AN ELECTRO-MAGNETIC-CHEMICAL HYPERSONIC PROPULSION SYSTEM

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ABSTRACT

The initial attempt to put this new propulsion system into context was by Bruno, Czysz and Murthy[1]. This utilized the work of a Parks College Senior Undergraduate Team of Yago Sanchez, Maria Dolores Esteve, Alfonso Gonzalez, Ignacio Guerrero, Antonio Vincent, & Jose Luis Vadillo from the 1966/1997 Capstone Design Course, AE P 450-1. Their two semester effort investigated the AJAX system concept, verified stated variables and magnitudes and quantified its characteristics[2].

To recap the history, beginning in 1990 there were articles about a new long range aircraft that cruised at hypersonic speeds, named AJAX. Its reported propulsion system employed a coupled Magneto-Plasma-Chemical Engine employing a coupled (MHD) generator/accelerator. Using available literature and discussions with Russian and Ukrainian citizens a first principle analysis of the system was performed to determine if the concept provided a real advantage. Working with citizens of Italy and the United States, that had visited Russia, the areas of incomplete information were sufficiently filled-in to proceed.

This paper focuses on the AJAX system as a total energy management system that utilizes available energy, normally not recovered, to drive an electric hydrocarbon fuel reforming process and an energy by-pass propulsion system that reduces the cycle entropy rise and can be used to power a beam energy device of unspecified design. The control of very large energy flows bypassed from the propulsion system to the directed energy system, over short time periods is a significant challenge. The apparent focus of this system is as a long range hypersonic cruise vehicle not a space launcher.

The authors wish to acknowledge the assistance of Professor Mark A. Prelas, Department of Nuclear Engineering, University of Missouri – Columbia. He has toured a number of the Russian nuclear facilities and provided first hand knowledge of the ionization devices that are a key part of the AJAX system. The authors Also wish to acknowledge the help in calculating ionization effects by Dr. P. Battistoni and Dr. L. Petrizzi of the Italian Nuclear Agency, ENEA, and the assistance of Ing. E. Giacomazzi.

INTRODUCTION

The configuration and operating features come from two sources.[3,4] The information with respect to the configuration and performance of the AJAX concept comes from a Russian document and the article "Space Wings of Russia and the Ukraine" in the September 1990 Magazine *Echoes of the Planet/Aerospace*[3]. The article states that the project originates in the State Hypersonic Systems Scientific Research Enterprise (GNIPGS) in Saint Petersburg which is headed by Vladimir Freistadt. The article goes on to state that realization of the AJAX project will come from cooperation of industrial enterprises, Technical Institutes, the VPK (Military Industrial Commission) and RAN (Russian Academy of Sciences). It is clear in the literature that AJAX is primarily a global range hypersonic cruise vehicle. All the discussions with individuals about AJAX stress the global range capability at hypersonic speeds. The general arrangement of AJAX is given in Figure 1, from reference 3. The followings elements were identified to constitute the AJAX system.

1. Bypass a portion of the free stream kinetic energy around the combustion chamber to reduce entropy rise of aerodynamic diffusion and the combustion process via a coupled MHD generator-accelerator system[5,6,7]. (Russian information supported by analysis).

2. Reforming of hydrocarbon fuel via a thermal decomposition process followed by an electrical process into a high hydrogen fraction fuel with about 20,200 But/lbm heat of combustion. It is assumed that the products are gaseous hydrogen and carbon monoxide. The quantity of water used or the disposal of the excess carbon for this process is unclear[8,9] (Experimental data and analyses from various sources including Russian)

3. Ionization of the flow entering the engine to permit the MHD generator-accelerator to function with the magnetic field strengths possible with superconducting magnets and the flow velocities present within the engine module. (Russian information supported by analysis).

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4. Powering of the fuel reforming process by an MHD generator in the nose of the vehicle[10] that with a particle beam generator in the nose, produces a plasma cloud at the vehicle nose results in a reduction of the vehicle total drag[11,12,13,14,15] (Russian information with experimental data obtained under Italian research effort with Russia).

5. Increase in the combustion volume and efficiency within the engine by means related to injection a plasma or hydrogen ahead of the fuel injector struts[16]. (Russian information with experimental data obtained under Italian research effort with Russia).

6. Diversion of the bypassed energy to a directed energy device on an intermittent basis.

AJAX CONFIGURATION

Figure 1, from reference 3, shows an isometric representation of the entire vehicle. This sketch differs from sketches of AJAX that show AJAX as a spatular nose delta configuration. Figure 1 and other figures from reference 3 show a totally integrated propulsion system, in which the bottom of the vehicle is an integral part of the propulsion system, i.e. inlet, engine module, nozzle. Figure 1 shows non-integral tanks. From their shape and location, the wing fuel tanks are also likely to store a non-cryogenic fluid. The sketch in Figure 1 shows four engines installed with 3–D internal compression local inlets. The text states that there are two turbomachinery engines and two MagnetoPlasmaChemical/Scramjet Engines.

Figures 1 and 2 from reference 1 give some indication of the size and layout of the configuration. Figures 1 from reference 1 is a three view sketch that gives the general size of a AJAX multi-purpose hypersonic plane that were accompanied with the following data.

The reported characteristics are:

Planform area	296 m^2
Wetted area	672 m^2
Take Off speed	130 m/sec
Landing speed	68 m/sec
Thermal management skin	17.1 kg/m^2
Take Off Gross Weight	240.0 tons
Propellant weight	149.3 tons
Operational Weight Empty (OWE)	90.7 tons
Payload	2.0 tons
Cooling fluid weight	11.0 tons
Trapped fluids and consumables	5.7 tons
Dry Weight (OEW)	72.0 tons
Airframe structure	36.0 tons
Thermal management structure	13.0 tons
MHD engines (2)	2.4 tons
Turbomachinery (2)	4.2 tons
Rocket accelerators (2)	7.1 tons
Airborne equipment	8.0 tons
Landing gear	1.3 tons

The structure plus thermal protection material weight is 49 tons. That corresponds to 72.9 kg/m^2 which is quite heavy compared to an integral tank arrangement[17,18]. But as shown in Figure 1, the propellant tanks are non-integral.

Flight time for 13,900 km (7,505 nautical miles) at Mach 8 at 33 km altitude is given as 130 minutes. Cruise speed is (for 60° N latitude) then 2,400 m/sec. From historical aircraft performance correlations, the

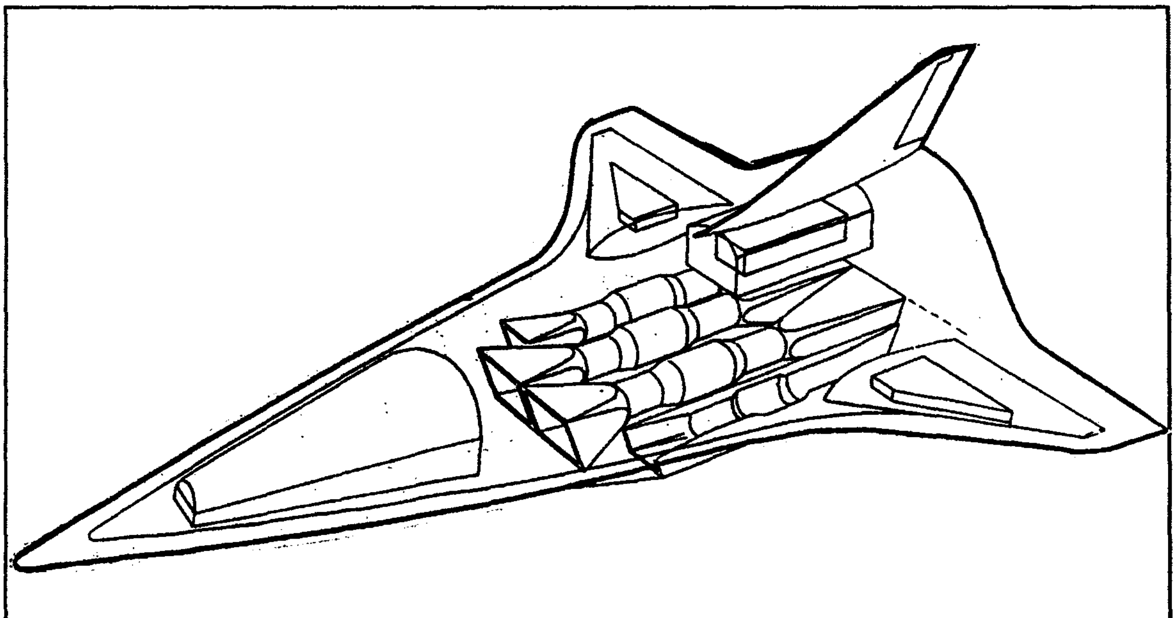


Figure 1 AJAX Multi-Purpose Hypersonic Plane, From Reference 3

climb & descent time & distance is 46 min. and 2,310 km. respectively. With ground operation that yields a cruise distance of 11,590. and a cruise time of 80 minutes. The overall weight ratio is 2.65. For climb, ground operation and reserves the weight ratio is 1.25. That leaves a weight ratio of 2.11 for cruise. With a cruise fuel fraction of 52.6% the range factor required is 15,400 km (8,315 nautical miles). The sketch of AJAX indicates a Küchemann's tau that yields an aerodynamic L/D of 4.4. The integrated propulsion system and centrifugal relief results in a final L/D of 5.1. The reported heat of combustion for Russian reformed hydrocarbon is 47.31 kJ/kg (20,340 Btu/lbm) or 4,826 km. Builder's analysis give a representative propulsion energy conversion efficiency of 49%. This results in a V•ISP is 2365 km, and the ISP is 985 sec. The required L/D ratio to achieve the stated performance is 6.5. Thus the drag has to be reduced by almost 50% in order to achieve the stated range. This suggests that by the ionization/plasma produced by the nose particle beam device and the nose MHD generator (which drives the hydrocarbon reformation process) the cruise drag has in fact been reduced. Remember:

$$\text{Range Factor} = V \cdot ISP \cdot L/D = \theta_p \cdot Q_c \cdot L/D = (\text{km})$$

$$\text{Küchemann's tau} = V_{tot} \Big/ \left(S_{plan}\right)^{1.5}$$

The authors' representation of AJAX with cited references and their applicability are shown in Figure 2.

