I_{sp} of 442 seconds. The rocket performance calculations used the same rocket primary subsystem from the ejector mode, operating with an assumed expansion ratio of 180 and a more optimal rocket-mode mixture ratio of 7.0. The high exit expansion ratio is meant to account for aftbody expansion along the trailing wedge of the fuselage.

Performance

The trajectory analysis was performed by the three degree-of-freedom version of the Program to Optimize Simulated Trajectories — POST[5]. POST is a Lockheed Martin and NASA code that is widely used for trajectory optimization problems in advanced vehicle design. It is a generalized event-oriented code that numerically integrates the equations of motion of a flight vehicle given definitions of aerodynamic coefficients, propulsion system characteristics, weight models, etc. Numerical optimization is used to satisfy trajectory constraints and minimize a user-defined objective function. Multiple objective functions and simultaneous trajectory branches cannot currently be defined in POST.

As can be seen in the mission profile (Fig. 2), the *Stargazer* trajectory is a branching trajectory because the flight path splits at the staging point. Thus, in order to model the *Stargazer* trajectory efficiently it was modeled as three separate POST input decks — one for the ascent trajectory subproblem, one for the orbital branch subproblem, and one for the booster branch subproblem. Each subproblem has its own independent variables, constraints, and objective function. (Note that because of conflicting objective functions, this way of simulation will not necessarily result in an optimal overall trajectory. Research to correct this deficiency is currently underway at SSDL.[6])

The ascent trajectory deck involves the portion of the flight from horizontal take-off to staging at Mach 14. The trajectory is constrained by a maximum dynamic pressure boundary, a 3g acceleration limit in rocket mode, and a wing normal force limit of 1.75 times the gross takeoff weight. The former is used as a surrogate for limiting internal engine pressures and external heating rates. The chosen wing normal force limit represents a compromise between wing structural weight and a more fuel-optimal, sharp pull-up at the beginning of rocket mode transition (Mach 10). The dynamic pressure boundary that *Stargazer* flies is 2,000 psf during the ramjet and scramjet modes between Mach 3.5 and 10. The transitions between the four engine modes (ejector, Mach 0 – Mach 2.5; ramjet, Mach 3.5 – Mach 6; scramjet, Mach 7 – Mach 10; and rocket, Mach 11 – Mach 14) are modeled as a linear ramp down of the preceding mode and a linear ramp up of the following mode. The staging vector at Mach 14 (weight, altitude, longitude, latitude, velocity, flight path angle, and azimuth velocity) must be supplied to the upper stage and flyback branches. The objective of the ascent trajectory is to maximize the weight at staging.

The upper stage deck is the simulation of the upper stage from staging to orbital injection. After a five second coast, the upper stage engine is ignited and it flies a trajectory controlled by pitch angles. The engine runs for about 230 seconds and then the upper stage coasts until the apogee of 200 nmi. is reached. At this point, the engine is restarted to provide an instantaneous velocity increment needed to circularize the orbit. The trajectory is constrained by a smooth pull-up at rocket ignition and orbital termination criteria. The objective of the upper stage trajectory is to maximize the weight at the end of the trajectory.

The flyback trajectory, from staging to return to KSC, is controlled by angles-of-attack and bank angles used for the turnaround to KSC, the altitude at which the turn begins, the heading coming out of the turn, and the time at which the ramjet is turned on. The trajectory is constrained by the termination conditions at KSC and the conditions at which the ramjet can be started. The ramjet flyback itself is constrained to result in flight of a constant heading at a constant altitude of approximately 70,000 ft., while maintaining Mach 3.5. The objective of the flyback trajectory is to minimize the weight of the fuel consumed.

The rocket mode transition for *Stargazer* begins at Mach 10. Mach 10 was chosen as a conservative upper end for scramjet propulsion. While there is an advantage in reduced gross weight to be had from higher Mach airbreathing mode operation, disadvantages in terms of higher inlet (engine) weight and reduced propellant bulk density also appear. The staging point of Mach 14 was chosen as a compromise between booster size and upper stage size. Since the goal is to reduce overall launch costs, a small low-cost expendable upper stage is desirable. However, increasing the staging Mach number too much significantly increases the flyback distance for the booster and thus leads to a very large and operationally expensive booster. Trade studies, to be introduced later, identified Mach 14 as a reasonable compromise for low recurring costs.

