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An Evaluation of Two Alternate Propulsion Concepts for *Bantam-Argus*: Deeply-Cooled Turbojet + Rocket and Pulsed Detonation Rocket + Ramjet

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An Evaluation of Two Alternate Propulsion Concepts for *Bantam-Argus*: Deeply-Cooled Turbojet + Rocket and Pulsed Detonation Rocket + Ramjet

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ABSTRACT

The *Bantam-Argus* reusable launch vehicle concept is a smaller version of the original *Argus* single-stage-to-orbit launch vehicle design. Like the original *Argus*, *Bantam-Argus* uses a Maglifter launch assist system to provide an initial horizontal launch velocity. *Bantam-Argus* is designed to deliver 300 lb. payloads to low earth orbit and, like the full sized *Argus*, the baseline *Bantam-Argus* concept utilizes two liquid oxygen/liquid hydrogen supercharged ejector ramjets as prime motive power.

This paper presents the results of an investigation of two alternate propulsion systems for the *Bantam-Argus* launch vehicle. First, a thermally integrated combined-cycle system consisting of two deeply-cooled turbojets and two liquid rocket engines was evaluated. Second, a combination propulsion system utilizing two pulsed detonation rocket engines and two standalone ramjets was evaluated.

The results show that both alternate propulsion systems have the potential to reduce both the dry weight and gross weight of the baseline *Bantam-Argus* concept (when resizing the vehicle while holding mission payload constant). The pulsed detonation rocket engine option is particularly attractive. However, these results must be treated with caution given the relative immaturity of the supporting propulsion data available for both alternatives. Trade studies on key performance parameters were performed to bound the potential gains to be expected from either alternative.

NOMENCLATURE

CPS	combined propulsion system
DCTJ	deeply-cooled turbojet
ΔV	velocity increment
GLOW	gross liftoff weight
HTHL	horizontal takeoff horizontal landing
I_{sp}	specific impulse (sec)
LEO	low earth orbit
LH2	liquid hydrogen
LOX	liquid oxygen
MER	mass estimating relationship
MR	mass ratio (gross weight / burnout weight)
O/F	oxidizer to fuel ratio
PDRE	pulsed detonation rocket engine
PMF	propellant mass fraction
q	dynamic pressure
RBCC	rocket based combined cycle
RLV	reusable launch vehicle
SERJ	supercharged ejector ramjet
SSDL	space systems design lab
SSTO	single-stage-to-orbit
TRL	technology readiness level
T/W	Thrust-to-Weight
VTHL	vertical takeoff horizontal landing
WBS	weight breakdown statement

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INTRODUCTION

Recent NASA-Marshall launch vehicle studies have focused on low cost launch systems to address small payload classes. A new low cost system capable of delivering approximately 300 lb. of payload to low earth orbit (200 nmi. circular orbit launched due east from a spaceport at Kennedy Space Center) is envisioned to capture small university explorer payloads and other small scientific cargoes. This low cost, small payload delivery mission has come to be known as the "Bantam" mission. NASA has established an aggressive launch price goal of less than \$1.5M per launch for the Bantam mission. At this price, about 24 flights per year are expected to be captured by the new system.

Several launch vehicle concepts have been proposed to address the Bantam-class mission. Some are low cost expendable rockets, but reusable launch systems have also been considered. The *Bantam-Argus* vehicle is one reusable Bantam concept proposed by Georgia Tech's Space Systems Design Laboratory (SSDL).

Original HRST-class *Argus*

The original *Argus* concept (Fig. 1) was developed for NASA's Highly Reusable Space Transportation System (HRST) study[1] in 1996 and 1997. *Argus* utilizes a Maglifter (magnetic levitation sled/track system) to accelerate the vehicle to 800 fps velocity at launch. Vehicle propulsion is provided by two LOX/LH2 supercharged ejector ramjet (SERJ) rocket based combined cycle (RBCC) engines. The original *Argus* was designed to autonomously carry a payload of 20,000 lb. to low earth orbit (LEO) from a fictitious Maglev launch site at NASA Kennedy Space Center[2]. After the launch assist, the vehicle is single-stage-to-orbit. Atmospheric entry is unpowered, but the vehicle is capable of five minutes of powered operations at landing using the highly efficient fan-only mode of its SERJ engines. This original concept was estimated to weigh 597 klb. at takeoff and 75.5 klb. dry (no payload or fluids)[2].

Figure 1 – Original Argus Concept (full sized)

SERJ Baseline *Bantam-Argus*

The *Bantam-Argus* concept (Fig. 2) is a scaled down version of the original *Argus* concept. *Bantam-Argus* is designed to deliver only 300 lb. of payload to LEO and was investigated by SSDL in 1998.

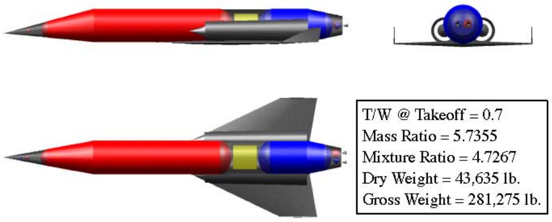

Figure 2 - Baseline SERJ Bantam-Argus Concept

Bantam-Argus uses the same propulsion and structural technologies as *Argus*. Structural materials include graphite epoxy propellant tanks, Titanium-Aluminide hot structure for wings, tails, and primary structure. Ultra High Temperature Ceramics (UHTCs) are used to provide a passive thermal protection for the nosecap and wing leading edges. Lightweight avionics and subsystems are used throughout. As with the original *Argus*, *Bantam-Argus* uses a Maglifter launch assist sled and track system to provide 800 fps of horizontal launch velocity at takeoff. This decreases the total ΔV needed to reach orbit, allows for smaller wings and reduces the vehicle's undercarriage weight.

