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An AJAX Technology Advanced SSTO Design Concept

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ABSTRACT

This paper presents an advanced single stage-to-orbit (SSTO) design concept based on our understanding of Russian AJAX technologies. The concept brings together a unique set of subsystem components to enhance the performance of an advanced combined cycle engine powered SSTO design concept. A magnetohydrodynamic (MHD) generator-accelerator energy bypass system is used to maintain subsonic flow in the engine combustion chamber. And, an electromagnetic drag reduction system is used to reduce wave and base drag during ascent and reentry. The performance of the advanced highly reusable SSTO is compared to a reference advanced air-breathing rocket-based combined cycle ejector ram-scramjet powered SSTO design concept. The results indicate an approximate 15% performance increase compared to the reference design.

INTRODUCTION

Two years ago NASA began the Highly Reusable Space Transportation (HRST) program to look beyond the space transportation price goal for the RLV. The goal of the HRST program is to identify concepts and technologies that have the potential to reduce space transportation prices to $100-200 per pound to low Earth orbit.

A team headed by ANSER proposed one of the system concepts funded under the HRST program. The ANSER team proposed an MHD augmented combined cycle powered SSTO design concept. To evaluate the performance of the proposed advanced SSTO concept, a reference combined cycle engine powered SSTO concept was formulated. The reference concept is a derivative of the NASA Access to Space study air-breathing SSTO design concept.

Approximately six 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. AJAX is powered by turbojet engines plus MHD augmented scramjet engines in a side-by-side configuration. In addition, beamed plasma and microwave energy are used to modify the flow field ahead of and around the aircraft. The fuel for the AJAX hypersonic cruiser is reformed kerosene. The Air Force and NASA have shown interest in the AJAX concept and its technologies. 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 have been conducted to investigate AJAX technologies. Russian researchers have attended technical meetings in the United states to present papers on AJAX technologies.

DESIGN CONCEPT

Design Philosophy

Inherent in the Russian AJAX design philosophy is the assumed ability to modify the flow field around the body of the aircraft and the air entering the engine inlet. Electromagnetic forces, microwaves and plasmas are proposed as the means to accomplish flow modifications. From the perspective of the flow field around the aircraft, a "virtual" configuration is established to optimize aerothermodynamic and propulsion efficiencies. The virtual configuration is varied as a function of flight speed to optimize performance. The NCB-3 lifting body configuration, or a modified wave rider configuration have been used for the actual configuration. The actual vehicle does not need to look like the NCB-3 configuration, or any of the virtual configurations created during the flight of the aircraft The optimum configuration for the actual vehicle has not been determined.

SSTO Advanced Concept

An advanced SSTO design concept that uses AJAX technologies was formulated by the design team. The technologies incorporated in the design concept include an MHD generator to extract power from the air entering the engine, a neutron beam to increase the conductivity of the flow entering the engine, an MHD accelerator in series with the MHD generator to by pass energy around the engine combustor and return the energy into the exhaust of the engine, a cold plasma beam, or air spike, to interact with the flow field ahead of the aircraft, and electromagnetic fields and microwave energy to modify the flow field around the aircraft. The features of the design concept are shown on figure 1.