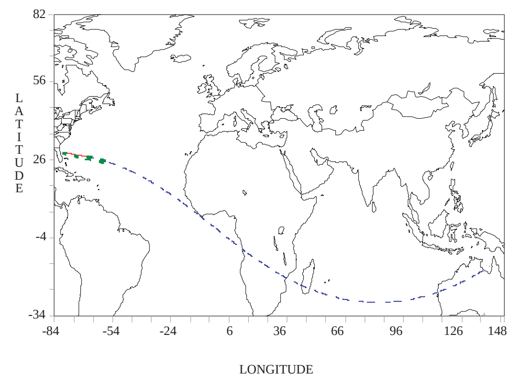

Fig. 12. *Stargazer* Groundtrack.

The booster and flyback trajectories were sent to the aeroheating analyst. The actual mass ratios (MR = gross weight/burn-out weight) and the booster mixture ratio were given to the weights and sizing analyst. These values were: ascent MR = 2.28, ascent mixture ratio = 1.32, flyback MR = 1.38, and upper stage MR = 3.33. Booster time of flight, approximately one hour, was passed to the operations analyst. The groundtrack for the entire three trajectories appears in Fig. 12. Fig. 13 shows a closeup of the turnaround and flyback.

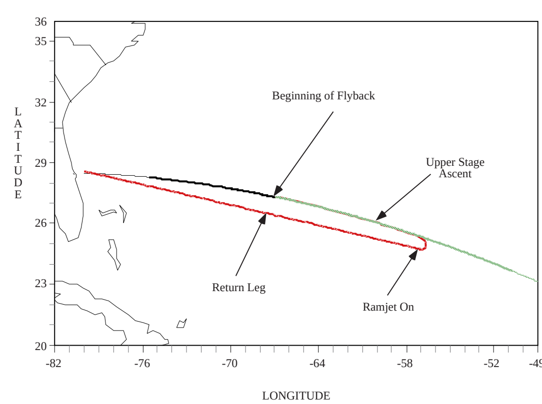

Fig. 13. Closeup of Turnaround and Flyback.

Aeroheating

The thermal protection system requirements for *Stargazer* were evaluated using the MINIVER code and

NASA Ames' TPS-X database. MINIVER is a thermal analysis code that was written by NASA that performs a 2-D flow analysis over the vehicle.[7] Input into MINIVER is the trajectory (altitude, velocity, angle-of-attack, and sideslip as a function of time) and the vehicle geometry. MINIVER models the vehicle geometry with simple geometries such as flat plates to model wings and swept cylinders to model leading edges. It produces centerline temperature distributions, convective heat rates, and heat loads over the simplified vehicle; these are calculated using empirical methods such as the Fay-Riddell Stagnation point method and the Eckert's Reference enthalpy method for flat plate heating.

Once MINIVER had been run, appropriate TPS materials were selected from a database. The database chosen for the *Stargazer* design was the NASA TPS-X material database, available on the NASA Ames Internet site.[8] Given the centerline temperature distributions, TPS materials were chosen. TPS unit weights, thicknesses, and area coverage percentages were calculated based on the results from MINIVER and the TPS-X database. These numbers were given to the weights and sizing analyst and the TPS types were given to the operations analyst.

Aeroheating analysis was not performed for every trajectory analysis. Because this analysis took a long time to perform and the coupling to the weights & sizing discipline was weak after the first iteration, it was only invoked when major configuration or trajectory changes occurred. Work is being done to make this entire aeroheating analysis process automated and thus quicker.[9]

A graphical representation of TPS used for the baseline *Stargazer* can be seen in Fig. 14. Flexible TABI blankets are used primarily on the leeward (top) surface. Ceramic TUFI tiles are used on the windward surfaces. Ultra-high temperature ceramic (UHTC) materials are used on the small radius wedge and wing leading edges. UHTC's are an alternative technology to actively cooled sharp leading edges and are capable of withstanding surface temperatures of nearly 4500° F. Reinforced carbon-carbon tiles are used in the high temperature nose regions between the UHTC and the TUFI tiles. Table 2 summarizes the TPS types, unit weights, and percentages of the total external wetted area covered by each. The second column lists values of the maximum radiation equilibrium temperature calculated by MINIVER based on the *Stargazer* trajectory, whereas the third column lists the maximum sustainable temperature of the material.