The MagnetoPlasmaChemical Engine energy flow diagram the accompanied Figure 2 in reference 3 providing a list of the system components and energy flows. This energy diagram for the AJAX system provided significant insight into the energy flows and the features described in the Introduction. The system names were translations from the Cyrillic text by the author of the referenced article:

1. Active Thermal Protection System
2. Control of aerodynamic characteristics in gas-plasma medium.
3. System of Directed Energy Transfer.
4. Thermal Energy. (Aerodynamic Heating).
5. Propellant.
6. Air Flow Kinetic Energy.[19,20,21]
7. Chemical Energy of Carried Fuel (70%).
8. Air Inlet.
9. MHD Generator.[22]
10. Combustion Chamber.
11. MHD Accelerator.
12. MagnetoPlasmaChemical Engine[23,24]
13. Energy Produced by Heat Regeneration (30%)[25].
14. Thrust.
15. Electric Energy.
16. Losses during Movement in a Continuous Medium (drag).

Although not specifically mentioned, the hydrocarbon reforming process is probably represented a item 12. A source of a similar figure is the paper presented at the 7th Aerospace Planes meeting in Norfolk by Philip Harsha[26]. The diagram and systems list clearly show the thermal integration inherent in the AJAX system and the elements of the thermal reforming mentioned by Sosounov in the ISABE meting[25]. For a cruise system the total heat load can be an order of magnitude greater than for the exit trajectory of a space launcher, so some

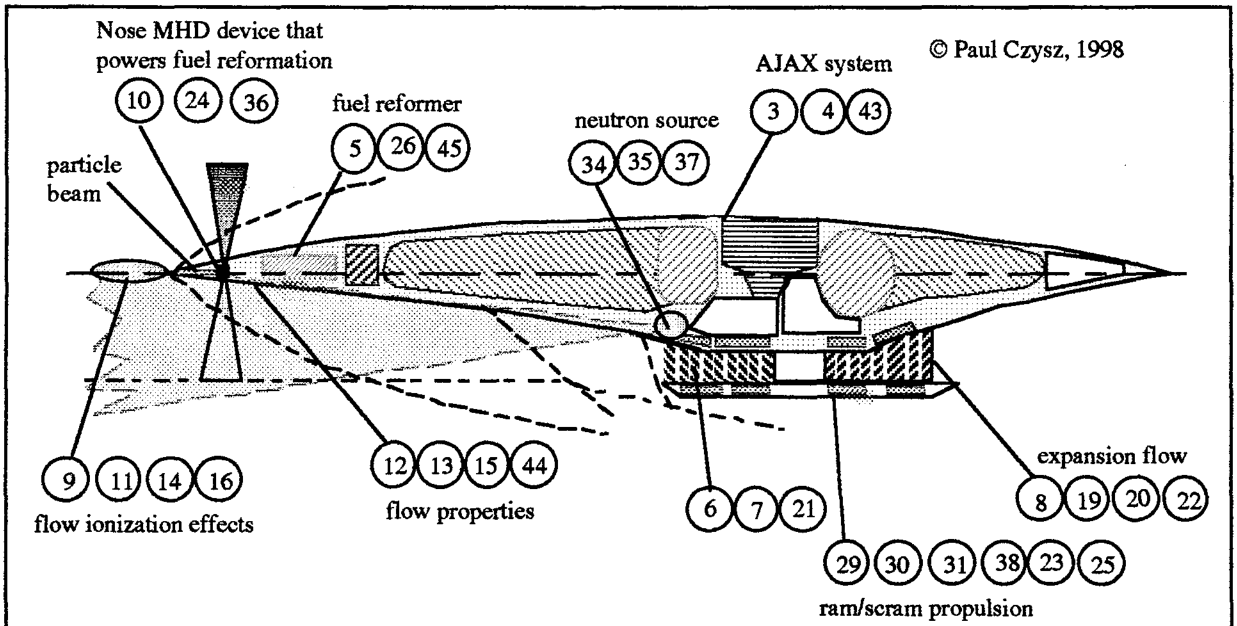


Figure 2 Cited References as Applied to AJAX System Concept

form of continuous energy management is required to prevent the airframe thermal capacitor from absorbing excess energy.[27] The total heat capacity of the reformed hydrocarbon fuels can equal or exceed that of liquid hydrogen. In the case of AJAX the thermal energy is not discarded but used to create thrust (30%). The fraction of the thrust energy provided by the recovered aerodynamic heating is in agreement with prior analyses.[28,29] For the AJAX fuel, the kinetic energy of the air stream at 1,750 m/sec equals the available fuel Brayton cycle energy addition. As indicated in the Introduction, the AJAX system is an energy management system that minimizes the entropy rise of the total aircraft system in hypersonic flight and makes the converted kinetic energy available for application. The authors used a first principles approach. Using the first and second laws of thermodynamics.[30] [31] Builder's analysis was used for the propulsion system.

MHD ENGINE ANALYSIS

Energy Bypass If sufficient fraction of the kinetic energy is removed from the incoming flow, the apparent inlet velocity could be maintained at V_{crit} and the engine would not transition to supersonic-through-flow. Critical speed is when the kinetic enthalpy ratio is equal to the kinetic enthalpy is equal to the optimum compression enthalpy ratio (Ψ). Then subsonic through-flow could persist to higher flight speeds. That is what the MHD bypass system accomplishes. Then the required bypassed energy is:

$$\Delta H = \frac{V_0^2}{2} - \frac{V_{crit}^2}{2} \left(\frac{MJ}{kg}\right)$$

$$\Psi = \sqrt{\frac{\eta \cdot (f/A) \cdot Q_c}{1-\eta}}$$

$$V_{crit} = \sqrt{g \cdot H_o \cdot (\Psi - 1)} = 1{,}755 \text{ m/sec}$$

The AEDC VKF Tunnel J test in the 1965-1971 time period showed about 3.14 MJ/kg added to the flow for the low power operation which represented about 46% of the incoming flow kinetic energy. That corresponds to the Russian cruise point of 2,400 m/sec. The maximum energy bypass solution the student team could find was 3,800 m/sec. This is in effect the energy equivalent of a constant corrected speed compressor maintained by energy bypass via a heat exchanger, such as in N. Tanatsugu's ATREX engine.[32]

Apparent Flight Speed The MHD engine inlet conditions are such that the engine appears to be flying at a slower speed than actual flight speed. The student team was objective was an SSTO launcher. They terminated energy bypass operation at 3,600 m/sec with scramjet operation continuing to Mach 16[33].. Apparent Flight Speed for the MHD ramjet remains at the critical speed value, that is 1775 m/sec (5,758 ft/sec) from 1,755 m/s to 3,600 m/sec (11,800 ft/sec). That is a limit was placed on the bypassed energy ratio at 1,755 m/sec which fixes the magnitude of the bypassed energy. Even then the apparent engine speed is always less than flight but greater than the critical speed. Above 3,600 m/sec the engine through-flow is supersonic. So supersonic flow has been delayed by 1,845 m/sec (6,050 ft/sec) by the application of the MHD energy by-pass system. The bypass energy fraction required to maintain subsonic flow and the V_{crit} operating point is:

V_0	ΔH	$\Delta H / H_{stag}$	H_{stag}
1,755	0.00	0.0%	1.54
2,000	0.46	23.0%	2.00
2,200	0.88	36.4%	2.42
2,400	**1.34**	**46.5%**	**2.88**
2,600	1.84	54.4%	3.38
2,800	2.38	60.7%	3.92
3,000	2.96	65.8%	4.50
3,200	3.58	69.9%	5.12
3,400	4.24	73.4%	5.78
3,600	**4.94**	**76.2%**	**6.48**
3,800	5.68	80.7%	7.22
m/sec	MJ/kg		MJ/kg

Figure 3 Energy Bypass Required

The method of solution can be found in reference 2. For

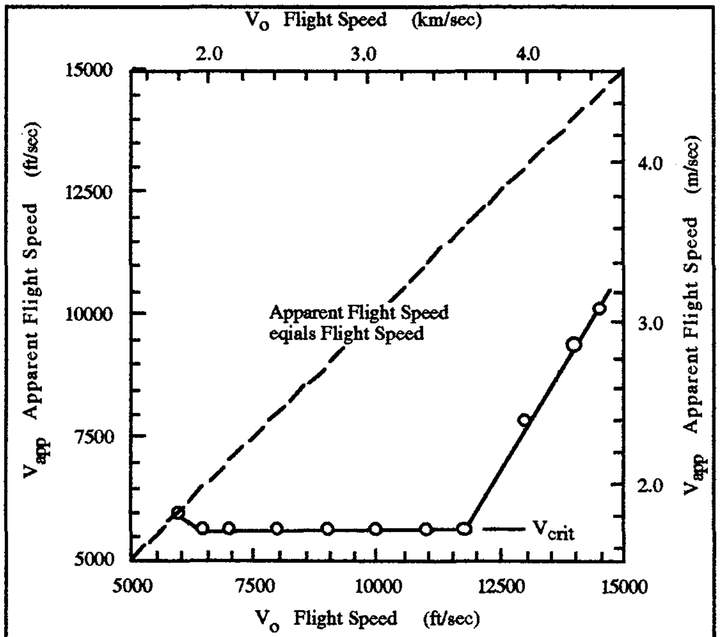


Figure 4. The Apparent Flight Speed for the MHD ramjet is That for Subsonic Through-Flow

the constant velocity case, the simple, 1-D, continuity, momentum and energy equations were solved to find the electrode current density, power output, and required magnetic field strength. The equations are:

$$\frac{d\rho}{\rho}+\frac{dA}{A}=0$$

$$\frac{d\rho}{dx}=-J_xB$$

$$\rho V c_p \cdot \frac{dh}{dx}=-JE$$

The power extracted (P_{ext}) and electrical conductivity (σ) are:

$$P_{ext.}=P_o\cdot\left(\frac{V_1}{V_0}\right)^2\cdot B^2\cdot\sigma^2\cdot[k\cdot(1-k)]$$

$$P_{ext}=\dot{m}\cdot\left[\frac{V_0^2}{2}-\frac{V_{crit}^2}{2}\right]\cdot\eta_{gen}\qquad(\mathrm{MW})$$

$$\sigma=\frac{3.34\times10^{-12}\cdot\alpha}{Q\cdot\sqrt{T_{stag}}}$$

Magnetic Field Strength It was assumed magnetic field strength would be similar to that available at DOE, Oak Ridge Tennessee and at Air Liquidé at Grenoble, France, from 4 to 21 Tesla. With a cryogenic fuel or oxidizer on board a superconducting magnet is feasible. The weight of the superconducting magnets will be discussed with the engine module.

