A Comparison of Selected Air-Breathing Propulsion Choices for an Aerospace Plane

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Abstract. This paper presents a comparison of three types of air-breathing rocket-based combined cycle propulsion systems for an advanced single stage-to-orbit aerospace plane. The propulsion systems include the NASA Access to Space (ATS) combined cycle engine, the Aerojet "strutjet" rocket-based combined cycle engine, and a proposed Russian AJAX MHD energy bypass rocket-based combined cycle engine. These propulsion systems are compared on the vases of performance and life cycle costs. The results indicate that the preferred choice based on performance is the AJAX MHD energy bypass rocket-based combined cycle energy bypass engine. No clear choice was indicated based on a life cycle cost comparison.

INTRODUCTION

During the NASA Access to Space study, both rocket-powered and air-breathing powered single stage to-orbit (SSTO) concepts were investigated. The Access to Space study air-breathing concept propulsion system was based on the NASP engine concept. After the termination of the NASP X-30 program and the completion of the Access to Space study, NASA selected a rocket powered SSTO concepts for further study. The current X-33 SSTO technology flight demonstration program. With the X-33 program successfully underway, NASA began the NASA Highly Reusable Space Transportation (HRST) program to look beyond X-33 enabled SSTO concepts. The intent of the HRST program was to identify concepts and technologies that could potentially provide greater space transportation cost reductions than that proposed for the next generation of reusable launch vehicles (RLV). A goal of $100-200 per pound was set for HRST systems candidates. ANSER proposed one of the system concepts funded under the HRST program (Chase, 1997).

The ANSER team proposed an MHD energy bypass ejector ram-scramjet combined cycle engine powered SSTO design concept. To evaluate the performance of the proposed advanced concept, a reference rocket based combined cycle engine powered SSTO concept was formulated using the Aerojet "strutjet". The weight estimates used to generate the reference SSTO design concept are based on updated Access to Space study air-breathing SSTO design concept weights.

Approximately five years ago several scientist returning to the United States from visits to Russia began mentioning a Russian project known as AJAX. AJAX is a project being conducted by the Lennets Holding Company in St. Petersburg. AJAX is a hypersonic cruiser concept that incorporates several advanced technologies to improve performance. Turbojet engines power AJAX plus MHD augmented scramjet engines in a side-by-side configuration. In addition, beamed plasma energy plus microwave energy is used to modify the flow field ahead of and around the aircraft. The fuel for the hypersonic cruiser is reformed kerosene. The Air Force and NASA have shown interest in the AJAX concept and its technologies. The Air Force sponsored two conferences to discuss AJAX technologies and their potential impact on hypersonic flight. Air Force and NASA scientists have made several visits to Russia to look at Russian AJAX research. Several joint United States and Russia research projects are currently underway to investigate AJAX technologies. Russian researchers have been invited to and attended technical meetings in the United States to present papers on AJAX technologies.

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CONCEPTS

Table 1 shows the design concepts considered for comparison in this paper. Concept 1 uses the Aerojet strutjet rocket based combined cycle engine. A unique feature of the Aerojet 'strutjet" is the integration of a distributed rocket engine into the ram/scramjet struts. Placement of the rocket engine in the walls of the struts enables the rocket engine to share the exhaust nozzle of the air-breathing ramjet and scramjet engine. The configuration of concept 1 is the same as the Access to Space air-breathing design configuration. Aerojet provided engineering data for the strutjet. Aerodynamic data were obtained from NASA LaRC. Concept 2 uses an MHD energy bypass ejector ramjet engine. The configuration of concept 2 is the same as concept 1. Dr. Paul Czycz provided performance data for the engine. Dr. Paul Czycz and Dr. Carlo Bruno from the University of Rome have been looking at the Russian AJAX concept for several years (Bruno, 1998). Both Paul and Claudio have direct contact with the Russian AJAX design team. The AJAX concept uses several subsystem to enhance the performance of the concept. AJAX technologies incorporated into the ANSER team concept include an MHD generator to extract power from the flow entering the engine, an ionization mechanism to ionize the flow ahead of the vehicle , around the body of the vehicle, and the airflow entering the engine, and an MHD accelerator to return the bypassed energy to the engine exhaust nozzle. During energy extraction the velocity of the air-flow is reduced. If the magnetic field of the MHD device is strong enough, the flow entering the combustor remains subsonic Supersonic flow does not occur in the engine combustor. The performance of a ramjet engine rather than a scramjet engine is obtained until the rocket cycle is initiated. Concept 3 is the NASA Access to Space air-breathing SSTO design concept. The NASP combined cycle type engine powers it.