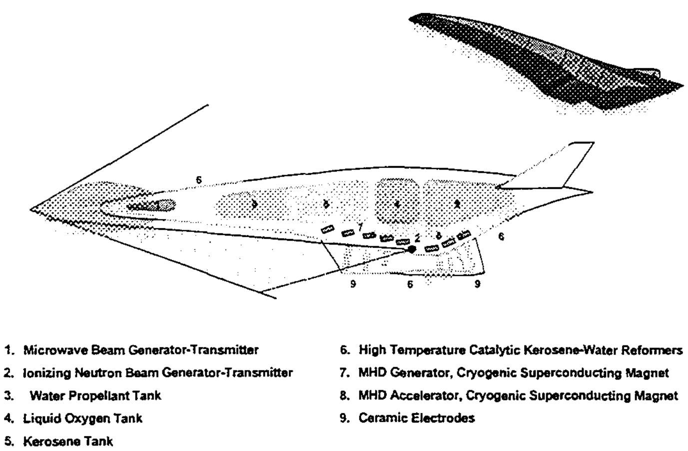

Figure 1. HRST SSTO Design Concept

Reference Rocket Based Combined Cycle SSTO design Concept

To evaluate the performance of the proposed advanced SSTO design concept, a reference rocket-based combined cycle engine powered SSTO design concept was also formulated by the design team for a 25,000 lb. payload delivery capability to the International Space Station. This equates to a payload of approximately 40,000 lb. to a 100 n. mi., 28 degree inclination orbit. The reference design concept configuration is a derivative of the NASA Access to Space air-breathing SSTO design concept. The Access to Space air-breathing SSTO propulsion system was replaced by the Aerojet combined cycle "strutjet" propulsion system. The Aerojet strutjet engine combines a liquid hydrogen/oxygen rocket with an air-breathing ejector ram-scramjet. The combustion chamber and exhaust nozzle of the rocket engine are shared with the ram/scramjet engine. The rocket engine is "buried " in the walls of the ram-scramjet engine. The configuration of the strutjet powered SSTO design remained the same as the Access to Space SSTO configuration. Eight individual strutjet propulsion modules were sized to fit under the 200' long Access-to-Space SSTO design concept airframe. Engineering data for the strutjet system were provided by Aerojet. Aero data were obtained from NASA LaRC. Figure 2 shows the reference SSTO design concept and a cutaway of the Aerojet strutjet engine.

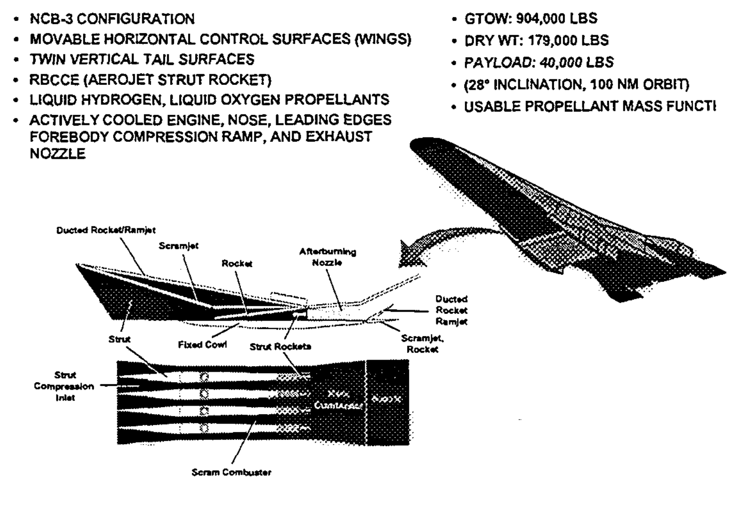

Figure 2. Reference SSTO Design Concept Configuration and Propulsion System

Figure 3 summarizes the specific impulse capabilities of the Aerojet strutjet combined cycle engine for the reference design concept. The combined cycle engine achieves an overall effective specific impulse of approximately 650 seconds. The required ideal velocity is approximately 30,500 feet per second. And, the required useable propellant fraction is approximately 0.84.