Figure 3 shows the mission scenario for *Bantam-Argus*. Its two SERJ engines are capable of multi-mode operation. Initially, the rocket ejector mode is used to accelerate the vehicle at takeoff (overall vehicle thrust-to-weight ratio at takeoff is 0.7). Between Mach

2 and 3 the embedded RBCC rocket primary is ramped down as the vehicle transitions to ramjet mode. By Mach 3 the vehicle is in pure ramjet mode. From Mach 3 to Mach 6 the vehicle flies a constant dynamic pressure (q) of 1500 psi. At Mach 6 the ramjet is turned off and the internal RBCC primary rocket is reignited and is used to provide the rest of the ΔV needed to reach orbit. Main engine cutoff places the vehicle into a temporary parking orbit of 50nmi x 150nmi x 28.5^{o} orbit. An orbital maneuvering system is used to raise the final orbit to 200 nmi. circular.

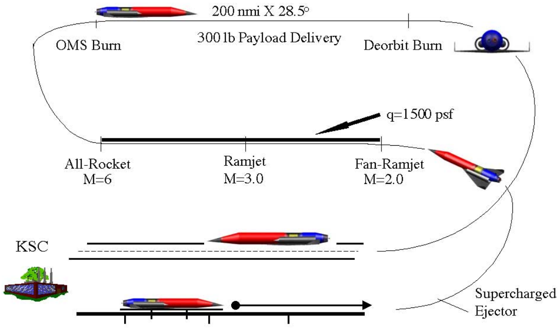

Figure 3 - Bantam-Argus Trajectory

The *Bantam-Argus* concept was converged using an iterative, conceptual design process between individual disciplinary codes similar to that described in Reference 2. Represented disciplines included trajectory optimization (POST[3]), aerodynamics (APAS[4]), mass properties, and propulsion (note that a similar iterative conceptual design process was used to converge the alternate propulsion versions discussed later in this paper). The vehicle was scaled up or down and the propellant tank configuration was adjusted until the required propellant mass fraction from the trajectory equaled that available in the tanks, and the overall mixture ratio of oxygen-to-hydrogen required for the ascent matched that available in the tanks. Limits were placed on axial acceleration, takeoff angle of attack, maximum dynamics pressure, and maximum wing normal force. Typically, 3 – 4 iterations through all of the disciplines is required to fully converge a conceptual design.

Table 1 gives the top-level weight breakdown structure (WBS) estimated for *Bantam-Argus*. The full three-level WBS contains nearly 100 lines and is omitted for brevity. For *Bantam-Argus*, the SERJ engines were estimated to have an installed sea-level static thrust-to-weight ratio of 23 using RBCC engine weight estimation tool developed at Georgia Tech (WATES[5]).

Table 1 - Bantam-Argus Top-Level Weights

WBS Item	Weight
Wing & Tail Group	5180 lb.
Body Group (includes tanks)	11,705 lb.
Thermal Protection System	3260 lb.
Main Propulsion (includes SERJ)	9555 lb.
OMS/RCS Propulsion	590 lb.
Subsystems & Other Dry Weights	7655 lb.
Dry Weight Margin (15%)	5690 lb.
Dry Weight	43,635 lb.
Payload to LEO	300 lb.
Other Inert Weights (residuals)	5100 lb.
Insertion Weight	49,035 lb.
LH2 Ascent Propellant	40,580 lb.
LOX Ascent Propellant	191,660 lb.
Gross Weight	281,275 lb.

Figures 4 and 5 show the SERJ engine thrust and I_{sp} produced for the *Bantam-Argus* ascent up to Mach 7. The SERJ performance numbers were generated using SCCREAM (Simulated Combined-Cycle Rocket Engine Analysis Module) an RBCC engine performance code developed at Georgia Tech[6]. These curves were generated for the final optimized flight path using the SERJ engine performance datasets generated by SCCREAM. Note the sharp drop-off in thrust and associated rise in I_{sp} as the vehicle transitions from ejector to ramjet mode from Mach 2 to 3. At Mach 6, the engine transitions to pure rocket-mode and the I_{sp} is reduced. Beyond Mach 6, the vehicle continues in rocket-mode with a mixture ratio of 7/1, until an axial acceleration limit of 3 g's is reached, at which point the rocket is throttled down to maintain this limit until the parking orbit is achieved. At transition to pure rocket-mode, the overall vehicle T/W is approximately 0.87.