Electrode Design The electrodes for the MHD device are assumed to be derived from the industrial ground based MHD generators developed by Valentin Petrovich Glushko's GDL-OKB beginning some 20 years ago. A number of Glushko's MHD generators are reported to be operational in the former Soviet Union. Little is known definitively about these devices, but the electrode material is reported to be a ceramic conductive composite (probably similar to Perovskites). One of the authors has seen in Japan and Russia functional gradient materials in which the composition varies continuously a metal surface to a ceramic surface on the opposite face. This may be the basis for the reported ceramic electrodes. The Russian literature lists the AJAX engine as generating about 100 MW of power. The student team determined that using the limitations reported for the AEDC Tunnel J experiments (1450 Btu/lbm energy bypass) each of the two engine modules were generating about 45 MW,. So the numbers reported and those calculated here are not inconsistent.

MHD ENGINE IONIZATION SOURCE

In order to extract energy from the incoming airstream via MHD the airstream must be sufficiently ionized (electron/ion density $\rho_e \approx 10^7$ to 10^9 e^-/cm^3). Compared with a ionization based on seeding air with low ionization potential metals such as K or Li, a neutron (n) source has some advantages; among them are: control by neutron beam spread angle and intensity (flux) and no need to worry about seed distribution and mixing times. In this respect ionization by neutrons is nearly instantaneous.

Neutron sources exist in Russia that can be triggered in such a way as to reach n fluxes comparable with those in a fission reactor[34]. Neutron energy E_n may be realistically assumed to be about 2 MeV average, with a rather broad energy spectrum. Once neutrons are focused by a mirror (beryllium) they ionize air following four main mechanisms:

1. elastic collisions with O_2 and N_2, where electrons (e^-) are stripped off due to the E_n >> ionization potential and the nuclei recoil with energy ≈O(KeV);
2. inelastic collisions;
3. inelastic transmutation of O_2, N_2 nuclei hit by the neutron into a different nucleus (a e^+ (positron) e^-, deuteron or other neutron), if E_n is ≈ O(1 MeV); and,
4. inelastic collisions with a nucleus followed by absorption of the neutron by the nucleus and release of a γ photon with energy ≈ O(1 MeV) This mechanism takes place if E_n is relatively low (slow neutrons).

The most likely mechanisms are the first and the fourth. Furthermore, the γ rays released ionize atoms and molecules by the photoelectric effect, by Compton effect and by forming $e^- - e^+$ pairs.[35] The effect of a neutron source of intensity I_n (neutrons/unit time) due to mechanisms 1 and 4 only may be estimated as follows:

The neutron source will be placed on the lower surface of the forebody, its mirror pointing in a generally forward direction (a microwave source has been depicted with its reflector flat against the forebody lower surface[36].} For a roughly 2-D forebody the volume V where interaction is effective is that where the mean free path λ for molecule-neutron is smaller than forebody size: at p = 1 atm λ = O(1) m. Thus ahead of the bow shock (where inflight pressure is << 1 atm) hardly any interaction takes place; interaction will be confined between forebody and bow shock only. Ionization mechanisms 1 and 4 can be quantified from the available literature.[37] The neutron energy dissipated, W, is fortunately nearly independent of the type of particle hit, and is ≈35 eV/ion pair for air.

Assuming all E_n is dissipated, the ion pairs created must be $\approx E_n / W$. The density of ion pairs, ρ_e can be estimated from I_n assuming the volume V where the source is effective is of order ℓA, where A is the intersection between cone of n radiated from the neutron source and the bow shock, and ℓ is an average distance between the n source and the bow shock. The solid angle of the cone is then $A/(4 \cdot \pi \cdot R^2))$. If ℓU_{air} is the residence time of air inside the volume, the neutron intensity to produce a certain ion pairs density is:

$$I_n \approx \rho_e \cdot (W/E_n) \cdot (\lambda/\ell)$$

where R is of the same order of ℓ.

For $\lambda \approx \ell \approx R = 10$ m, $U_{air} = 1000$ m/s (speed behind nose shock wave), $E_n = 2$MeV, W = 35 eV and to produce a substantial ionization level $\rho_e = 1 \times 10^8$ e^-/cm^3, the I_n must be of order 2×10^{13} n/s. 1000 m/s is the minimum speed at which the MHD devices are though to operate. U_{air} is at least 90% of the free stream speed. The MHD propulsion operates where $1600 \le U_{air} \le 4000$ m/s.

This intensity is not very high compared to that in fission reactors, where I_n may be upwards of 10^{14} n/s. A neutron source that pulsates between sub- and critical (such as that available in Russian laboratories like Ozimosk 16) will have intensities close to this latter value, therefore producing enough ionized air to control its flow by a large enough magnetic field.

Solution Space Discussions with Russian engineers and scientists indicated a low ionization level, between 10^7 to 10^9 electrons/cm^3, as representative of the operational level for the MHD propulsion system. The Tunnel J experiments at AEDC were carried out at magnetic field strengths of 4 to 5 Tesla using a potassium carbonate seed. So one question was, what is the magnetic field strength that is consistent with the stated electron density for the flow speeds determined through the engine. The pertinent equations are:

For the generator output:

$$J \cdot E = \sigma V_I^2 B^2 (1-K) K$$

where K is assumed to be 1/2

The accelerator input is then:

$$V \frac{dV}{dx} = \frac{m}{\rho A} \cdot a \frac{dM}{dx} = \frac{JB}{\rho} \cdot \frac{M\gamma}{M^2\gamma - 1}$$

The student team solved these relationships for the required magnetic field strengths given the range of electron densities predicted for the flow speed into the engine based on the Builder analysis. The complete set of governing equations were input into the MathCad software to seek the solution boundaries for given levels of the magnetic field strength. The results are presented in Figure 5.

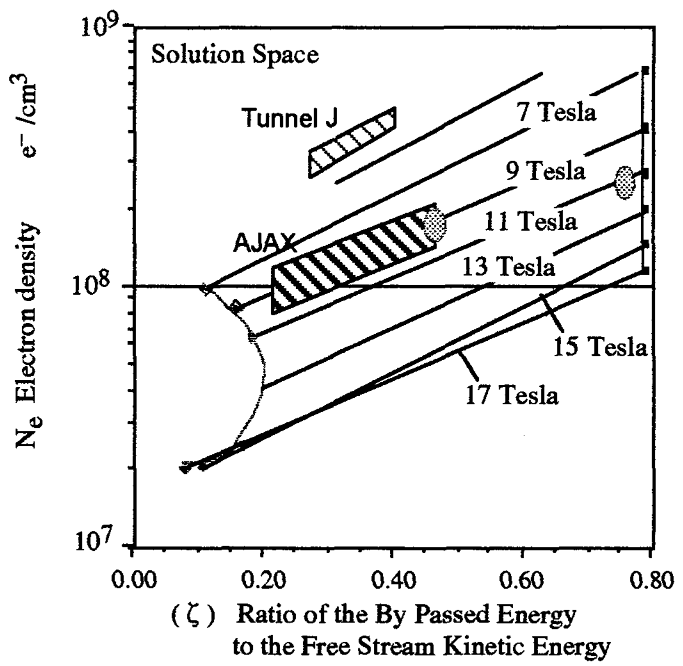


Figure 5 Solution Space as Determined by the Student De-

The left limit is the lowest engine flight speed and corresponds to the critical speed, about 1,800 m/sec (5,500 ft/sec). The right limit is the maximum speed for which a solution could be found. The right limit represents about 3,800 m/sec (12,470 ft/sec) flight speed and an energy bypass approaching 80% and is the upper limit of the solution space. The flight speed of 2,400 m/sec (7,900 ft/sec) corresponds to a 46% energy bypass limit corresponding to the flow energy addition of the AEDC low power MHD accelerator tests. Whether by coincidence or physics, that corresponds also to the maximum speed reported for AJAX. For greater speeds the bypassed energy represents a higher level than that of the low power AEDC Tunnel J accelerator tests but less than that demonstrated with the high power tests.

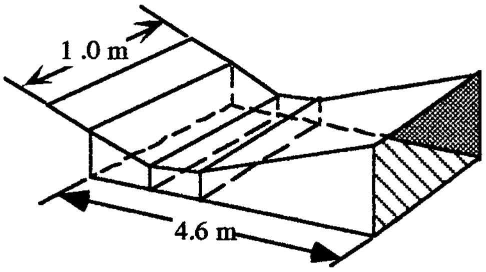
For the conditions represented in Figure 5, the flow at the entrance to the combustor remains the same, as if the aircraft were flying at 1755 m/sec. By bypassing the energy, it is as if the engine were a conventional turbojet with a precooler, and the engine operated as equipped with constant corrected speed compressor. If the electron density can be maintained at levels of 10^8

or greater, the magnetic field strength can be limited to 10 Tesla for the lower energy bypass solution. Or about twice that for the AEDC experiments some 30 years ago conducted without the benefit of superconducting magnets. Cryogenic superconducting magnets have been built with magnetic field strength of over 20 Tesla. Figure 5 does not indicate a technology limiting magnetic field strength as a requirement.