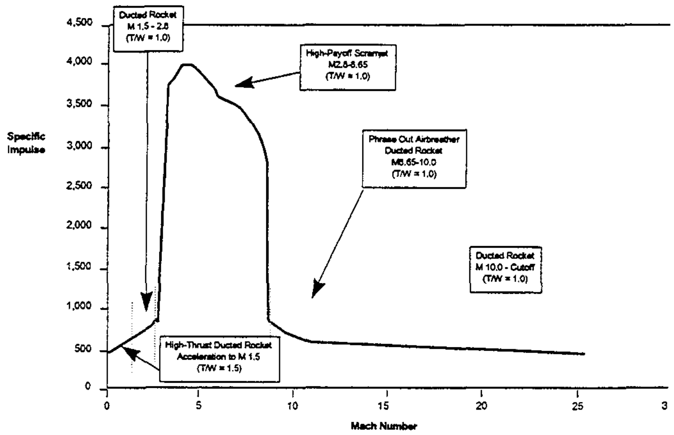

Figure 3. Specific Impulse Capability of the Reference SSTO Design Concept

Design Methodology

The OTIS design optimization code was used to determine the optimum performance conditions. Some modifications were made to the NASA Access to Space design concept weights to be consistent with the weight data used on the MHD augmented engine design concept. Aerodynamic data were based on NCB3 configuration data. Weight data include a 15% "weight margin". Since this work was primarily a technology impact assessment study, the vehicle gross takeoff weight and size were initially assumed constant, thus weight and volume reductions in the resultant system appear as excess payload. Later as the design was better understood the payload was fixed and the gross take-off weight was determined for each design case. The primary reason for this tactic was the large uncertainty in the sizes and weights of the candidate technologies. The "fixed weight" method allows quick modification of system weights and sizes as the technology assessment progressed, instead of requiring a completely new study for a "sized" vehicle where system assumptions are intrinsically buried in the defined vehicle.

Magnetohydrodynamic (MHD) Energy Bypass System

One of the most severe limitations on an air breathing SSTO design concept is the requirement that supersonic combustion ramjet (SCRAMJET) engine cycles are required for a substantial portion of the high Mach number ascent. Passing supersonic flow through the combustor not only creates a technology challenge in engineering such a system, but also results in substantially lower performance capability than a ramjet cycle. The magnetohydrodynamic (MHD) energy bypass engine does not have a scramjet cycle during ascent. The elimination of the scramjet cycle is accomplished by extracting energy from the flow prior to entering the combustion chamber. Both pressure and temperature are reduced at the entrance to the combustion chamber. The extracted energy is returned to the flow in the exhaust nozzle by an MHD accelerator. The energy bypass system begins prior to the speed at which the flow in the engine would be supersonic at the combustor entrance. The free stream condition at which this occurs is approximately Mach 5. The MHD energy by pass system prevents supersonic flow at the combustor entrance until the engine transitions to the final rocket cycle. Below Mach 5 the engine operates as a normal ramjet. The energy bypass engine uses a ducted rocket for take-off and climb to Mach 2 at which point the rocket engine is turned off and the engine operates as a ramjet. The rocket engine is turned back on at Mach 12 and runs during the final ascent to orbit.

The MHD bypass system has several major components which distinguish it from other propulsion systems. Figure 4 shows a cutaway view of the MHD propulsion system. As with the Aerojet strutjet, the underbody of the vehicle forms the compression ramps leading to the inlet. The final ramp is shown as the contracting section at the left of the engine cutaway. Aft of the inlet compression section is the MHD generator duct. In this duct, energy is extracted in the form of electrical power, effectively slowing down the incoming gas stream. The gas then enters the expanding combustor duct where fuel is injected from the sidewalls and burned. The gas proceeds through the MHD accelerator duct, where the electrical energy is returned to the air stream. Finally, an expanding duct forms the beginning of the expansion nozzle which continues external of the engine exhaust nozzle.

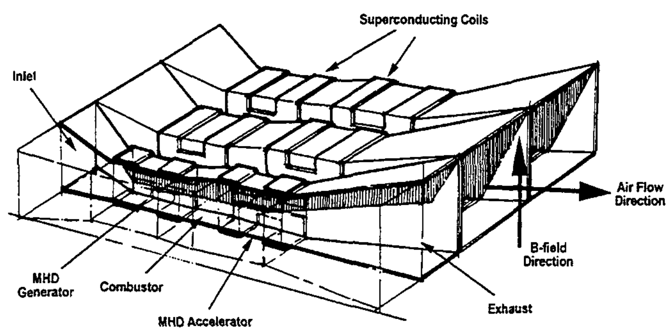

Figure 4. MHD Engine Configuration

The heaviest component of the system is the superconducting coil magnets which surround the MHD channels. The magnetic field strength in the MHD channels is determined by the conductivity of the flow and the amount of energy to be extracted. The current and windings required to generate the magnetic fields are heavy. New materials and promising data from

Russian indicate that a tenfold reduction in the weight of candidate magnet systems is possible compared to current magnet weights.