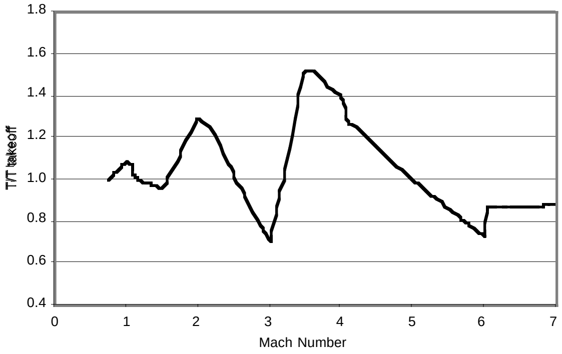

Figure 4 – Thrust profile for SERJ Bantam-Argus

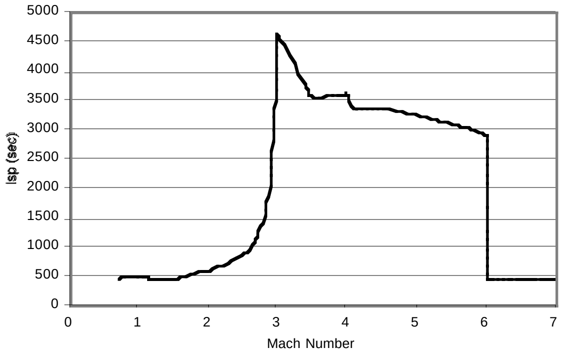

Figure 5 – I_{sp} profile for SERJ Bantam-Argus

For subsequent investigations of alternate propulsion systems, this *Bantam-Argus* equipped with two SERJ RBCC engines will be considered the "baseline". The primary objective of the present research is to assess any potential advantages of two alternate propulsion concepts for the *Bantam-Argus* vehicle. For these comparisons, the Maglifter launch assist parameters and overall vehicle technologies (other than propulsion) were kept the same as the baseline case. However, the ascent flight path was modified to accommodate the propulsion system being considered.

ALTERNATE PROPULSION SYSTEMS

Deeply-Cooled Turbojet + Rocket Combined-Cycle

This cycle uses a deeply-cooled turbojet and a LOX/LH2 liquid rocket engine. The rocket engine and the turbojet are thermally integrated by using the LH2 rocket fuel to precool the air entering the turbojet (Fig. 6, from Reference 7). This leads to weight reductions over a non-deeply cooled turbojet because simpler and lightweight materials can be used to compress and combust the cooled air.

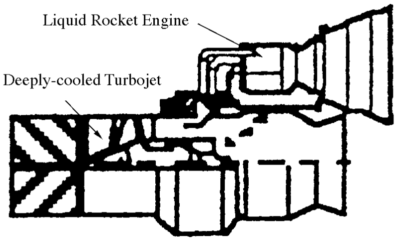

Figure 6 - Thermally Integrated DCTJ + Rocket

There are many different operational modes that are utilized by DCTJ + Rocket combined-cycles. These modes are characterized by the contributions of the DCTJ and the rocket to the total net propulsive thrust. They range from full turbojet to full rocket and various combinations of each. It has been suggested that super cooled LOX injection into the turbojet inlet while in the lower atmosphere will prevent icing and yield as much as 20% more DCTJ thrust[8]. This is yet another option available in the DCTJ + rocket combined-cycle.

In order to evaluate this cycle for the *Bantam-Argus* configuration, a non-proprietary source of engine information was required (Georgia Tech's SSDL does not currently have the capability to analysis DCTJ + Rocket propulsion in-house). Two sources were found.

Balepin and Maita[8] and subsequently Balepin and Hendrick[9] have published in the open-literature, engine performance data on a proprietary derivative of a DCTJ + Rocket combined-cycle engine known as the KLIN cycle. Figures 7 and 8 represent KLIN cycle engine thrust and I_{sp} trends for a representative ascent of a KLIN-powered launch vehicle along a 1100 psf trajectory. The actual thrust values in the reference were for a vertical takeoff DCTJ combined-cycle vehicle. Therefore, the thrust values used in this study were linearly scaled to provide the required sea-level vehicle T/W of 0.7. Note that the DCTJ and the Rocket operate together up to Mach 1.5 (with LOX spray pre-cooling to prevent icing). After Mach 1.5, the rockets are turned off. The I_{sp} increases significantly in this mode while the thrust drops.