MHD ENGINE CONFIGURATION

The current concept for a scramjet engine can be found in the StrutJet®. The engine module cowl is a slender rectangle forming a semi-two-dimensional flow engine geometry. The module width is generally about 1.03 m (40 inches). The combustor length is about 0.4 meters long. So depending on the size of the vehicle, that sets the combustor height, the engine module is a wide flat rectangle.

This design is very inappropriate for an MHD design, as the magnet-electrode configuration favors a near square with rounded corners. So to arrive at a suitable MHD ramjet design, the traditional integrated two-dimensional



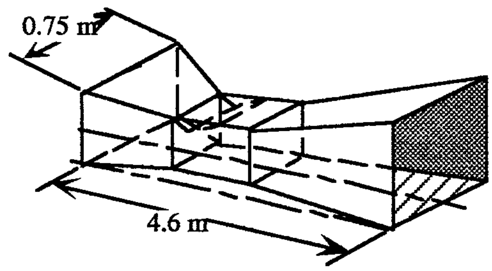
$A_{cowl} = 0.6\ m^2$
Module weight ≈ 1400 kg
S_w/A_c ≈16, frictional thrust loss ≈12%
Relative thrust = 1.0, T/W ≈ 29
Relative weight =1.0

Figure 6 Traditional Scramjet Module

flow ramjet was transformed into a three dimensional flow ramjet with the same cowl inlet area. This configuration was then transformed into an MHD ramjet design with the same cowl area but lesser contraction area (see reference 1).

Traditional Scramjet Module (Figure 6) for fully integrated propulsion systems is dictated by the unsupported span and the combustor length. For current engines this is 40 inches width (1.03m) and a combustor length of 15.7 inches (0.4 m).[38,39] This sets the minimum surface area of the combustor. The smaller the vehicle, the smaller engine module height, so the greater wetted area per unit cowl area. The greater the wetted area per unit cowl area, the greater the internal friction losses. There is a minimum sized ramjet module size, therefore vehicle size, for which the internal losses are too large for thrust to exceed drag sufficiently for good acceleration (about 21 m).[40] These modules are for an operational class vehicle (dry weight ≈ 75 tons).

In reference 17 the ramjet engine had no internal rocket ejectors as the StrutJets or Billig engines have. That means the older 1970 data gives an engine thrust to weight ratio about 73% less than possible with an ejector engine. The vertical struts in the StrutJet add significantly to the internal drag, therefore thrust loss. If the engine in Figure 6 had 5 vertical struts the engine T/W would be 22 not 29. The approach was to use lifting vortices to accomplish the mixing. So the estimates for this paper used an engine with rocket/hot fuel injectors on the wall as by Swithenbank of the University of Sheffield or Billig of Pyrodyne.

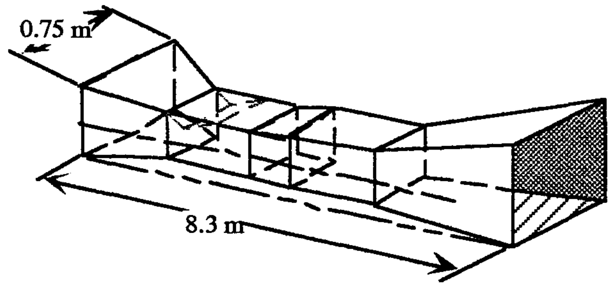


$A_{cowl} = 0.6\ m^2$
S_w/A_c ≈7.0, frictional thrust loss ≈7%
Relative thrust = 1.05, T/W ≈ 67
Relative weight =0.45

Figure 7 AJAX Scramjet Module

AJAX Scramjet Module. (Figure 7) This module has the same cowl area of 0.6 m^2 and contraction ratio as the traditional ramjet engine module. The internal contraction geometry is three dimensional. The total contraction ratio 29, the same as for the traditional module. The unsupported span is less so wetted area to cowl area ratio is 56% less than the traditional module. The module weight is 55% less and thrust to weight ratio is 130% greater. These differences are functions of vehicle size. The differences increase as size is decreased.

AJAX MHD Ramjet Module. (Figure 8) This module has the same cowl area of 0.6 m^2 and contraction less than the conventional ramjet, about 20 instead of 29. This results from the fact that the MHD through-flow speed is essentially constant with increasing flight speed. The internal contraction geometry is three dimensional. Two slightly diverging sections have been added, each with a length/height ratio of 5, to accommodate the MHD generator and accelerator cryo



$A_{cowl} = 0.6\ m^2$
$S_w/A_c \approx 16$, frictional thrust loss ≈20%
Relative thrust = 0.92, T/W ≈ 42, (no magnets)
Relative weight =0.63, (no magnets)
Relative thrust = 0.92, T/W ≈ 21, (w magnets)
Relative weight =1.25, (w magnets)

Figure 8 AJAX MHD Ramjet module

magnets. A module for an operational vehicle without cryogenic magnets has a module T/W 42, or 44% greater and weight is 63% of the traditional module in spite of the added duct length. The ducts are square within 10%. That is $0.9 \le h/w \le 1.1$. In reality the ducts do not have square corners, but are more like "superellipses".

MAGNET WEIGHT

Lightweight superconducting magnets windings can be designed following the description by Scortecci et.al.[41] With liquid Helium as the cryogenic coolant, the Low Temperature Super Conduction (LTSC) wire material may be a composite copper-embedded niobium-Titanium. For higher induced B field intensity composite copper-Niobium-tin is better, but mechanically weaker. High Temperature Super Conduction (HTSC) materials such as BSCCO 2212 need liquid hydrogen,

but are still in the testing stage for commercial quantities and applications. Nevertheless, current industrial opinion is that the will be very soon commercially available and therefore will be the HTSC wire material of choice.

The maximum current density (J) depends nonlinearly on the magnetic intensity (B).[42,43] For example, Nb_3Sn the maximum J_c is 1500 A/mm^2 at B=10 T decreasing to 650 A/mm^2 at B=14 Tesla. Inperfect insulation and non-cylindrical coil geometry may lower these values by a factor of eta (η) that will be included in these calculations. Eta is always less than one. Choosing a wire diameter dw with a cross sectional area A_w and a B intensity yields the maximum J_c for assigned coil length L_{coil} , and equivalent coil diameter D_{coil} , the number of wire layers, N_{layers}, total wire length, L_w, and wire weight, W_{wire} can be calculated.

$$N_{layers} = 4B/(\mu_o \pi d_w J_c \eta)$$
$$L_w/(L_{coil} \cdot \rho_{wire}) = B/(\mu_o A_w J_c \eta)$$
$$W_{wire} = L_{wire} \cdot \rho_{wire}$$

Where μ_o is the permeability of free space ($4\pi\ 10^{-7}$ in SI units) and ρ_{wire} is the weight of wire per unit length, of the order 4 to 5 grams/m. For example, choosing a commercially available 0.78 mm diameter wire, with a B of 10T, lowers the value of J_c to 80% of its 1.0 B value. Assuming a conservative eta = 0.333, and the number of layers is 36, then the per unit coil diameter and length is 41.5 km for a total weight of 205 kg (452 lbm). To this estimate is added the weight of the insulation between turns (with nitrocellulose paint) and between layers (G-10 type fiberglass and epoxy). This contributes modestly to the weight. The coil is surrounded by a thermally protected jacket (where the cryogenic coolant circulates). For a stainless steel jacket 1 mm thick, surrounded by foal insulation, the additional weight per unit length is on the order of 30kg/m. Circulating LH2 adds another 7 to 8 kg/m. An overall estimate is then about 240 kg/m for inlet ducts such as in Figure 8. Although this does not directly include the cryogenic pumps to circulate the coolant, a significant weight margin was added. Using superconduction MHD technology for energy management is indeed engineeringwise feasible.

For the engine module in Figure 8, the forward generator magnet weighs 567kg (1,250 lbm) and the rear accelerator magnet weighs 594 kg (1,316 lbm) for a total magnet weight of 1,310 kg (1,894 lbm). By coincidence that is the module weight without the magnets. Does the performance of this engine warrant the weight and complexity? It would appear that it does. For a thrust to weight of the module that is only 25% greater than the traditional, all of the benefits of the MHD cycle can be realized.

FUEL REFORMING ENERGY SOURCE NOSE IONIZATION SOURCE

The remaining issue is the energy source for the final electrical reforming of the hydrocarbon fuel, and the source of the nose plasma/ionization that is attributed the drag reduction. In what appears to be a completely unrelated report, reference 10 clearly identifies the MHD device that drives the fuel reforming and show that its effects extend a significant distance from the nose to create a broad ionized flow field. The governing equations describing the operation of the performance of this device are given in reference 10, and are not repeated here. Figure 9 and 10 are taken from reference 10.