Eighteen flow path elements comprise the MHD energy by pass engine used in this study.

The physics associated with the magnetohydrodynamic process is fairly simple. In the presence of a magnetic field, a moving conducting gas generates electrical potential at right angles to the magnetic field and it's velocity vector. The power that can be extracted is given by:

$$\text{Power (W)} = 0.25 * \sigma * V^2 * B^2$$

where σ - electrical conductivity of the gas stream (mho/m)

V - velocity of the gas stream (m/s)

B - magnetic field strength (tesla)

The power extracted is a strong function of both field strength and flow velocity. As the vehicle accelerates, the power extraction capability of the MHD device increases rapidly; thus allowing the device to extract sufficient energy to keep combustor conditions constant in the Mach 5-12 range. For reasonable field strength values (5-10 tesla) and flight velocities above Mach 5, 50-100 megawatts can be extracted from a sufficiently ionized gas stream. It is the ionization of the gas that is the key to the process, since free stream air does not have sufficient conductivity to produce useful power.

The most important component of the MHD system is the super conducting magnets used to create the magnetic field in the channels. The magnets used in this design are top, bottom "saddle" type magnets which create a nearly uniform magnetic field in the MHD channel. Figure 5 shows a typical cross section of an MHD duct. The magnetic coils are composed of either Niobium-Titanium, or Niobium 310 wire, sheathed in a liquid helium bath bounded by an insulating tube. The helium bath keeps the coil temperature between 1.8 and 4.2 degrees Kelvin. The coils are suspended in a vacuum vessel which minimizes heat transfer out of the cold structure to the magnet casing. Operationally, the superconducting coils would be chilled to 1.8 degrees, charged and sealed for the duration of the launch. The heat flux in the MHD channels occurs for only a few minutes, the superconducting coils rise in temperature only a few tenths of a degree, thus the integrity of the field is maintained. The magnet weight accounts for more than 85% of the MHD system weight, therefore the importance of detailed analysis of this component cannot be underestimated.

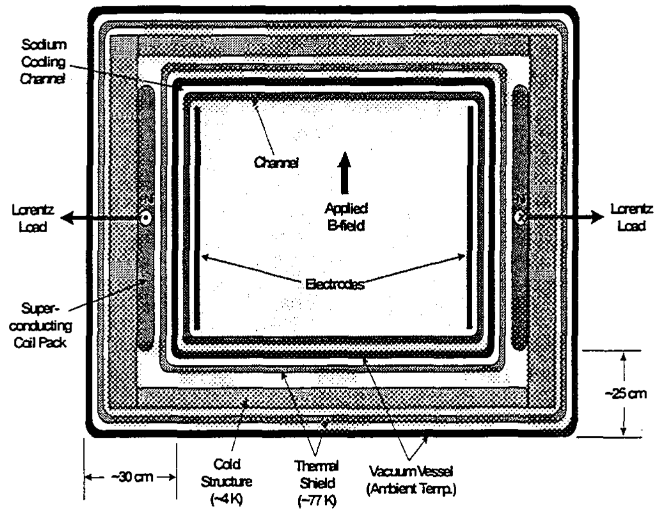

Figure 5. MHD Duct Cross Section

The remainder of the MHD system is relatively simple compared to the superconducting coils. Each individual generator channel is connected to it's complimentary accelerator channel via a series of buss bars. Each channel is separated into discrete sections with diagonally located electrodes along the channel sidewalls. These electrodes are directly connected to the accelerator electrodes which correspond to a matching velocity profile. The front of the generator is connected to the back of the accelerator. The electrodes are composed of a linear gradient ceramic material which can tolerate high heat at the surface yet conduct electricity away from the surface to the conducting base. The magnet casing is kept cool with liquid sodium cooling channels which surround the air channel. The liquid sodium is in turn cooled by the cryogenic fuel in a heat exchanger located above the engine modules.