PERFORMANCE ASSESSSMENT

The results of the performance assessment for each of the trade cases are shown on table2. The results of the trade study cases indicate the following: The performance capability design concept 1, the Aerojet "strutjet" RBCC engine powered SSTO, is approximately the same as the NASA Access To Space air-breathing SSTO, design concept 3. At first this is rather surprising considering the average effective specific impulse of design concept 3 is approximately 1200 seconds compared to design concept 1 of approximately 700 seconds. The ascent flight paths of the two options are considerably different. The closure delta velocity requirement of the design concept 3 is approximately 40, 000 fps compared to the closure delta velocity of design concept 1 of approximately 30, 000 fps. The reduction in closure velocity of approximately 10, 000 fps offsets the 500 second specific impulse advantage of design concept 3. Design concept 3 does not pull up out of the atmosphere until a Mach number between 16 and 17, whereas, design concept 1 does a pull-up maneuver between Mach 8 and 9. An early pull-up reduces drag losses and reduces maximum temperatures, which in turn reduces thermal protection system weights. NASA LaRC data indicates that the penalty for a late pull-up, Mach 16.5, compared with an early pull-up, Mach 10, only increased TPS weight by 8% to 28% depending on which TPS materials were used.

Table 1. Design Concept Matrix

		Concept 1 Reference	Concept 2 AJAX	Concept 3 Access to Space (ATS)
Description	Configuration	ATS	ATS	Lifting Body
	Propulsion System	Aerojet Strutjet RBCCE	MHD Energy Bypass RBCCE	Combined Cycle
	Transition Mach No.	Mach 9	Mach 12	Mach 12+

Table 2. Performance Summary

	Concept 1	Concept 2	Concept 3
Fuselage, Tanks	43,320	36,355	63,897
TPS	26,827	21,963	42,057
Wing, Tails, Flaps	14,481	11,856	22,739
Landing Gear	13,407	10,981	18,975
Propulsion	53,430	29,082	64,615
MHD System		46,503	—
Equipment	27,183	27,183	27,183
Dry Weight (w/o MHD)	178,648	137,420	239,466
Dry Weight (w/ MHD)	178,648	183,923	239,466
Propellant & Fluids	685,697	516,768	652,207
LH2	248,287	144,978	308,927
LOX	436,636	371,157	315,721
Payload	40,000	40,000	40,000
TOGW	904,354	740,690	916,673
Swet	21,882	17,915	24,590
Structure Factor	4.480	4.530	5.234
Total Volume Available	78,845	58,407	93,923
Total Volume Required	78,845	58,407	93,923
Volume Surplus/Deficit	0.00%	0.00%	0.00%
Planforrn Area	8,907	7,292	10,009
Tau	0.0938	0.0938	0.0938
Takeoff Wing Loading	101.54	101.58	91.58
Landing Wing Loading	24.55	30.71	26.42
Delta-V Total	29,739	28,749	40,643
Average ISP	693	793	1,173
Mass Ratio	3.726	3.036	2.857
Drag Loss	2,855	1,769	10,899
Gravity Loss	1,664	1,724	2,670
Other	88	136	1,528

Design case 2, the hydrogen fueled MHD energy bypass ejector ramjet powered design has the lowest gross take-off weight (GTOW). The GTOW of design case 2 is approximately 25% less than the reference design case. MHD weight estimates used in the analysis are based on United States super conducting magnetic forecasts. Liquid Helium temperature magnets were assumed. If Russian MHD weights had been used in the computations, the gross weight of design concept 2 would have been reduced by an additional reduction of 25% compared to design concept 3. Dr. Paul Czysz provided modified Russian MHD engine performance equations. Aerojet strutjet performance was assumed during ducted rocket and rocket engine cycle operations. The reduction in weight is a result of a combination of the reduction in delta velocity required and increased engine performance. Drag losses were found to be approximately 7-9% of the total closure velocity requirement. Whereas, design concept 3 had drag losses that comprised approximately 30% of the closure velocity requirement. These results indicate that the use of drag reduction devices could be beneficial in those situations where drag losses are a significant part of closure velocity requirements

It is interesting to note the mission energy requirements. The mission energy requirements for cases 1 and 2 are very low for an air-breathing SSTO design concept compared to the NASA Access to Space air-breathing design concept, case 3. During the NASP competition phase, contractor design concepts had closure velocity requirements between 40,000 and 50,000 fps. Whereas, cases 1 and 2 were more that 10,000 fps lower than case 3, the NASA Access to Space SSTO design concept.