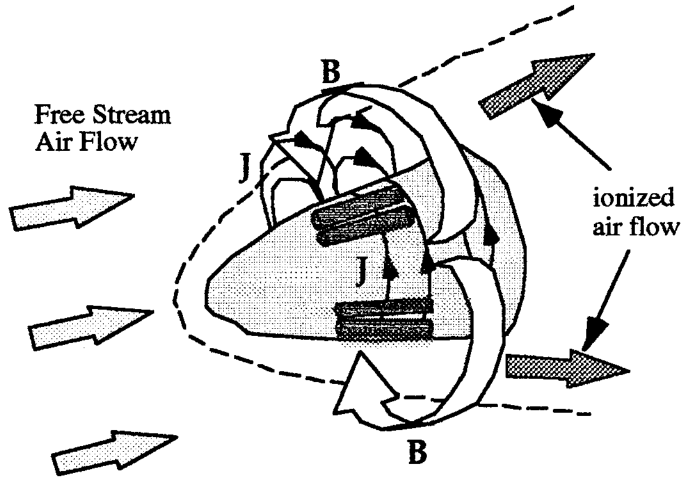


Figure 9 The Schematic of the Multipole Magnetic System Installed on a Hypersonic Vehicle From Figure 11, IAF-97-V.5.10

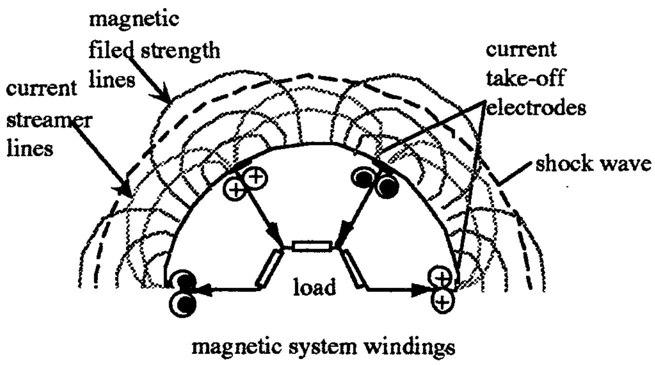


Figure 10 cross-sectional View of magnet System From Figure 12, IAF-97-V.5.10

References 12 through 20 from reference 10 discuss various aspects of MHD flow control. Quoting from reference 10: "The MHD flow control system (MHDFSC) under consideration consists of two main components: a magnet system that produces a desirable level of magnetic induction in the interaction region; and MHD generator/accelerator represented by an electrode system installed on the vehicle upstream surface. A proper load control subsystem is assumed available and its design and operation are outside of the scope of this paper, but within current technology grasp."

From references 23 and 24 can be found: " In the concept considered, the magnetic system is assumed to be simulated by a one or two winding coils zigzag shaped. This winding system provides a multipole magnetic induction distribution. The depth of the significant magnetic field penetration into the flow is normal to the surface direction and is defined by the period size of the winding in the azimuthal direction. Considering the hypersonic viscous shock layer as the most probable field for MHD influence, one can hypothesize that the most preferable winding configuration is that in which the characteristic thickness of HVSL is used as the estimation for the half period size. It is assumed implicitly that the flow direction size of the winding considered is typically much greater than the azimuth period." Continuing from reference 10: "The main effect of the MHD interaction is clearly seen: the bow shock stand-off has increased several times." It is stated that the power supply can be used a pulse source of powerful current.

Thus both the apparent reduction in the vehicle total drag and the powering of on-board electrical devices can be attributed to the nose coupled MHD generator-accelerator.

FUEL REFORMING

In reference 26 the endothermic reforming of a hydrocarbon fuel with the addition of water and catalyst coated passages in the skin adjacent to hot aerodynamic flows. There are three different thermochemical structural reactors shown involving different catalysts and flow passage geometries that span heat transfer rates from 0.1 MW/cm^2 to 10 MW/cm^2. To achieve a high methane conversion ratio, the maximum wall temperature must be in the 700 to 900 °C range (1,290 to 1650 °F) This puts the last endothermic conversion panels in the vicinity of the last inlet ramp and the engine module. How ever conventional endothermic reforming has a very poor heating value since the water to carbon ratio considered was two. That results in a partially oxidized fuel with a poor hydrogen to carbon ratio, that is two. In order to achieve the heat of combustion reported for the reformed fuel the carbon hydrogen ratio needs to be much higher, considering the quantity of CO that accompanies the reformed hydrocarbon.

Professor Bruno has examined the possibility of using an electrical process to complete the reforming process, powered by the nose MHD device. The simulated reforming processes of methane (CH_4) and RP-1 (rocket kerosene) were performed using the NASA program CEC-71 in reference 8.

Conventional kerosene reforming produces CH_4 and other species at about 400 °C (673°K) and produces CO + H_2 + H_2O at about 800°C (1073°K). As shown previously this process requires water to proceed, and results in oxidized carbon species. To produce hydrogen gas only, the C-H bonds must be broken in such a way that C forms only as carbon (graphite or other solid structure). This implies that no oxygen take part in the reaction, i.e. pure pyrolysis, perhaps involving a catalyst. It could proceed rather fast at high temperatures and become very endothermic, since C-H bonds would have to break without the help of oxygen (it is the oxygen that balances endothermicity by forming CO and CO_2). It seems reasonable to conclude that the most practical way to produce only H_2 gas from methane or kerosene it to pass it through plasma or arc heater with no oxygen present and trust large negative values of the Gibbs function of soot at higher pressures to make carbon condense into a solid[44].

Oxygen-free (pyrolysis) of methane yields growing fractions of hydrogen (molecular and atomic) as the temperature grows, going from 67% to 81% form 2000 °K to 5000 °K at atmospheric pressure. At this pressure solid carbon is also formed for sufficiently long residence time in the reformer that the process can be assumed to be in equilibrium. At atmospheric pressure the solid carbon fraction goes from 30% at low reforming temperature (2000°K) to essentially zero at 5000°K. This trend is also found at pressures up to 100 atm. The remaining species formed are C_xH_y species ($x = 1,2,3$ and $y = 0,1,2$), all soot precursors. If the fuel is RP-1 the trend is similar, but the carbon fraction at one atmosphere and lower temperature (2000°K) is about 50% with a corresponding 50% of hydrogen being formed. For the higher temperature (5000°K) the hydrogen fraction reaches 84%. The effect of pressure is similar to that for the case of methane. Typical results for $H_20 + CH_4$ are:

T = 2000°K	T = 5000°K
H_2 = 75%	H_2 = 12%
CO = 25%	H = 71%
	CO = 15%

It is possible to conclude that high temperature pyrolysis of methane or kerosene can provide large amounts of hydrogen and other hydrocarbon species at high temperatures. At lower temperature operation substantial amounts of solid carbon are also formed, and must be dealt with. If this is the last step in the reforming process, then the high temperature atomic and molecular hydrogen injected into the combustion chamber through a supersonic nozzle provides a significant increment of thrust as stated in references 29, 31, 38, & 40.

One remaining area of analysis is the hydrocarbon to water ratio. It needs to be verified that an endothermic hydrocarbon and reduce the CO formation and carried water can be kept to a minimum. That would have a significant advantage since water is an already oxidized fuel. Water however makes a very tolerant energy absorbing working fluid. In years past water-hydrogen heat exchangers[45] have been considered, so the absorbed thermal energy can be converted to useful thrust via the supersonic fuel injectors, and that is a possibility. That is a steam augmented engine!

Two questions remain: 1) what is the AJAX system concept the authors determined having reviewed the known facts and the results of the analyses, and 2) did the analyses confirm or deny the key parameter values discussed with respect to the MHD propulsion system by the Russian and Ukrainian sources?

AJAX SYSTEM CONCEPT

Figure 3 from reference 3 provides a rather direct view into the AJAX concept. Few of the details are provided as to what the hardware is that provides the functions. However one of the authors (Prof. Bruno) has direct knowledge of the plasma experiments, and the plasma is not thermal plasma but a cold plasma. There is serious doubt that that plasma can provide the electron density necessary for the MHD generator-accelerator work. Professor Mark A. Prelas of the University of Missouri-Columbia, Department Nuclear Engineering. provided much insight into the potential for air ionization based on hardware and demonstrations he witnessed during visits to the formerly classified Russian and Ukrainian Facilities. In addition references 2, 3 & 4, two papers give some insight into the ramjet work at CIAM[46,47]. and TSNIIMASH[48]. Some of the related Russian drag reduction and plasma work was discussed by one of the authors..[49]. Figure 11 provides a limited interpretation that emphasizes the MHD energy bypass propulsion system. However that interpretation is not the complete AJAX picture and is used here just to provide an explanation for a vehicle that is a directed energy system and has a much wider application than a space launcher. In fact it is not a good space launcher, but is a very good long range hypersonic cruise vehicle.

Within reference 3 the discussion of AJAX gave a an explanation in a figure entitled "*Roles And Missions For The Use of a Directed Energy System For Peaceful Purposes.*" These are:

1. Space debris burning
2. Ionosphere and upper atmosphere research
3. Ozone generation
4. Communication with artificial satellites
5. Water surface and atmosphere ecological conditions diagnostics
6. Ore deposits prospecting
7. Earth vegetation research and monitoring
8. Seismic conditions and tunnel monitoring
9. Ice Conditions and snow cover monitoring
10. Long-range communication and navigation

AJAX ESTIMATED PERFORMANCE

The estimates performance of AJAX is shown in Figures 12,13, 14, and 15. The literature identifies four directed energy aircraft. NEVA-25 and NEVA-26 Hypersonic Airplanes are identified in reference 3 with the