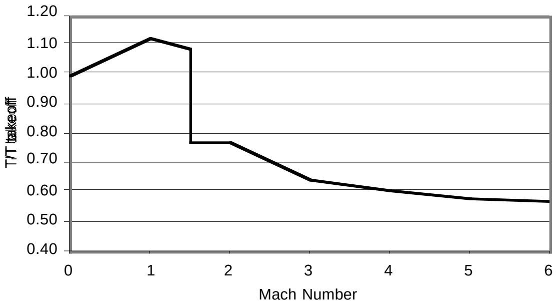

Figure 7 - Thrust profile for DCTJ combined-cycle A

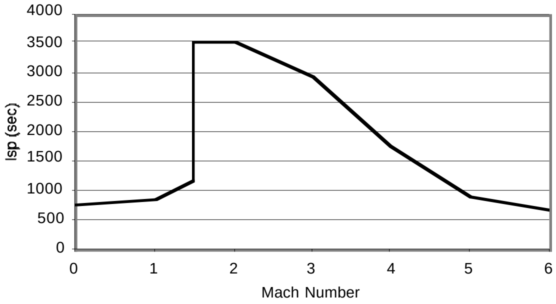

Figure 8 - I_{sp} profile for DCTJ combined-cycle A

In Balepin's original data, the net thrust with only the DCTJs operating decreases rapidly above Mach 4. Early simulations run by the authors suggested that more thrust was needed between Mach 4 and 6. Therefore, the authors added a small amount of rocket thrust beginning at Mach 4 and ramping up to Mach 6 to maintain the thrust level at a steady value above Mach 4. This generally requires a rocket throttle setting of 10% - 30% of its maximum value. The original I_{sp} data was penalized accordingly in this mode by the addition of the rocket propellant flow required. After Mach 6, the engine was converted to pure rocket-mode. The rocket was sized to maintain an overall vehicle T/W of approximately 1.0 at this transition point. The overall installed engine T/W of this DCTJ + Rocket engine variant was taken to be 21[9]. This data set is more "DCTJ-oriented" and will be referred to as DCTJ + Rocket dataset A.

A second set of DCTJ + Rocket engine performance data was obtained from Dr. Paul Czysz of Parks College[10]. This generic and previously unpublished data is derived from work performed by Czysz on KLIN-like propulsion systems. Figures 9 and 10 present the data provided by Czysz. As before, the thrust trend data was linearly scaled to provide a vehicle T/W of 0.7 at sea-level static conditions (Czysz' original data was for a vertical takeoff launcher).

By comparison, the second dataset utilizes more rocket thrust between Mach 1.5 and 6 at the expense of a small amount of Isp. This second, "rocket-oriented" dataset will subsequently be referred to as DCTJ + Rocket dataset B. The overall combined-cycle engine was assumed to have a T/W of 24 for dataset B. A rocket-mode I_{sp} of 453 seconds with a mixture ratio of 5.5/1 was used for both datasets above Mach 6.

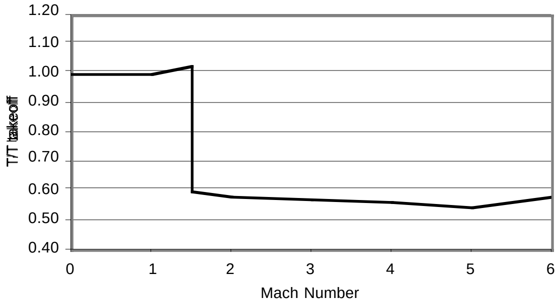

Figure 9 - Thrust profile for DCTJ combined-cycle B

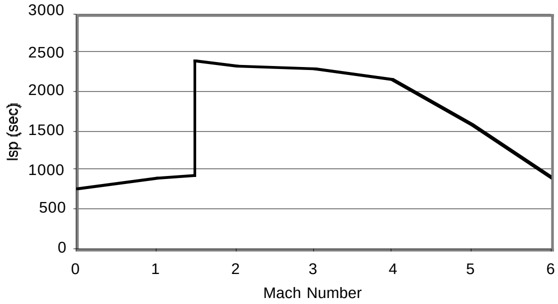

Figure 10 – I_{sp} profile for DCTJ combined-cycle B

As will be shown, the thrust and I_{sp} differences between the two representative datasets produce very little difference in required ascent Mass Ratio (related to propellant mass fraction by MR = 1/(1-PMF)). However, a significant difference exists in the local oxidizer-to-fuel ratio along the ascent trajectory (Figure 11). The "DCTJ-oriented" dataset (dataset A) uses <u>no oxidizer</u> for much of its trajectory. The O/F ratio is zero in places, indicating all of the propellant being consumed is low-density hydrogen. This creates a low propellant bulk density for the vehicle, and tends to increase its size.

One the other hand, the “rocket-oriented” dataset B shows a significant amount of oxygen being consumed during the section of the trajectory between Mach 1.5 and 6. This effect significantly improves the overall tanked O/F ratio and thus the propellant bulk density. The vehicle can therefore be smaller, lighter, and more compact for approximately the same Mass Ratio.

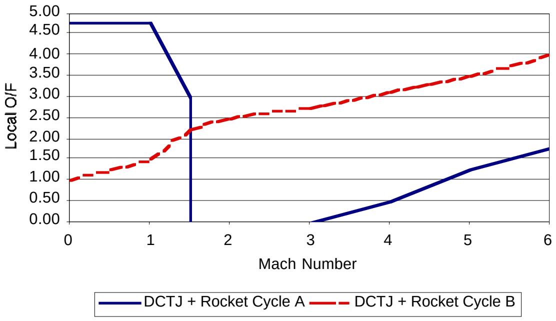

Figure 11 – Local Mixture Ratio (O/F) for DCTJ + Rocket Cycles A and B

It should be noted here that the authors had no in-house ability to verify or validate the DCTJ + Rocket engine data obtained from these two sources. The process by which a DCTJ + Rocket engine consuming significant amounts of on-board oxygen can still produce ramjet-like engine I_{sp}’s is still unclear. In addition, the installed net engine T/W at takeoff were taken to be 21 and 24 for the two datasets, respectively. In the opinion of the authors, these numbers are aggressive (high). They rival installed sea-level T/W estimates for RBCC engines, which do not have heat exchangers or significant pump/compressor requirements. Therefore these DCTJ + Rocket datasets are viewed with a certain amount of skepticism that remains to be dispelled as the engine analysis matures.