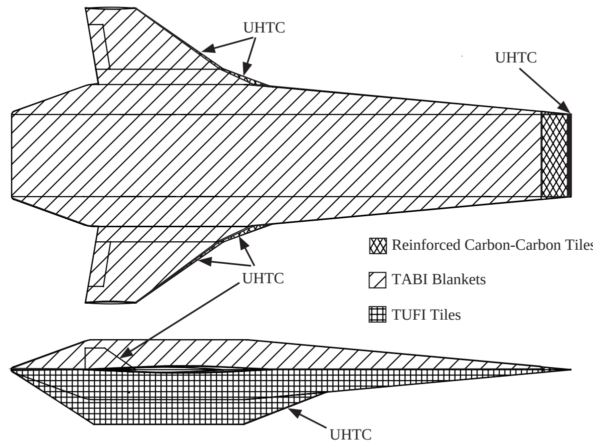

Fig. 14. *Stargazer* TPS Illustration.

Table 2. *Stargazer* TPS Types.

Type	Calc. Temp. (F°)	Temp. Limit (F°)	Unit Weight	% of wetted area covered
TABI	1850	2200	0.4 psf	48
TUFI	2300	2400	1.3 psf	48
RCC	2900	3000	2.3 psf	3
UHTC	3900	4500	1.5 psf	minimal

Weights & Sizing

The weights and sizing analysis for *Stargazer* uses a photographic scaling set of parametric mass estimating relationships (MER's) that have a NASA Langley heritage. This analysis is performed on an Excel spreadsheet. Using the results of the trajectory analysis, the upper stage and booster are photographically scaled up or down until the available mass ratio and the required mass ratio match. As previously mentioned, the weights and sizing spreadsheet for the *Stargazer* booster and upper stage was linked to the analytical configuration/packaging spreadsheet. Since changing the vehicle scale changes the capture area, gross weight, SLS thrust requirements, etc., the disciplines in the main iteration loop in Fig. 4 must be iterated until the vehicle size converges (typically 4 or 5 iterations).

The baseline MER's were adjusted downward by linear scaling factors to reflect the selection of advanced materials and other technologies that were selected for *Stargazer* (note that the baseline MER's were for near-term construction and materials). Primary booster structural materials included graphite epoxy for the propellant tanks and advanced metal matrix composites (e.g. titanium-aluminide) for other structure such as exposed wings, the wing carry through, and verticals. Other subsystem highlights include an autonomous flight control system, high rate electromechanical actuators, high power density fuel cells, lightweight avionics, a lightweight power distribution system, and fiber cabling for vehicle health monitoring. The upper stage used more conventional subsystem technologies to reduce cost.

For the baseline *Stargazer*, the converged design had a gross weight of 115,450 lbs. and a dry weight of 34,750 lbs. The upper stage weighed 1,750 lbs. including the 300 lb. payload. A graphical breakdown of the percentages of various components of the booster dry and gross weights appears in Figs. 15 & 16. The booster used 77,700 lbs. of propellant: 36,600 lbs. of LOX and 41,100 lbs. of LH2, 13,000 lbs. of which were used for the flyback.

The weights and sizing analysis provided a great deal information to the other analysts. Gross weight, upper stage weight, wing reference area, and maximum wing normal force were given to the trajectory analyst. All weights in the 28-point weight breakdown structure were sent to the cost analyst. Required sea-level static thrust was used by the propulsion analyst and the configuration analyst used the actual vehicle dimensions.