Performance for the MHD energy by pass is computed by using data for a ramjet engine. Dr. Paul Czysz provided modified Russian MHD engine performance equations. Figure 6 shows the effective specific impulse as a function of flight velocity used to predict the performance of the vehicle. In essence, the engine "thinks" it is traveling at a much slower Mach number than the vehicle's actual velocity, thus it has a higher specific impulse compared to an engine without the energy by pass system. The higher specific impulse reduces fuel requirements, SSTO weight, and volume.

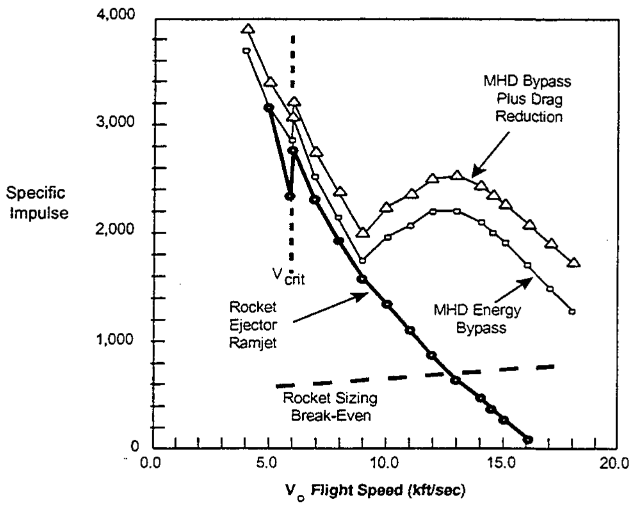

Figure 6. MHD Engine-Specific Impulse

PERFORMANCE ASSESSMENT

The results of the performance assessment comparison are shown on table 1. The results of the trade study cases indicate the following:

1. The AJAX design case has the lowest gross take-off weight (GTOW). The GTOW of AJAX design case is approximately 25% less than the reference design case. MHD weight estimates used in the analysis are based on U. S. super conducting magnetic forecasts. If Russian MHD weights had been used in the computations , the gross weight would have been reduced by an additional reduction of 25%. Aerojet strutjet performance was assumed during ducted rocket and rocket engine cycle operations. The design of the flow path, shown previously on figure 4, is based on the strength and configuration of the magnetic field and material choices. There are no vertical struts like that used in the Aerojet strutjet engine.

2. The increase in dry weight was approximately 3% compared to the dry weight of the reference design. The MHD estimated weight of approximately 46, 000 lb. (approximately 25% of the dry weight) was almost compensated for by reductions in other dry weight elements as a result of the increase in engine performance. If Russian MHD weight estimates had been used instead of United States estimates, the increase in engine performance caused by the MHD would have more than offset the weight of the MHD system. Hydrogen fuel weight was reduced by almost 40 %, which reduces hydrogen tank weight and the overall size of the aircraft.

3. The reduction in GTOW weight is a result of a combination of delta velocity required and increased engine performance. The optimum trajectory implicit simulation (OTIS) design code was used to determine engine cycle transition and the ascent flight profile. The closure velocity requirements for both the reference and the performance MHD augmented engine design concepts are very low for an air-breathing SSTO design concept compared to the NASA Access to Space air-breathing design concept. During the NASP competition phase the contractor design concepts SSTO closure velocity requirements varied between 40,000 and 50,000 fps. The air-breathing component of the closure velocity