Pulsed Detonation Engines

While not considered a new technology, pulsed detonation propulsion systems are the subject of increased attention for space launch applications. Several companies are currently investigating two major classes of pulsed detonation engines (PDEs). An airbreathing variant uses atmospheric air as the oxidizer and tanked propellant for fuel (similar to the World War II V-1 engine). This variant is currently thought to be useful for space launch only up to about Mach 4 or so, given increases in the total temperature of the captured airstream at high velocities. Pegg and his colleagues have shown that airbreathing PDEs have potential application as the low speed cycle of an airbreathing space access vehicle[11].

The second pulsed detonation engine concept is a rocket variant that uses tanked oxidizer and tanked fuel as propellants. No atmospheric air is used in the combustion process. This version is referred to as a pulsed detonation rocket engine or PDRE. PDREs appear to have application to both the low speed and final acceleration portions of space launch vehicle trajectories.

A PDRE realizes increased fuel economy by changing the combustion process of a traditional liquid rocket engine. The LOX/LH2 PDREs utilize a transient combustion process to produce thrust. A Chapman-Jouguet detonation wave is repeatedly initiated inside of the combustion chamber. This detonation wave raises the temperature and pressure of the fuel, producing thrust. The constant volume combustion process results in about the same increase in pressure but a larger increase in net product enthalpy and temperature, when compared to a conventional constant pressure combustion process[12]. This increased product enthalpy and temperature are responsible for the increased fuel economy (I_{sp}) attributed to a PDRE system.

Individual PDREs operate at frequencies near 50 Hz. This poses a problem for the turbomachinery responsible for feeding the fuel and oxidizer. In order to create a more steady state fuel and oxidizer demand, it has been proposed that several PDREs can be grouped in clusters, with each PDRE in the cluster firing at the same rate[12] (Fig. 12, from Reference 12). If several clusters are grouped together, with each firing at different times, the combined clusters will demand a near steady state fuel and oxidizer flow rate. In this way a single PDRE is actually composed of several clusters of individual combustion chambers. The complex turbomachinery and multiple combustion tubes needed in a PDRE system add additional weight, when compared to a traditional liquid rocket engine.

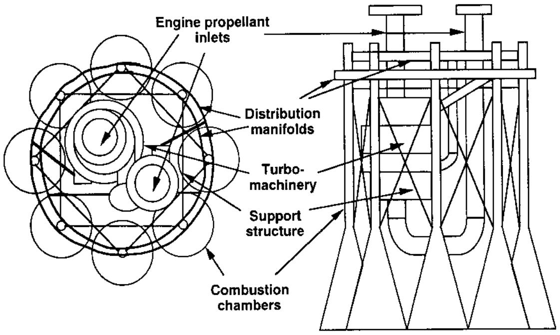

Figure 12 – Schematic of a Typical PDRE

PDRE Application to *Bantam-Argus*

For the current study two LOX/LH2 PDRE engines were investigated as replacements for the initial ejector mode and the final rocket-mode of the baseline *Bantam-Argus* concept. Since the rocket primary in the baseline RBCC engines was thus unnecessary, it was removed from both RBCC engines, leaving them simple, conventional ramjets. Since the PDREs and the conventional ramjets were not physically or thermally integrated, this PDRE + Ramjet system will be referred to as a combination propulsion system (CPS) as opposed to a combined-cycle.

For the *Bantam-Argus* mission, the PDREs provide all the vehicle's thrust until Mach 2, at which point they throttle down and the ramjets begin to provide the needed thrust. By Mach 3, the PDREs are off and the ramjet is the sole propulsion source. The vehicle then flies a constant q trajectory of 1500 psf until Mach 6. At this point the ramjets turn off and the PDREs place the vehicle in orbit. Note that the supercharging fan present in the baseline SERJ design was also removed for this investigation, thus this alternative does not have the five minute powered landing capability present in the baseline design.

The PDRE performance numbers used in this analysis were obtained from the final report of Boeing Rocketdyne's 1997 Highly Reusable Space Transportation Propulsion Option Study[12]. Table 2 shows the specifics of the PDRE used. This study considered several advanced propulsion concepts for NASA HRST. Aggressive assumptions on engine performance and weight were assumed. In particular, note that the vacuum I_{sp} of the LOX/LH2 PDRE was estimated to be 492.2 seconds – nearly 10% higher than the I_{sp} delivered by the Space Shuttle Main Engine! The installed engine T/W at vacuum was estimated to be 112.3. Compared to currently operating LOX/LH2 rocket engines, this represents a significant improvement (a much higher number), but T/W is consistent with other weight estimates made by Boeing for next generation, HRST-class rocket engines. In fact, the PDRE T/W estimate is about 4% - 5% lower than estimates for an advanced staged-combustion cycle LOX/LH2 rocket engine from the same study that utilized similar advanced materials and construction assumptions.