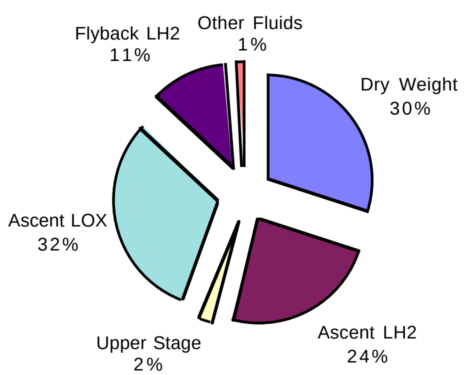

Fig. 15. Gross Weight Breakdown.

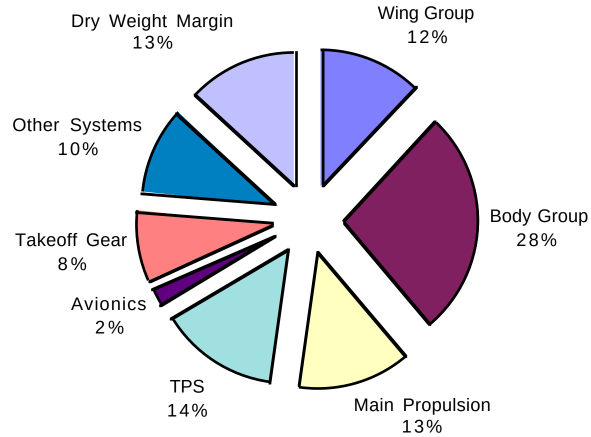

Fig. 16. Dry Weight Breakdown.

Operations

The operations analysis for *Stargazer* was evaluated with the enhanced Architectural Assessment Tool (AATe).[10] This tool, created at NASA KSC, is an Excel spreadsheet that is a low fidelity ground processing operations model. Its inputs are in the form of qualitative and quantitative answers to questions related to vehicle tank placement, TPS data, vehicle dimensions, engine details, etc. The concept is judged in several categories relative to a Space Shuttle baseline. Is the concept expected to be an order of magnitude better than the Shuttle with regards to operability? Two orders of magnitude? The results are aggregated into a final quantitative measure of the vehicle operability.

Using this score, AATe predicts ground operations costs associated the reusable vehicle elements. Assuming that the fictitious company operating *Stargazer* (Bantam, Inc.) is able to share some common services across a larger, notional spaceport at KSC, the annual fixed operations costs were estimated to be $1.97M. Variable costs per flight were estimated to be $2.14M/flight. These cost estimates include ground labor costs, replacement hardware inventory and replacement costs, and a proportional amount of fixed base operating costs.

Economics

The tools used for the *Stargazer* cost analysis included CABAM[11] (Cost and Business Analysis Module) and Crystal Ball.[12] CABAM is a spreadsheet tool developed at Georgia Tech that utilizes parametric cost estimating relationships (CER's) to determine the cost characteristics and financial feasibility of advanced space launch vehicles. Crystal Ball© is a third-party add-on to Microsoft Excel© that utilizes Monte Carlo simulation techniques to determine the possible outcomes when variability is introduced into the problem. By combining these two tools, an analysis of the effects of variability in weight can be completed. The inputs to the cost analyst include a weight breakdown for both the booster and the upper stage, technology and complexity assumptions, and operations cost numbers.

The economic analysis assumes that the vehicle makes a maximum of 24 flights/year with the development program starting in 1999. *Stargazer* is developed and built as a government asset, but is operated by a fictitious commercial company subsequently referred to as Bantam, Inc. Initial operating capability (IOC) occurs in 2011 and the program lasts 14 years after IOC (until 2025). All dollars presented in this analysis are stated in constant 1999 year dollars. To reduce fleet acquisition costs, only a single *Stargazer* booster is constructed. Other assumptions include the following,

- the government pays all of the DDT&E, fleet acquisition, and facilities expense.
- the government subcontracts to Bantam Inc. to operate the vehicle 24 times per year.
- primary labor and other ground operations costs are provided by Bantam Inc.
- Bantam Inc. makes a 10% "fee" above the recurring cost of the flight.