SSTO DESIGN CONCEPT	Reference Case	AJAX Design Case
Velocity Cutoff of AB	11,910	12,943
Mach Cutoff of A/B	11.78	11.96
Fuselage, Tanks	43,320	36,355
TPS	26,827	21,963
Wing, Tails, Flaps	14,481	11,856
Landing Gear	13,407	10,981
Propulsion	53,430	29,082
MHD System		46,503
Equipment	27,183	27,183
Dry Weight	178,648	137,420
Dry Weight (w/ MHD)	----------	183,923
Propellant & Fluids	685,697	516,768
LH2	248,287	144,978
LOX	436,636	371,157
Payload	40,000	40,000
GTOW	904,354	740,690
Wetted Surface Area	21,882	17,915
Structure Factor	4.480	4.530
Total Volume	78,845	58,407
Total Volume Required	78,845	58,407
Volume, Surplus, Deficit	0.00%	0.00%
Planform Area	8,907	7,292
Tau	0.0938	0.0938
Takeoff Wing Loading	101.54	101.58
Landing Wing Loading	24.55	30.71
Delta-V, Ducted Rocket	3,321	3,419
Delta-V, Air-breather	12,728	12,923
Delta-V, Rocket	13,290	12,008
ISP, Ducted Rocket	488	505
ISP, Air-breather	1,699	3,549
ISP, Rocket	474	474
Delta V, Total	29,739	28,749
Average ISP	693	793
Mass Ratio	3.726	3.036
Drag Loss	3,855	1,769
Gravity Loss	1,664	1,724
Other Loss	88	136

Table 1. Performance Results

be approximately 7-9% of the total closure velocity requirement. The results indicate that the use of drag requirement comprised approximately 55%. This is because drag losses were found to reduction devices could be beneficial in those situations where drag losses dominate the closure velocity requirements. Drag reduction may pay off for a design concept like the NASA Access to Space design concept where transition from the air breathing cycle occurs between at Mach 16-17. In the Access to Space design concept the drag losses comprise approximately 30% of the closure velocity requirement. The NASA Access to Space design concept was not included in the design concepts trade-off matrix.

Figure 7 presents the ascent to orbit flight pro file for the MHD energy by pass engine design case. This figure shows the engine cycle change locations. Take-off and climb out to Mach 2 uses the ducted rocket. The MHD *begins to come on-line* at approximately Mach 2. Artificially induced ionization of the flow coming into the engine is require. As flight speed increases the velocity in the engine increases, and the amount of power that is extracted and bypassed increases. The magnetic field for the MHD device is initiated on the ground with ground power. Because the MHD employs a superconducting magnetic it is assumed the field strength of the magnetic continues at the level initiated on the ground prior to take-off. At approximately Mach 5 the flow at the entrance to the engine combustor would become transonic. However, the MHD generator at this point is extracting sufficient energy from the airflow entering the engine to prevent the airflow from becoming supersonic. The OTIS design optimization code was used in this study to define magnetic field strength requirements and the optimum transition Mach number at which engine cycle transitions occur. The optimum transition to the rocket cycle for the second and final time occurs at Mach 12 at which time the magnetic field

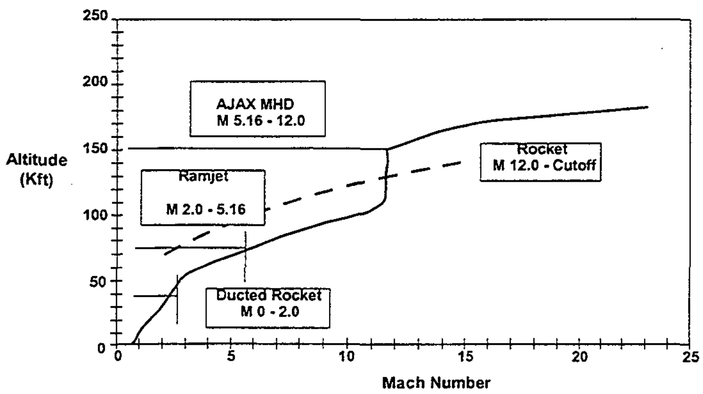

Figure 7. Ascent to Orbit flight Profile

strength requirement is approximately 8 TESLA. After completing the transition to the rocket cycle the aircraft does a pull-up maneuver to get out of the atmosphere as quickly as possible to minimize drag losses and heating. As indicated on table 1 the drag losses and the closure velocity requirement are significantly less than the NASA Access to Space air-breathing SSTO design concept. The rocket cycle continues until the aerospace craft achieves orbit.