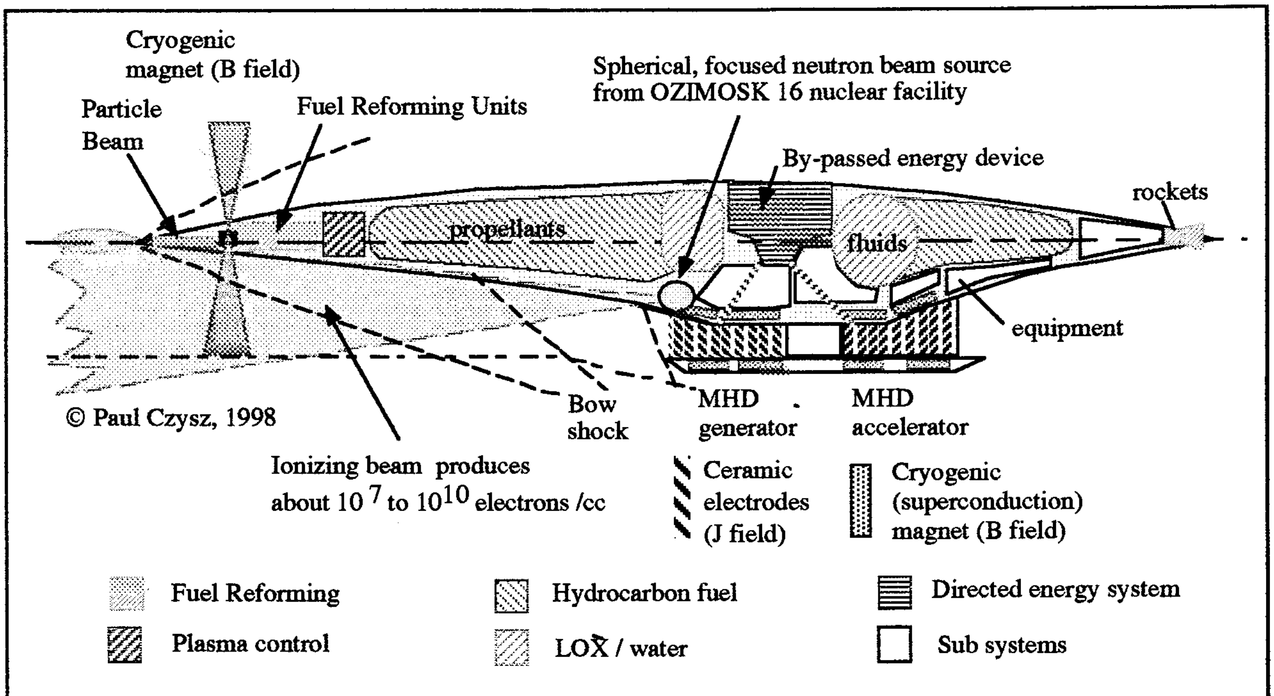


Figure 11 AJAX Concept as Represented by Authors from Personal Conversations and Reports

capability to reach destinations 4,800 to 11,000 km (2,600 to 5,940 nautical miles) distant. NEVA-23 and NEVA-24 Hypersonic airplanes are identified with the capability to reach destinations 10,000 to 19,000 km (5,400 to 10,260 nautical miles) distant. The global coverage of these aircraft is represented originating from Moscow. The former range reaches all of Africa, Asia, Europe, and Northeast North America. The latter increases that coverage to all of North and South America and Australia.

The student team's results are consistent with the MHD parameters identified by Russian researchers in terms of the ionization level and the magnetic fields obtainable with superconducting magnets

To assess the impact of the MHD propulsion system, a very conservative ejector ramjet was used without any energy recovery from the cryogenic fuel, that is no LACE or Deeply Cooled cycle. This rocket ejector ramjet engine was integrated into a simple Microsoft EXCEL trajectory analysis to determine the weight ratio as a function of range, given the time, distance and propellant required to ascend and descend from the cruise Mach number and altitude. The thrust to drag ratios were conservatively selected so as to be prudent. For comparative purposes the impact of the plasma drag reduction is indicated. From the Russian data the drag reduction benefit is realized at Mach numbers as low as 2.5. The combination of the MHD and the plasma worked together to maintain the total benefit of the entire speed range..

The sizing program from references 33 and 40 were used to size a fully reusable horizontal takeoff and landing hypersonic cruise aircraft. The program determined the minimum size vehicle that could achieve the range specified with a takeoff wing loading of 440 kg/m^2 (90 lbf/ft^2). Subcooled hydrogen at 4.66 lbf/ft^3 and normal boiling point liquid oxygen at 71 lbf/ft^3 was assumed. The structure was assumed to weight of 18.0 kg/m^2 (3.7 lbm/ft^2). This is well within the current industrial capability.

First lets look at the estimated range performance for a MHD powered aircraft, Figure 12 and then the estimated power that can be bypassed by an operational sized vehicle to a directed energy device, Figure 13.

Cruise Performance The cruise results are presented for a conventional reformed hydrocarbon, a conventional reformed hydrocarbon with an MHD engine, and a conventional reformed hydrocarbon with an MHD engine with plasma drag reduction, and a hydrogen fueled cruiser. A would be expected the hydrogen fueled cruiser significantly outperforms both hydrocarbon fueled aircraft. What is surprising is that the projected AJAX system outperforms the hydrogen fueled aircraft at speed less than 12,000 ft/sec (3,650 m/sec). So a vehicle with hypersonic global range factor comparable to that with hydrogen is possible with a hydrogen fuel if it is an AJAX system. These range factors agree very well with the example from reference 3 that begins this report. So it wild appear on a range performance basis the AJAX MHD energy system does justify its com-

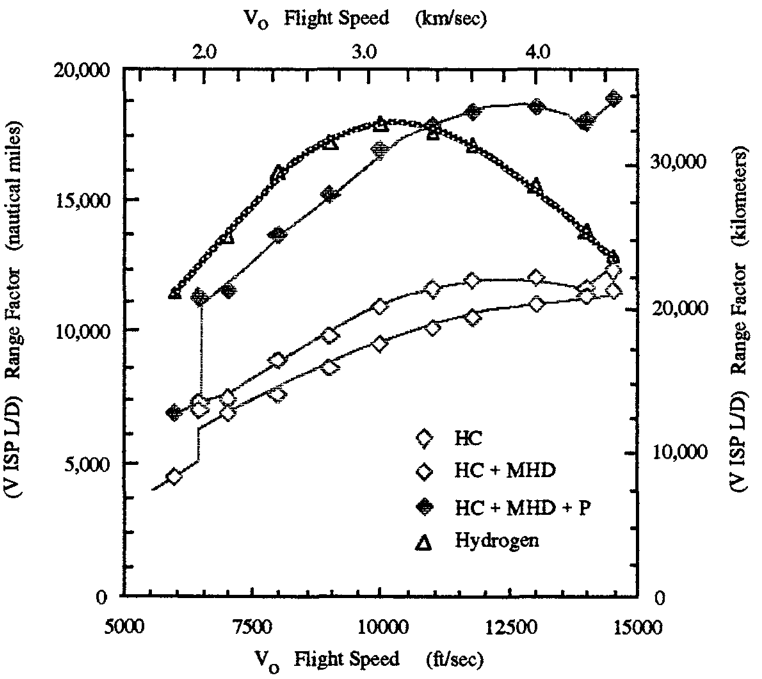


Figure 12 Estimated Range Factor

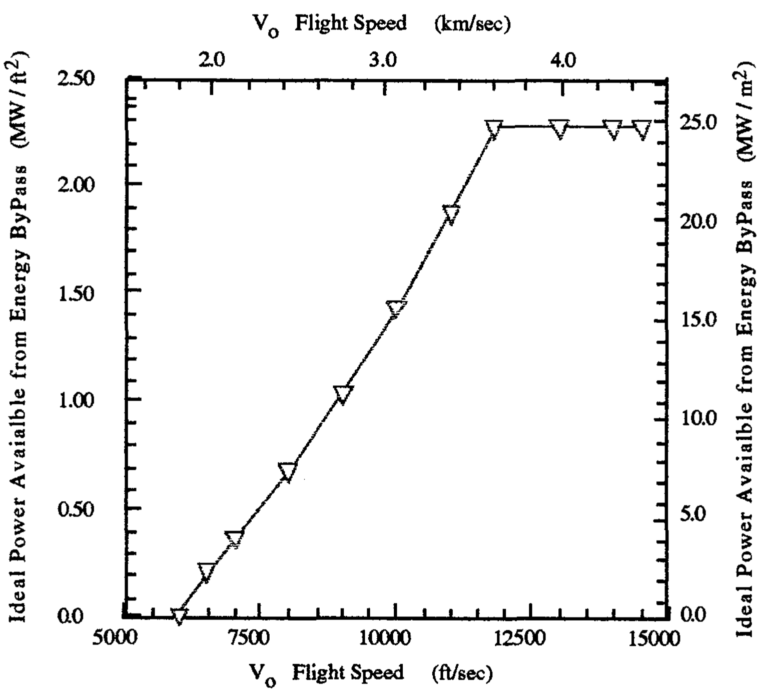


Figure 13 Ideal Power Available to Drive the Directed Energy System from the MDH Energy bypass System

plexity because it avoids the complexity of a global hydrogen distribution system.

Directed Energy Referring to Figure 13, at the best range factor speed, each engine module is capable of delivering about 15 megawatts per square meter of cowl inlet area. For a representative global range aircraft, the total cowl inlet area for four MHD engines is 30 m^2. That results in an available energy of about 450 MW of power. The assumption is that there are NO turbomachinery engines, and all four engines are MHD ejector ramjets with substantial rocket ejector thrust at low speeds.

For whatever purposes this system is put to, it is capable of directing an energy beam of considerable impact to objects either above or below its flight path.

Propellant Weight For 16,000 km cruise range (8,600 nautical miles) the propellant mass is given for an aircraft with a 78 ton (172,000 lbm) Operational Weight Empty (OWE). That is dry weight + trapped liquids + payload + crew. The same three MHD conditions are given. As might be expected, the propellant weight for the reformed fuel alone is about twice the weight for the hydrogen fuel, and it has not yet reached a minimum at its operating speed limit. The MHD propulsion system with its accompanying drag reduction however provides a different story. Here the hydrocarbon is equal to the hydrogen fuel weight required to fly 16,000 km.

So up to this point we have equality of the MHD hydrocarbon system, with is existing distribution system and personnel familiarity equaling a hydrogen fuel system in weight and performance. It would appear that the AJAX concept is indeed a worthwhile investment if it has the features and capabilities that the authors have credited with..