For the uncertainty analysis, triangular distributions were placed on each of the weight component groups with the most likely values obtained from the weight breakdown structure (WBS). To account for expected weight growth, component weights ranged from -5% to +20% of the most likely value provided by the weight analyst. Utilizing Crystal Ball, approximately 5,000 Monte Carlo uncertainty simulations were run with CABAM. These simulations produced a distribution of expected vehicle DDT&E cost and production cost. A sample output graph in the form of a frequency distribution can be seen in Fig. 17. The reported cost results reflect the mean, or averaged, values output from the Monte Carlo simulation. A cost margin of 20% was included in addition to the uncertainties.

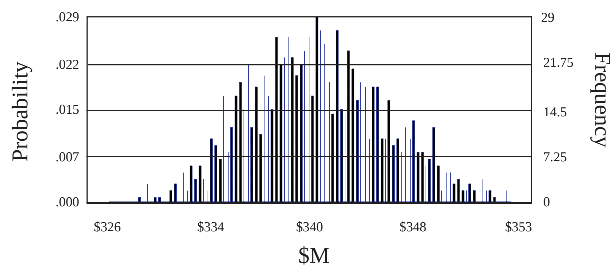

Fig. 17. Sample Frequency Distribution.

Some economic results for the baseline *Stargazer* can be seen in Fig. 18 and Table 3. The liability insurance cost was assumed to be $100K per launch. The LRU (line replacement unit) hardware cost is the maintenance hardware for the booster. Upper stage cost is the average unit cost for the first year of production. The total recurring cost/flight was estimated to be $3.170M of which over 50% is ground labor costs associated with operating the reusable booster. After the addition of the 10% fee charged by Bantam, Inc., the total price charged/flight becomes $3.487M,

Table 3. *Stargazer* Mean Non-Recurring Cost.

Item	Mean Non-Recurring Cost
DDT&E	$1,911M
Booster Airframe	$1,759M
Booster Engines	$126M
Upper Stage	$26M
TFU	$540M
Booster Airframe	$366M
Booster Engines	$172M
Upper Stage	$2M
Total Non-Recurring Cost	$2,451M

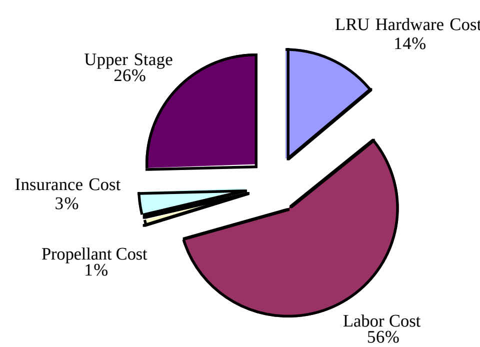

Fig. 18. *Stargazer* Mean Recurring Cost/Flight Breakdown.

significantly more than the \$1.5M recurring price target. Table 3 gives numerical results for the vehicle's non-recurring cost (note that only one booster is purchased for this limited mission model).

Expendable Upper Stage

A quick-look assessment of *Stargazer's* system configuration and economics indicated that the low flight rate of Bantam class vehicles would make it difficult to recover the pre-IOC investment of a fully reusable upper stage. Cost trends for the expendable upper stage option show that lower up-front costs (DDT&E and TFU) and lower ground operations cost (less infrastructure and simpler integration) outweigh its disadvantage in expendable hardware cost per flight. In addition, the reusable booster stage is significantly smaller and lighter when carrying an expendable upper stage, which results in lower DDT&E, TFU and operations costs for the booster stage. Thus, an expendable upper stage was baselined for *Stargazer*.

A pressure-fed engine was initially envisioned to provide a simple and cost effective propulsion solution for the expendable stage. However, at low staging Mach numbers the burn time and propellant volume requirements exceeded the practical limit for blowdown pressure-fed systems. The need to keep the tank weights reasonable at the low staging Mach numbers led to the decision to baseline a pump-fed engine. The resulting pump-fed engine is a LOX/RP-1 gas generator cycle operating at a chamber pressure of 650 psia, area ratio of 50, and an engine mixture ratio of 2.17. The engine generates 1,750 lb. of vacuum thrust with an I_{sp} of 328 sec.