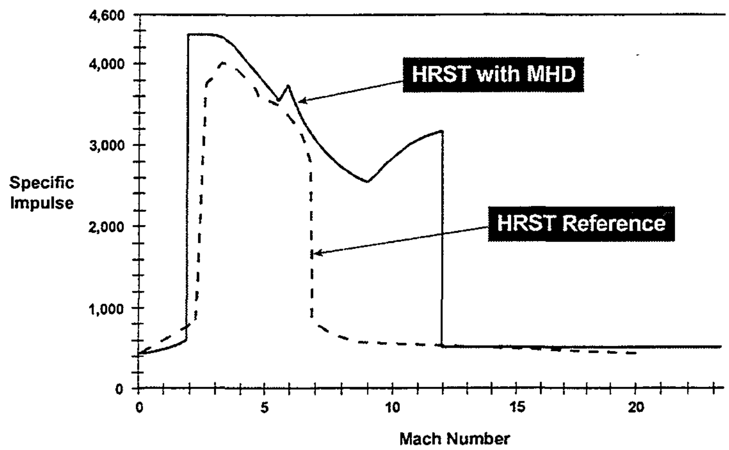

Figure 8. Engine Performance Comparison

Figure 8 presents a comparison of the MHD energy by pass engine performance to that of the Aerojet strutjet engine in the reference design concept. Clearly the MHD engine outperforms the strutjet engine by a significant amount which accounts for the reduction in GTOW.

CONCLUSIONS

The idea of creating a "virtual" aerospace craft with respect to the flowfield around vehicle and the engine performance, represents a basic change in aircraft design philosophy. Traditionally, the environment through which the aircraft is to fly is defined, and then the aircraft is designed to operated in that environment. The higher the speed the more difficult it is to define the flight environment and simulate it in test facilities to verify the design. As speed increases more performance is needed by all elements comprising the aircraft design concept. Cost and technical risk increase. The "virtual" aircraft approach is different in that the environment is changed to accommodate the aircraft. By changing the environment less stress is place on the performance of the aircraft. It has been proposed to change the operating environment by using a combination of magnetic fields, plasmas, and RF energy sources. To change the environment around the aircraft it is necessary to make the flow conducting. This is a key requirement of the system. How it is to be done and level of conductivity is needed is a question yet to be defined. The engine of AJAX uses an MHD energy by pass system to control the velocity in the engine combustor. An 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 reduction is 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 could represent a major breakthrough in hypersonic flight

This design data base used to formulate a "virtual" aircraft is based on the best information available at this time. The results of the study indicate that if the environmental modifications systems can be built to operate in the manner assumed in this study, both cost and technical risk will be reduced. The results indicated that an MHD energy by-pass system could increase the performance of the engine sufficiently to reduce the GTOW by approximately 25%. compared to the reference design concept. Hydrogen requirements were also reduced by approximately 40%, which reduced the size of the design concept. The ideal velocity requirements were reduced by approximately 3% compared to the reference design concept. Whereas, the ideal velocity requirements compared to the NASA Access to Space air-breathing SSTO were reduced by approximately 30% . A transition to the rocket cycle at Mach 12 rather than Mach 16-17 in the case of the NASA Access to Space air-breathing SSTO design concept paid off.

Drag reduction did not show a performance advantage. Based on the representation used for the cold plasma drag reduction system in this study, the cold plasma trade case was preferred to the air spike trade case. However, little is known about the phenomenology of cold plasmas at this time. Both NASA and the Air Force are currently investigating cold plasmas. A close look at the composition of the ideal velocity requirements for both designs indicate that drag losses were not a significant factor compared to the NASA Access to Space air-breathing SSTO design concept. The drag loss reduction based on the Access to Space design concept drag losses was between 30-50%., which is a significant reduction in drag losses. However, the benefits of drag reduction extend beyond drag losses in the SSTO ideal velocity equation. Drag reduction when accompanied by a reduction in heat transfer rate could substantially reduce thermal protection weight. If heat transfer rates are substantially reduced an all metallic SSTO design concept could be a possibility. The advantages of an all metallic aircraft have been shown by the Boeing RASV military space plane design concept in the 1980s. The reduction in TPS weight combined with the characteristics of an all metallic airplane could be the low cost choice, instead a performance optimum design

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