COST ASSESSMENT

Current cost estimating relationships may not be applicable to the kind of SSTO design represented by concept 2. An important feature of design concept 3 is the potential to reduce cost dramatically. If flow control and MHD energy bypass engine weight requirements are offset by system performance gains, vehicle manufacturing and operational costs could be significantly reduced. Factors contributing to the cost reduction are an all metallic aerospace plane, an integrated semi-monoque construction, and the absence of a thermal protection system. The MHD devices described in this study are relatively simple devices. The elimination of the scramjet cycle from the combined cycle engine would significantly reduce the complexity of the engine. The aircraft would resemble supersonic aircraft with good transonic performance capability rather than a hypersonic aircraft. Except for the MHD and drag reduction systems, the aircraft would be costed and operated like a supersonic airplane. Known CERs applicable to a supersonic aircraft could be used. In the 1980s Boeing proposed an all metallic assisted SSTO concept. The Air Force Have Region program demonstrated that the all metallic RASV structural concept could be built and operated in the SSTO environment. And, weight data could be accurately predicted. New materials and manufacturing techniques today could have a profound impact on the Boeing design cost and manufacturing techniques.

The assumptions used in the generation of the cost data are critical, especially those pertaining to operations and aircraft procurement. In this study we assumed that the initial buy was for two aircraft. The RDT&E aircraft could be retrofitted to operational status if a replacement aircraft or if increased demand occurred earlier than anticipated. Initially it was assumed the aircraft could be turned around in a week. Based on one flight per week for each aircraft would provided an initial annual capacity approaching 4 million pounds, which is greater then four times the current United States demand. It was assumed that only one aircraft would be operated initially and the second aircraft maintained in a standby status to ensure client schedules would be met in case anything unexpected happened to the first aircraft. As demand increased the second aircraft would be brought on-line and a second aircraft buy would be initiated if needed. The RDT&E cost for the MHD energy bypass system was estimated at $1.2 billion and an initial unit cost of $40 million. Nineteen MHD units were required per aircraft. Drag reduction subsystems would be in the range of $1-200 million. There would be one RDT&E aircraft and one structural test article. Life cycle costs were based on an operational life of 20 years. The total number of flights was 940. A summary of the cost projections for design concepts 1, 2 and 3 is shown on table 3

TABLE 3. Cost Data Summary

- 1997 base year
- One RDT&E vehicle
- Two production vehicles
- One operational vehicle
- Two deployment vehicles
- 47 flights per vehicle per year
- 7.77 day turnaround time
- 940 total system flights

	Concept 1	Concept 2	Concept 3
RDT&E	$13.5B	$13.3B	$16.6B
Production	$4.1B	$4.5B	$4.2B
Procurement	$2.9B	$2.6B	$3.2B
O&S	$9.6B	$9.0B	$9.5B
Total	$30.1B	$29.4B	$33.5B
Total Cost Per Flight	$32.1M	$31.4M	$35.6M
Recurring Cost Per Flight	$10.3M	$9.6M	$10.0M
Total Cost Per Pound	$802.0M	$785.0M	$1,424.0M
Recurring Cost Per Pound	$257.0M	$240.0M	$403.5M

Before commenting on the cost results, it is accepted that the absolute cost numbers are most likely inaccurate. The uncertainty in cost projection is historically large, and large underestimates in cost projections have been experienced in most cases, unfortunately. While the cost model used in this cost analysis is considered to be as good as other cost model, absolute costs should not be considered to be accurate. However, relative cost comparisons can identify broad trends and provide comparative evaluations. The first observation is that the RDT&E costs for all the trade cases considered were about the same, and represented about 45% of the life cycle costs. From a commercial venture perspective government support for RDT&E will be as essential in the future as it is now in the case of the X-33 program. It is interesting to note that RDT&E cost of the MHD energy by system in design concept 2 appears to pay for itself. The increased RDT&E costs associated with the performance enhancement subsystems are offset by a reduction in the RDT&E costs associated the rest of the system. For example, the MHD augmented ejector ram engine is about the same as the ejector ram-scramjet engine. While not proven by this cost analysis, it does appear that a performance optimum and a cost optimum could be the same concept. Additional cost analysis is required before this observation can be validated.