Other major components of the expendable stage include graphite epoxy tanks and structure and a low production cost avionics suite. Models for the subsystems & upper stage components were incorporated into the weights and sizing model. Dry and gross weights of the stage were determined by scaling the LOX tank to obtain the required stage mass ratio.

Trade Studies

Several trade studies were performed on the *Stargazer* vehicle. A staging Mach number trade was performed to establish the staging Mach number for the baseline vehicle. These Mach numbers ranged from Mach 11 to Mach 15; for each, a converged vehicle was designed. The 'best' staging Mach number was used for a fuel type trade and an engine T/W trade. The baseline *Stargazer* uses LOX/LH2 propellants with an (assumed) installed engine T/W_e of 20 (takeoff thrust divided by total engine weight including inlet). A trade study with the T/W_e set at 15 was evaluated. The fuel trade evaluated the vehicle with a hydrocarbon fuel with an engine T/W_e of 15. The results of these trades are given in the following sub-sections.

Staging Mach Number Trade

A trade on staging Mach number was performed by varying that Mach number from Mach 11 to Mach 15. For each of these Mach numbers, a converged vehicle was designed. The purpose of this trade was to see which staging Mach number would result in a vehicle that had the minimum recurring cost per flight. Recurring cost per flight was chosen as the dependent variable for this trade because it reflects changes in both the booster and the upper stage.

The results from this trade can be seen in Fig. 19. Recurring cost and booster gross weight are plotted against staging Mach number indicating sensitivities. Recurring cost and booster gross weight are normalized in the plot by the baseline Mach 14 values.

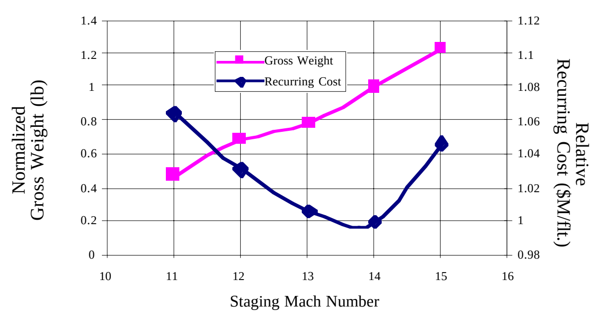

Fig. 19. Normalized Staging Mach Number Trends.

The plot shows that the minimum recurring cost is achieved by staging between Mach 13 and Mach 14. Mach 14 is the integer Mach number that has the minimum recurring cost per flight. Before Mach 14, the upper stage cost has a dominant effect on recurring cost. At Mach 15, the booster is very large and replacement hardware and propellant are the drivers in the higher recurring cost. Mach 14 was thus used as the staging Mach number for all the other converged vehicles.

Engine T/W$_e$ Trade

Another trade was performed to weigh the effect of changing the RBCC T/W$_e$. The baseline T/W$_e$ was 20. For the trade, that value was changed to a more conservative value of 15. This suggested that a larger, more expensive version of *Stargazer* would be the result. The vehicle configuration, i.e, internal component placement, aerodynamics, and TPS layout were the same as that used for the baseline, but the vehicle was resized to carry additional engine weight. A weight comparison can be seen in Fig. 20. Cost comparisons are summarized in Table 4. Note the increase in recurring price per flight of nearly $250,000 due to the larger booster and larger TPS area.

Table 4. *Stargazer* Economic Comparison.