Propellant Volume is always a problem for a hydrogen fueled aircraft. Although hydrogen has 2.75 tines the energy per pound it has 10 times the volume for the same mass. Even with improved performance the 11,051 ft^3/Btu for hydrogen when compared to the 398 ft^3/Btu for kerosene presents a volume problem. The volume problem is reflected as an increase in the Küchemann tau that drives the supersonic and hypersonic lift to drag ratio. This affects launch vehicles less than cruise aircraft because it directly relates to the cruise range factor.

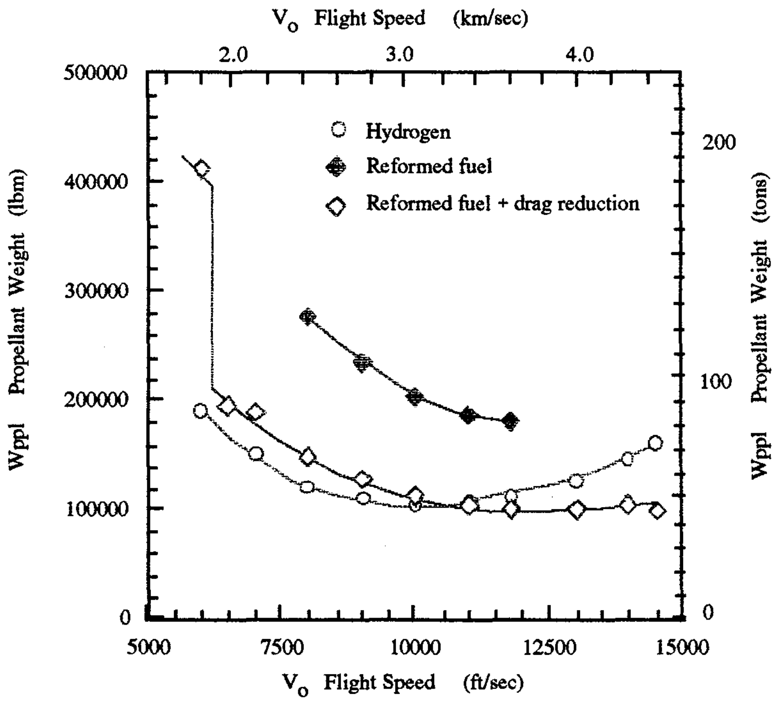


Figure 14 Propellant weight, OWE =78 tons.
Range =16,000 km

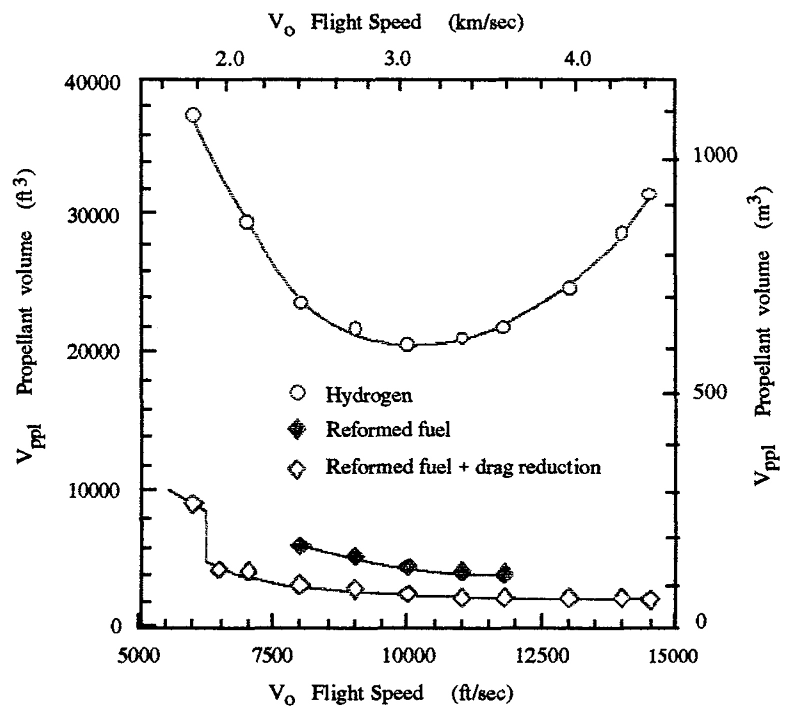


Figure 15 Propellant volume, OWE =78 tons.
Range =16,000 km

That problem is clearly identified in Figure 15. The all hydrogen aircraft has over 6 times the volume of the volume of the hydrocarbon fueled aircraft even at the minimum difference between the curves. The clear advantage of the AJAX reformed hydrocarbon, MHD-Plasma energy system shown. For the same weight aircraft, the volume approaches an order of magnitude less volume. In terms of Küchemann's tau that is a substantial increase in the cruise Lift to Drag ratio. An acceleration dominated vehicle, such as a space launcher does not benefit directly from an increase in lift to drag ratio, since it is only thrust to drag that impacts its weight ratio, and maximum lift to drag ratio does not occur at minimum drag. The AJAX system concept, if it is an actuality, is an original application of basic principles to change the paradigm for long range cruise hypersonic aircraft fueled with hydrocarbon fuels. The result is a hydrocarbon fueled aircraft with the range factor and propellant fraction of a hydrogen fueled aircraft with the volume of a hydrocarbon fueled aircraft and the available energy to drive a powerful directed energy device.

CONCLUSIONS

1. The AJAX Magneto-Plasma-Chemical engine integrates diverse technical capabilities into a managed energy aircraft system with impressive hypersonic cruise aircraft with substantial directed energy device capabilities.
2. With a change in propulsion module geometry, the MHD propulsion system with cryogenic magnets achieves the performance of a hydrogen engine with a reformed hydrocarbon fuel and the system weight only a minor weight penalty and a major drag reduction benefit.
3. The energy bypass MHD propulsion system has a significant performance advantage over a conventional rocket ejector ramjet by delaying the conversion to supersonic through-flow.
4. The plasma drag reduction has a significantly greater impact on cruise range than acceleration to orbital speed.
5. The student design team's analyses of the available solution space found no discrepancies in the values for electron density and magnetic field strength reported in Russian information.

6. The available data for the performance of the AJAX class of vehicles is consistent with thermally and electrically reformed hydrocarbons as fuel. The accompanying decrease in volume points to emphasizing cruise rather than acceleration to orbit.
7. The energy bypass ramjet propulsion system offers a significant advantage if the goal is to avoid supersonic through-flow operation. Subsonic through-flow operation can be maintained in the 1755 m/sec (5758 ft/sec) to 3,600 m/sec (11,800 ft/sec) range.

LIST OF SYMBOLS

A	area
A_{cowl}	Engine module cowl area
A_c	Engine geometric capture area
B	Magnetic intensity, (Tesla)
C_p	Specific heat at constant pressure
E_n	Neutron energy
f/A	fuel air ratio
g	Acceleration of gravity
H_o	Static, free stream enthalpy
H_{ke}	Kinetic enthalpy, $V^2/2$
ISP	Thrust per unit propellant flow rate
ISPE	(T-D) per unit propellant flow rate
I_n	Neutron source intensity
J	Electric field strength, (Volts/m)
m	mass flow rate
OWE	Gross weight minus propellant
P_{ext}	Power extracted
Q	Brayton cycle heat addition, $(f/A)\cdot Q_c$
Q_c	Heat of combustion
RF	Range Factor = V•ISP•(L/D) (page 3)
S_{plan}	Planform area
S_w	Wetted area
T	thrust
U_{air}	Speed behind nose shock wave
V	Velocity, or speed
V_{crit}	Ramjet critical speed (see page 4)
V_o	Flight speed, free stream velocity
V_{tot}	Total volume
W	Weight
α	air ionization level
η	Energy conversion efficiency
ψ	Enthalpy compression ratio (ref. 30)
ϕ	Fuel equivalence ratio
τ	Küchemann's tau (see page 3)
θ	Product of inlet and nozzle efficiency
ρ	Density
ρ_e	Electron density
σ	Electrical conductivity
σ	Atmospheric density ratio,

REFERENCES

1 Bruno, Claudio, Czysz, Paul & Murthy, S.N.B., "Electro-Magnetic Interactions in Hypersonic Propulsion Systems" AIAA 97-3389, 33rd AIAA/ASME/SAE/ASEE joint Propulsion Conference, Seattle, Washington, July 1997.

2 Esteve, Maria Dolores, et.al., "ODYSSEUS, Technology Integration for a Single Stage to Orbit Space Transport Using MHD Driven Propulsion," Senior Design Study, Parks College of Aerospace and Aviation, Saint Louis University, St. Louis, MO, May 1997.

3 Novichokv, Niloaly, "Space Wings of Russia and the Ukraine," _Echo of the Planet/Aerospace_, Moscow, Sept. 1990.

4 Private Communications, IAF Congress, Graz Austria.

5 E.P. Gurianov, E.G. Sheikin, "Leninetz" Holding Company, St. Petersburg, Russia, "Using the MGD Systems on Hypersonic Vehicles."

6 Carlson C. P. Pian, Robert Kessler, and Edwin W. Schmitt, Textron Defense Systems, Everett, Massachusetts, "Magnetohydrodynamic Generator Design for a Combined-Cycle Demonstration Powerplant," Journal of Propulsion & Power, Vol. 12, March-April 1996.

7 B. C. Lin & J. T. Lineberry, ERC, Incorporated, Tullahoma, TN, "An Assessment of T-Layer MHD," AIAA 95-1933, 26th AIAA Plasmadynamics & Lasers Conference, June 19-22, 1995/San Diego, CA.

8 Gordon, S. and McBride, B.J., "Computer Program for the Calculation of Complex Chemical Equilibrium Composition, Rocket Performance, Incident and Reflected Shocks, and Chapman-Jouguet Detonations" NASA SP-273

9 Evgeniy P. Gurijanov, "Leninetz" Holding Company, St. Petersburg, Russia & Philip T. Harsha, North American Aircraft Division, Rockwell International, Seal Beach, California, "AJAX, New Directions in Hypersonic Technology," AIAA Paper 96-4609.