Table 2 - PDRE Data

Propellants	LOX/LH2
Mixture Ratio (O/F)	6.9
Feed Pressure	1500 psi
Nozzle	Bell
Exit Pressure	4.5 psi
Power Cycle	H_2 Rich Staged Combustion
Thrust (unscaled)	
Sea-level	421,000 lb.
Vacuum	539,980 lb.
I_{sp}	
Sea-level	384.3 sec.
Vacuum	492.9 sec.
Vacuum T/W	112.3

Figure 13 and 14 show the thrust and I_{sp} curves for the PDRE + Ramjet CPS up to Mach 7 (beyond Mach 6, the vehicle continues to operate in PDRE mode). The conventional LH2 ramjet performance numbers were generated using SCCREAM. The ramjet weight was based on a capture area to GLOW relation developed from the baseline *Bantam-Argus* vehicle designed to produce an overall vehicle thrust-to-drag ratio near 2 at ramjet takeover. The installed weight of the conventional ramjet was determined by WATES to be 85 lb/ft^2 of cowl area. This gives the overall CPS an installed T/W at takeoff of ~25, which is comparable to the baseline SERJ *Bantam-Argus* value. The PDRE required thrust was sized from the GLOW and the T/W at takeoff requirement of 0.7.

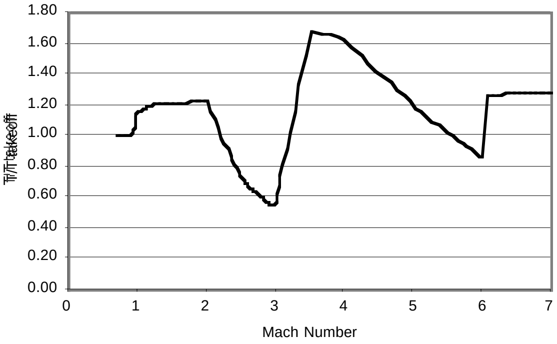

Figure 13—Normalized Thrust profile for the PDRE + Ramjet CPS

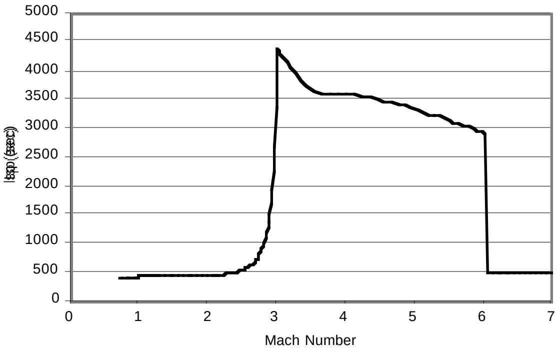

Figure 14 - I_{sp} profile for the PDRE + Ramjet CPS

RESULTS

Conceptual vehicle designs were converged for each of the candidate alternate propulsion systems using the iterative, multidisciplinary design process discussed earlier. The sizing results for *Bantam-Argus* with each of the alternate propulsion options were compared to the baseline SERJ vehicle. In addition, a *Bantam-Argus* vehicle with just PDRE propulsion (i.e. all-rocket propulsion, no ramjet segment) was also analyzed for comparison.

DCTJ + Rocket Results

The two DCTJ combined-cycle datasets yielded very different results. The DCTJ cycle A (the DCTJ-oriented set) resulted in a vehicle with a slightly higher GLOW and dry weight when compared to SERJ *Argus*. However, DCTJ cycle B (the rocket-oriented set) showed considerable improvements over the baseline *Bantam-Argus* design. Table 3 shows the comparison between the two DCTJ combined-cycles and the baseline SERJ *Bantam-Argus*.

Table 3 - DCTJ + Rocket combined-cycle results

	GTOW	Dry Wgt	MR	O/F
Baseline Bantam-Argus	281275 lb.	43635 lb.	5.736	4.727
DCTJ Oriented (Set A)	288438 lb.	48595 lb.	5.306	3.348
Rocket Oriented (Set B)	210588 lb.	35779 lb.	5.252	4.529

As discussed earlier, the dominate difference between the two DCTJ + Rocket datasets is the increased tanked O/F ratio predicted by dataset B. The ascent Mass Ratios are very similar, while the O/F ratio produced by set B is 35% higher than that of set A. This produces a lower overall propellant bulk density, which in turn leads to a smaller, more compact vehicle.

Relative to the baseline SERJ vehicle, the dataset B vehicle has a higher I_{sp} during initial acceleration while also providing a comparable (or higher) thrust from liftoff to Mach 6. The installed engine T/W is also slightly higher than the SERJ T/W (24 vs. 23). Therefore, the converged dataset B vehicle shows a clear advantage over the baseline in terms of both dry weight and gross weight. Set B (from Czysz) appears to combined the high Isp of the DCTJ-oriented option with a higher LOX consumption associated with the baseline RBCC. As mentioned earlier, the authors view this propulsion data as immature and lacking of detailed analysis support in the open-literature. However, these results do seem to point toward a direction of compromise in advanced space vehicle propulsion between the extremes of high I_{sp} on one end and higher propellant bulk density on the other. The "middle ground" explored here may offer some attractive size and weight advantages for next generation systems.

One of the most uncertain features of the DCTJ combined-cycle is its weight. An overall engine T/W of 21 was used for the DCTJ cycle A and an overall engine T/W of 24 was used for DCTJ cycle B. Changing these T/W assumptions has a great effect on the final vehicle weight results. Sensitivity studies were conducted to evaluate the effect of changing engine T/W for both DCTJ + Rocket datasets. Figures 15 and 16 show this effect for each cycle. Depending on the weight estimation used, the results for each cycle could change dramatically. For example, if the net installed T/W of the DCTJ + Rocket cycle falls below 15, neither concept shows an advantage over the baseline SERJ-powered option.