SUMMARY

The conceptual idea of a "virtual" aircraft presented in this paper represents a basic change in aircraft design philosophy. Traditionally, the environment into which the aircraft is to fly is defined and the aircraft is then designed to operated in that environment. The higher the speed the more difficult it is to define the flight environment by computational methods, or in ground test facilities. As speed increases more and more performance is needed by all aircraft subsystems. Cost and technical risk increase. The "virtual" aircraft approach is based on changing the environment to accommodate the aircraft. By changing the environment less stress is placed on the performance capabilities of the aircraft. The Russians working on the AJAX project propose to change the operating environment ahead of and around the aircraft using a combination of magnetic fields, plasmas, and RF energy sources. To change the environment ahead and around the aircraft it is necessary to make the flow conducting. How the ionization is to be accomplished, and the level of conductivity needed, requires more work before it becomes clear how it is best done. The AJAX engine uses a MHD energy bypass system to control the velocity in the engine combustor. A MHD generator is used to extract energy from the flow entering the engine, thereby slowing the speed of the air entering the engine combustor. Flow through the combustor is maintained at subsonic speed. By maintaining subsonic flow in the combustor the performance of a ramjet rather than a scramjet engine is obtained. The ramjet produces a higher level of performance than a scramjet engine and is much easier to design and build. Drag and heat transfer reductions are obtained by using a combination of magnetic fields, "cold" plasmas and microwaves. If the methods used to reduce drag and increase engine performance can be made to work in an aircraft design it will represent a major breakthrough in reducing the cost of hypersonic flight cost. Development risk may also be reduced significantly.

The assessment presented in this paper study is an attempt to formulate a "virtual" aircraft based on the best information available at this time and compare that system with traditional approaches. The results of the study indicate that if the environmental modifications systems can be built to operate in the manner assumed in this study, overall performance will increase and cost will decrease. The results indicate that a MHD energy bypass ejector ramjet propulsion system could increase the performance and reduce the GTOW by approximately 25 % compared to the reference SSTO design concept. Hydrogen requirements were also reduced by approximately 40%, which will significantly reduced the size of the aerospace plane. While mission energy requirements for a single stage-to-orbit mission were only reduced by approximately 3% compared to the design concept 2, the energy requirements compared to design concept 3 are reduced by approximately 30%.

Clearly, a transition to the rocket cycle at Mach 12 paid off, rather than Mach 16-17 for design concept 3 reduced the drag losses significantly. Drag reduction in the case of a single stage-to-orbit mission did not show a performance advantage. A close look at the composition of the ideal velocity requirements for the three design cases considered indicates that drag losses were not a significant factor for concept 1 and 2 compared to design concept 3. . Drag losses were between 30-50% of the energy required to achieve orbit for concept 3. The benefits of drag reduction could extend beyond drag losses. Drag reduction accompanied by a reduction in heat transfer rate could substantially reduce thermal protection weight. If heat transfer rates are substantially reduced, an all metallic aerospace plane is a possibility. The cost advantages of an all metallic aerospace plane were shown by the Boeing RASV military space plane design concept in the 1980s to be significant.

The assumptions used in the generation of the cost data are critical, especially those pertaining to aerospace plane operations and maintenance. In this study we assumed that an initial buy of two aircraft. Assuming one flight per week for each aircraft would provide an initial annual capacity approaching 2 million pounds. This capacity is greater then twice the current United States demand for launch services. It was therefore assumed that only one aircraft would be operated initially, and the second aircraft would be maintained in a standby status to ensure client schedules would be met in case anything unexpected happened to the first aircraft. As demand increased the second aircraft would be brought on-line and a second aircraft buy would be initiated.

The results indicate a factor of approximately three is needed to recover the initial RDT&E and procurement cost over the recurring cost per flight. Government support of the RDT&E cost is very important for a commercial venture. Even though an RDT&E cost of over one billion was assumed for the MHD energy bypass ejector ramjet engine system, the costs of and MHD energy bypass ejector ramjet engine powered design concept, was competitive with the reference design concept.

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