10 V.M. Batenin, V.A. Bityurin, G.S. Ivanov, N.N. Inozemzev, P.A. Gorozhankin, Institute of High Temperatures of Russian Academy of Science Moscow, RUSSIA. "Electromagnetic Complex Concept for the Horizontal Start and Landing of a Reusable Air-Space Aircraft," 48TH International Astronautical Congress, October 6-10, 1997/Turin, Italy.

11 P. Tretyakov, Institute of Theoretical and Applied Mechanics SB RAS, Russia. "Supersonic Flow Around Axisymmetric Bodies with External Supply of Mass and Energy."

12 Sergey V. Zhluktov, Institute for Computer-Aided Design, Moscow, Russia & Sergey V. Utyuzhnikov & Grigoriy A. Tirskiy, Moscow In-

stitute of Physics and Technology, Moscow, Russia, "Numerical Investigation of Thermal and Chemical Nonequilibrium Flows past Slender Blunted Cones," Journal of Thermophysics & Heat Transfer, Vol. 10, No. 1, January-March 1996.

13 V.A. Gorelov, M.K. Gladyshev, A.Y. Kireev, A.S. Korolev, & I.V. Yegorov, Central Aerohydrodynamic Institute, Zhukovsky-3, Moscow, Russia, & V.N. Byzov, Flight Research Institute, Zhukovsky-3, Moscow, Russia, "Computational and Experimental Investigations of Ionization near Hypersonic Vehicles," Journal of Spacecraft & Rockets, Vol. 33, No. 6, November-December 1996.

14 V.A. Gorelov, M.K. Gladyshev, A.Yu. Kireev, A.S. Korolev, V.S. Nikol'sky, TsAGI, Zhukovsky, Russia, V.N. Byzov, B.M. Fedosov, LII , Zhukovsky, Russia, "Ionization Near Hypersonic Vehicles: The Experience of Numerical, Laboratory and Flight Investigations," AIAA 95-1940, 26th AIAA Plasmadynamics & Lasers Conference, June 19-22, 1995/San Diego, CA.

15 Phil Smereczniak, Group Manager, MDH Programs, McDonnell Douglas, "Electromagnetic Drag Reduction (EMDR) Program," Developed for Aeronautical Systems Center Planning Directorate (ASC/XR), Contract F33657-96-D-2004-0002.

16 P.K. Tretjakov, Institute for Pure and Applied Mechanics, Russia, V.I. Golovitchev, CRS4 Research Center, Cagliari, Italy, & C. Bruno, Dept. Mechanical & Aeronautical, University of Rome, Italy, "Experimental and Numerical Study of Counterflow jet Flame Stabilization in a Supersonic Air Stream," XII ISABE, Melbourne, Australia, September 10-15, 1995.

17 Anon. "Hypersonic Research Facilities Study, Phase III Final Studies, Volume IV, Part 1, Flight Research Facilities," Prepared under NASA contract NAS2-5458. NASA CR 114327, October 1970. Declassified October 1982.

18 Vandenkerckhove, J. "A Peep Beyond Marginality"

19 Kuan Chen, University of Utah & Thomas L. Eddy, EG & G Idaho, "Thermodynamic Charts for Nonequilibrium Plasma Flow in a Supersonic Nozzle," Journal of Thermophysics & Heat Transfer, Vol. 10, No. 1, January-March 1996.

20 Deepak Bose and Graham V. Candler, University of Minnesota, Minneapolis, Minnesota, "Kinetics of the $N_2 + O \rightarrow NO + N$ Reaction Under Thermodynamic Nonequilibrium," Journal of Thermophysics & Heat Transfer, Vol. 10, No. 1, January-March 1996.

21 F. Nasuti, University of Rome, Rome, Italy, M. Barbato, CRS4 Research Center, Cagliari, Italy, & C. Bruno, University of Rome, Rome, Italy, "Material-Dependent Catalytic Recombination Modeling for Hypersonic Flows," Journal of Thermophysics & Heat Transfer, Vol. 10, No. 1, January-March 1996.

22 J. Cole, J. Campbell, and A. Robertson, NASA Marshall Space Flight Center, Huntsville, AL, "Rocket-Induced Magnetohydrodynamic Ejector-A Single-Stage-to-Orbit Advanced Propulsion Concept," AIAA 95-4079, AIAA 1995 Space Programs & Technologies Conference, September 26-28, 1995/Huntsville, AL.

23 A. Lanshin, V. Sosounov, Central Institute of Aviation Motors (CIAM), Moscow, Russia, "Russian Aerospace Combined Propulsion Systems Research and Development Program ("ORYOL-2-1): Progress Review," AIAA-96-4494, 7th International Spaceplanes & Hypersonic Systems & Technology Conference, Norfolk, VA/November 18-22, 1996.

24 P.K. Trtyakov, V.M. Fomin, and V.I. Yakovlev, Institute of Theoretical and Applied Mechanics SB RAS, Novosibirsk, Russia, "New Principles of Control of Aerophysical Process, Research Development".

25 V.A. Sosounov, A.S. Roudakov, V.S. Semenov, V.I. Kopchenov, A.I. Lanshin, O.N. Romankov, Central Institute of Aviation Motors, Moscow, Russia, "Two Generations of Russian Scram Flying Test Beds. The "Oriel" Programme," XII International Symposium on Airbreathing Engines, 11-15 September, 1995, Melbourne, Australia

26 Harsha, Philip and Gurijanov, Evgeniy P., "AJAX: New Directions In Hypersonic Technology," AIAA 96-4609, 7th Aerospace Planes and Hypersonic Technologies Meeting, Norfolk, Virginia, April 1996.

27 Anon. "Hypersonic Research Facilities Study, Phase I Preliminary Studies, Part 2 - Flight Vehicle Synthesis," Prepared under NASA contract NAS2-5458. NASA CR 114324, October 1970

28 Czysz, Paul, ""Space Transportation Systems Requirements Derived from the Propulsion Performance Reported in *The Hypersonic and Combined Cycle Propulsion Session* at the 1991 IAF Congress," IAF-92-0858, 43rd IAF Congress, Washington, DC, September 1992.

29 Ahern, John, "Thermal Management of Air-Breathing Propulsion Systems," AIAA 92-0514, 30 Aerospace Sciences Meeting and Exhibit, Reno, Nevada, January 1992.

30 Builder, Carl H., "On the Thermodynamic Spectrum of Airbreathing Propulsion," AIAA 64-243, 1st AIAA Annual Meeting, Washington, DC, July 1964.

31 Czysz, P.. "Thermodynamic Spectrum of Airbreathing Propulsion," SAE 881203, Future Transportation Technology Conference and Exposition, San Francisco, California, August 1988.

32 Tanatsugu, N. et.al, "Development Study on ATREX," AIAA 96-4553, 7th AIAA International

Spaceplanes and Hypersonic Systems & Technology Conference, Norfolk, Virginia, November 1996.

33 Czysz, Paul A., Froning, H. David, & Longstaff Roger, "A Concept for an International Project to Develop a Hypersonic Flight Test Vehicle," AIAA , AIAA Joint Propulsion Conference, July 1997, Seattle, Washington,

34 Prelas, Mark, personal communication, 1997

35 Segre, E., "Nuclei and Particles", The Benjamin /Cummings Publ. Co., Inc., Menlo park, pp. 54-55. 1998

36 Gurianov E.P., Kuranov, A.L., and Sheikin, E.G., "Using the MGD Systems on Hypersonic Vehicles", XIII ISABE Proceedings, Fig. 1, 1997

37 Knoll, G.F., "Radiation Detection and Measurement", J.Wiley, NY, p. 132, Table 5-1, 1989.

38 Riggins, David, "Scramjet Engine Performance Analysis, Evaluation, and Optimization, 1996 JANNAF Propulsion and joint Subcommittee Scramjet Workshop, Dec. 1996, Albuquerque, NM

39 Ibid. #4

40 Czysz, Paul & Murthy, S.N.B., "minimum Size Hypersonic Research Vehicle/Demonstrator and Demonstrator Single Stage to Orbit Launcher. HyperTech Concepts, Jan. 1996, For Dassault Aviation, St. Cloud, France.

41 Scortecci, F.,Capecchi, G., Andrenucci, M., Mei, G., and Garré, R., "Development of a Superconduction Magnet for Applied Field Arcjet Thrusters," IEPC-93-119, 23rd International Electric Propulsion Conference.

42 Anon. "Europa Metalli SpA, 1998, Materials Data Reference Sheets.

43 Garré, R., Personal Communication, April 1998.

44 Glassman, I., "Combustion," Chapter 6, Section E, p398 & p568, Academic Press, New York 1996

45 Anon. "The Water-Cryogen Heat Exchanger" AEC-NASA Tech Brief 70-10591, October 1970, Washington, DC

46 Lanshin, A. and Sosounov, V., "Russian Aerospace Combined Propulsion Systems Research and Development Program ("ORYOL-2-1"): Progress Review, AIAA 96-4494, 7th AIAA International Spaceplanes and Hypersonic Systems & Technology Conference, Norfolk, Virginia, November 1996.

47 Sosounov, V.A. et.al., "Two Generations of Russian SCRAM Flying Test Beds. The ORIEL Program" Proceeding of the XII International Symposium for Air Breathing Engines (ISABE), September 1995, Melbourne, Australia.

48 Anfimov, Nicolai A., "In Searching for an Optimal Concept of Future Russian Reusable Space Transportation System," Proceeding of the International Workshop on Spaceplane/RLV Technology Demonstrators, pp. 97-122, March 1997, Tokyo, Japan.

49 Bruno, C. "Some Ideas for Future Launchers Technology," Proceeding of the International Workshop on Spaceplane/RLV Technology Demonstrators, pp. 67-96, March 1997, Tokyo, Japan.