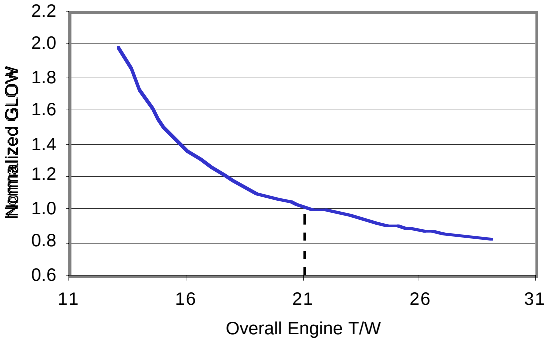

Figure 15 - Effect of overall DCTJ cycle A engine T/W on Normalized GTOW

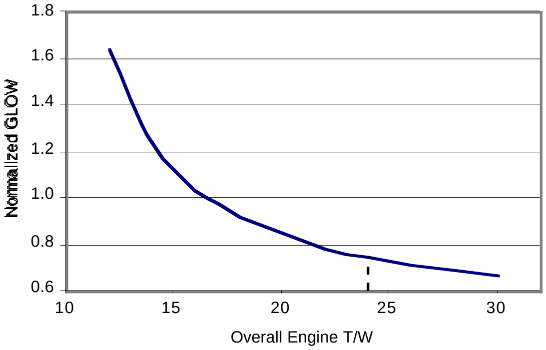

Figure 16 - Effect of overall DCTJ cycle B engine T/W on Normalized GTOW

PDRE + Ramjet Results

The PDRE + Ramjet combination propulsion system results showed a dramatic improvement in the baseline vehicle's weight (Table 4). Recall that the PDRE was taken to operate at a vacuum I_{sp} of 492.9 in rocket-mode. The rocket-mode (from Mach 6 to orbit) makes up a significant portion of the propellant consumption for the *Bantam-Argus* trajectory, therefore the clear advantage of the increased rocket-mode I_{sp} is to be expected. Relative to the baseline SERJ engine, the PDRE operating in low speed boost up to Mach 2 – 3, loses a small amount of average I_{sp} in that portion of the trajectory, but the higher local O/F ratio during PDRE operation of 6.9 tends to offset that disadvantage. The ramjet mode (Mach 3 to 6) of this option is very similar to the baseline.

Table 4 - PDRE + Ramjet CPS and All-PDRE results

	GTOW	Dry Wgt	MR	O/F
SERJ Argus	281275 lb.	43639 lb.	5.736	4.727
PDRE + Ramjet CPS	179563 lb.	31256 lb.	5.126	5.203
All-PDRE propulsion	174170 lb.	25326 lb.	6.071	6.900

The wild-card case of a simple all-PDRE *Bantam-Argus* showed the greatest weight reduction of all cases considered in this investigation! Here the conventional ramjets were removed completely from the vehicle along with the constant dynamic pressure portion of the trajectory. The vehicle was allowed to follow a rocket-style trajectory from the end of the Maglifter launch assist track directly to orbit using only the PDREs. The overall tanked O/F in this case is simply 6.9 (the highest value obtained in all cases). Coupled with nearly a 500 second I_{sp} and an installed PDRE T/W above 112, this concept has the potential to be a real winner. Of course, the uncertainty associated with actually meeting the 492.9 second PDRE I_{sp} and T/W claims must be carefully considered.

To assess the effects of performance uncertainty, the effect of PDRE I_{sp} was explored. Figure 17 shows the trends discovered as PDRE I_{sp} was varied. Even with a relatively more conservative I_{sp} of 455 seconds, the PDRE + Ramjet CPS and all-PDRE vehicles still show a marked improvement over the SERJ *Bantam-Argus* concept. However when the predicted I_{sp} fell below 475 seconds, the PDRE + Ramjet CPS showed better results than the all-PDRE option.

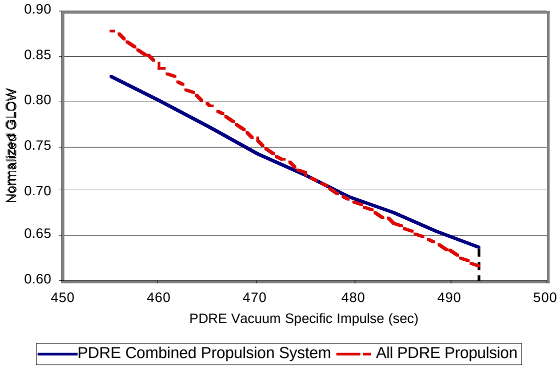

Figure 17 - Effect of PDRE I_{sp} on Normalized GTOW

A sensitivity analysis on the PDRE installed T/W assumption (112.3) was not conducted in this investigation, but the authors expect a similar trend. A more conservative T/W assumption will increase the concept gross weight – perhaps even until it exceeds that of the baseline SERJ concept. As before with the DCTJ + Rocket data, the authors view the current open-literature support for these PDRE I_{sp} and T/W numbers as immature and incomplete. However, the conclusion that must be drawn from this study is that should PDRE's even come close to meeting their performance and weight claims, the potential payoff for vehicle size and weight is significant (with or without an accompanying ramjet).