Item	Stargazer Vehicle LOX/LH2 T/W$_e$ = 15	Stargazer Vehicle LOX/LH2 T/W$_e$ = 20
Total DDT&E	$2,018M	$1,911M
Total TFU	$610M	$540M
Propellant Cost/flt.	$0.034M	$0.030M
Labor Cost/flt.	$1.929M	$1.775M
LRU Hardware Cost/flt.	$0.491M	$0.452M
Upper Stage/flt.	$0.827M	$0.813M
Insurance Cost/flt.	$0.100M	$0.100M
Total Rec. Cost/flt.	$3.381M	$3.170M
Price Charged/flt.	$3.719M	$3.487M

Hydrocarbon Propellant Trade

The baseline *Stargazer* used a LOX/LH2 combination of propellants. A fuel trade was performed to investigate the effect of having a hydrocarbon fuel on the booster. The hydrocarbon *Stargazer* uses four ejector *ramjet* engines, as opposed to the ejector scramjet engines of the hydrogen version. This means that the hydrocarbon version fully transitions to rocket mode at Mach 7, not Mach 11. Preliminary results suggest that using hydrocarbon propellants offers advantages.

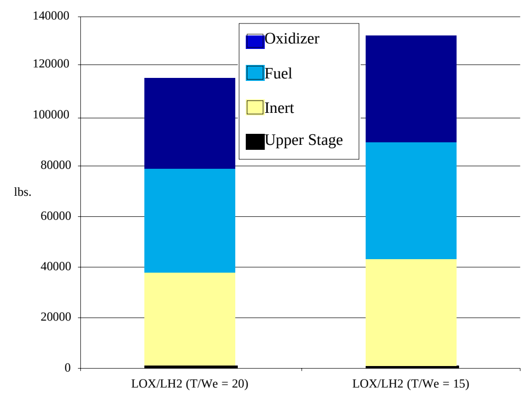

Fig. 20. *Stargazer* Weights Comparison.

Stargazer, with a LOX/hydrocarbon propellant combination, has the potential to greatly reduce recurring cost relative to the LH2 booster configuration. The density of hydrocarbons is greater than LH2, resulting in a smaller vehicle and a smaller dry weight. The DDT&E and TFU costs will therefore be reduced. Operations are made simpler due to the facts that 1) the fuel is not cryogenic and 2) the vehicle's TPS wetted area is smaller. This *significantly* reduces labor and materials costs when assessed by the AATe tool. The combination of the vehicle using less propellant and the inexpensive cost of hydrocarbon fuel, lowers the propellant cost. Because staging still occurs at Mach 14, the upper stage is similar in size and cost to that of the hydrogen vehicle. Totaling all these factors in the recurring cost, it can be deduced that indeed a recurring cost closer to the goal of $1.5M might be achieved using hydrocarbon fuel. Work on this trade is currently progressing. Methane, propane, and JP fuels are being considered and appear attractive for this mission.

SUMMARY

A new conceptual launch vehicle design, *Stargazer*, in the Bantam-X payload class has been presented (Fig. 21). Details of the concept design including external and internal configuration, mass properties, engine performance, trajectory analysis, aeroheating results, and concept cost assessment were given for the baseline vehicle. Details of the design process used have been presented. Results of trades for staging Mach number and engine T/W$_e$ were shown for the vehicle.

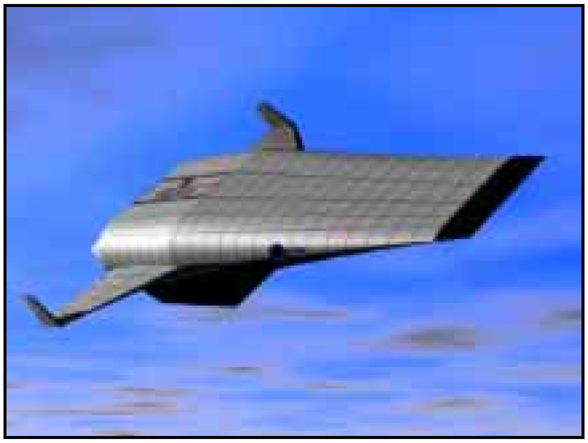

Fig. 21. *Stargazer*.

The $3.487M estimated price/flight of the baseline LOX/LH2 *Stargazer* clearly does not currently meet the aggressive goal set by the Bantam-X project. In fact, it is over twice the $1.5M price goal. Ground operations cost associated with the booster is a significant driver in the recurring cost (~60%). Preliminary results indicate that higher density and easier to handle hydrocarbon fuels might offer economic advantages.

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