ANALYSIS SUMMARY

This paper analyzed the effects of the various propulsion systems on the vehicle's overall size and weight. The substitution of a DCTJ (deeply-cooled turbojet) combined-cycle for the SERJ engines had mixed results. Two sets of DCTJ + Rocket combined-cycle engine data were obtained and used to resize the baseline *Bantam-Argus*. One dataset was biased toward "more DCTJ" (DCTJ Cycle dataset A) and yielded a slightly heavier vehicle. However, a second dataset for the same cycle biased toward "more rocket" (DCTJ Cycle dataset B) lead to a 25% decrease in the vehicle's GLOW and an 18% decrease in dry weight. This benefit was largely attributed to the dataset's higher overall O/F ratio for the ascent while maintaining a high I_{sp}. Trade studies on the DCTJ combined-cycles' overall T/W were conducted to determine the effect of this assumption.

A PDRE + Ramjet combination propulsion system was then used in place of the baseline SERJ. The PDRE + Ramjet CPS showed a marked improvement over the baseline *Bantam-Argus* design, with a GLOW decrease of 36% and a dry weight decrease of 28%. The baseline vehicle was also sized with only the PDRE as the propulsion system (no ramjet or airbreathing trajectory segment at all). This further improved the GLOW with a decrease of 38% and a dry weight decrease of 42%. Trade studies were performed on the PDRE baseline I_{sp} of 492.9 seconds to determine the effects. Even with an I_{sp} of 455 seconds, the PDRE + Ramjet still shows a 17% decrease in GLOW. Also, once the I_{sp} of the PDRE drops below 475 seconds the PDRE + Ramjet CPS yields a lower GLOW than the all-PDRE *Bantam-Argus*. Sensitivities of the PDRE with respect to engine installed T/W (112.3 baseline) were not performed in this study.

CONCLUSIONS

Several alternate propulsion systems were evaluated on the *Bantam-Argus* launch vehicle concept to determine which provided the lowest gross weight for a constant 300-lb. payload delivery requirement. Based on the propulsion data obtained, it was determined that the all-PDRE *Bantam-Argus* concept is the best choice (Fig. 18).

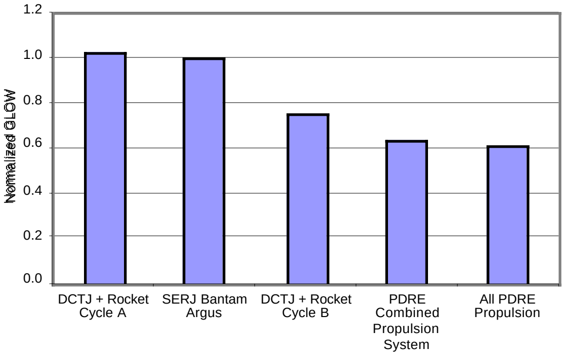

Figure 18 – GLOW comparison of all vehicles analyzed (with baseline assumptions)

This vehicle provided the lowest GLOW of the four options considered. However, other observations may be drawn for this study.

1. The all-PDRE and PDRE + Ramjet CPS dominance in this study is a strong function of this engine's large increase in rocket-mode I_{sp} over a conventional LOX/LH2 liquid rocket engine, coupled with only a slight increase in weight. However, PDREs are at a relatively low TRL (approx. 2-3)[12]. Since the technology is immature, the engine performance and weight numbers have a greater degree of uncertainty associated with them.

2. The PDRE I_{sp} trade study shows that even with an I_{sp} around a more conventional value of 455 seconds, the PDRE vehicles still are an improvement over a SERJ-powered *Bantam-Argus*. Also, if the PDRE's I_{sp} is as high as claimed, the ramjet component of the CPS actually reduces the vehicle's performance. However, once the I_{sp} drops below ~475 seconds, the PDRE + Ramjet CPS vehicle yields the best results.

3. For this study, an aggressive T/W assumption was obtained for the PDRE engines (112.3 in vacuum). The results reported here will certainly be sensitive to that assumption. A sensitivity study was not performed on PDRE T/W, but the authors expect that some reduction in T/W can be absorbed before the PDRE is no longer the most attractive option.

4. The DCTJ combined-cycle results show good promise for this propulsion system for a HTHL SSTO mission. Previous studies have shown marked improvement when a DCTJ combined-cycle is place on an all-rocket VTHL SSTO vehicle[9]. This study shows that this cycle can also be competitive when used on traditional RBCC vehicle configurations.

5. Of the two datasets considered for a deeply-cooled turbojet + rocket combined-cycle, the results indicate a preference for the "rocket-oriented" version. While this version has a slightly lower I_{sp} than the "DCTJ-oriented version", it's increased installed T/W and in particular it's higher propellant bulk density result in a new *Bantam-Argus* concept that is lighter than the baseline SERJ concept.

6. As with the PDRE data, the DCTJ + Rocket performance (thrust, I_{sp}, and local O/F data) and weight data obtained for this study is considered to be poorly supported and detailed in the open-literature. A sensitivity study on the obtained values of engine T/W indicate that reductions of 20% - 25% from the assumed values will increase vehicle gross weight above that of the baseline SERJ concept.

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