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AJAX: NEW DIRECTIONS IN HYPERSONIC TECHNOLOGY

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I INTRODUCTION

The "AJAX" hypersonic vehicle concept has been developed over the past several years by the Leninetz Holding Company in St. Petersburg, Russia. It involves technologies developed at Leninetz and at other scientific institutes also located in St. Petersburg. The concept involves a series of hydrocarbon-fueled hypersonic vehicles, including designs for high Mach number cruise missions as well as two-stage- and single-stage-to-orbit vehicles. Fundamentally the concept involves the capture of energy otherwise lost from the vehicle in flight at high Mach numbers, and the recycling of this energy to increase the efficiency of the overall system. The feasibility of the approach depends on developing the systems required to capture energy from the flow and efficiently recycle it. AJAX technologies include:

- Steam reforming of the hydrocarbon fuel through chemical regeneration, utilizing the endothermic nature of the steam reforming process to cool the vehicle and its engines, while producing methane and ultimately hydrogen on board the vehicle for use in the high-speed scramjet engine cycle.

- MGD generation of electrical power through deceleration of the inlet flow, with the power generated used to provide the inlet stream ionization necessary to allow the MGD interactions to occur, and the excess power available at high Mach numbers available for other uses, including producing a nonequilibrium plasma around the vehicle.

- Creation of a nonequilibrium cold plasma adjacent to the vehicle, to reduce shock strength, drag, and heat transfer.

Each of the technologies included in the AJAX concept provides a potentially revolutionary benefit in terms of hypersonic vehicle applications (as well as applications to other aerospace systems). Both the hydrocarbon reforming and MGD flowfield control processes involve technologies which are conventional in other applications (refinery production of hydrogen and wind tunnel flow acceleration, respectively), so that the AJAX application of them can be characterized as an unconventional application of a conventional technology. The physical phenomena that occur in a nonequilibrium plasma have been convincingly demonstrated in small-scale laboratory experiments, both in Russia and in the United States. Exploitation of these phenomena in a vehicle application is a much larger step than use of the other two technologies, but the benefits of such exploitation would be huge, so that the plasma phenomena can be characterized as a high-risk, high-payoff technology. None of these technologies have been reduced to actual vehicle-level practice, but component-level development has been carried out. All of the technologies are worthy of further development for a broad variety of aerospace applications.

II THE AJAX TECHNOLOGIES

The AJAX hypersonic vehicle concept involves a variety of different technologies combined together into a synergistic system. As described by Vladimir Fraishtadt, who is credited with the origination of the concept (Ref. 1), the basic philosophy of AJAX is that an efficient hypersonic vehicle cannot afford to lose energy to its surroundings, but must take advantage of the energy fluxes surrounding it. These energy fluxes include both the enthalpy of the air flowing around the vehicle and the heat transfer from the vehicle to its surroundings. Since this energy derives from the motion of the vehicle, it is not "free", but efficient recycling of this energy can reduce the overall energy requirements of the system. The AJAX concept also avoids what in Fraishtadt's opinion is the Achilles heel of other hypersonic concepts, the use of cryogenic fuels.

Figure 1 shows, in cartoon form, the different systems that together make up the AJAX hypersonic vehicle concept. The use of a hydrocarbon fuel, T-6 aviation kerosene, is central to the concept, but to make this fuel usable in a high-speed propulsion system, part of it is converted to hydrogen in a steam reforming process. This steam reforming process is highly endothermic, and the energy required to keep it going is supplied by cooling the engine and vehicle surfaces. In the version of the concept shown, a two-stage engine is used, with the low-speed stage provided by a turbojet, which operates to about Mach 55, and the high speed stage provided by a supersonic combustion ramjet (or scramjet) which takes over at this Mach number. The inlet of the scramjet is controlled by an MGD (magnetogasdynamic) generator which allows the use of a fixed geometry inlet while also generating substantial amounts of electrical power. This electrical power may be used for a variety of purposes, which include operating an ionization apparatus which produces the weakly ionized flow required to provide the MGD interactions in the inlet. At high speeds, where the MGD generator provides more power than is required to operate the ionizer, the excess electrical power can be used to operate an MGD accelerator in the exhaust nozzle or to provide a directed energy beam which can be used to alter the characteristics of the flow around the vehicle.

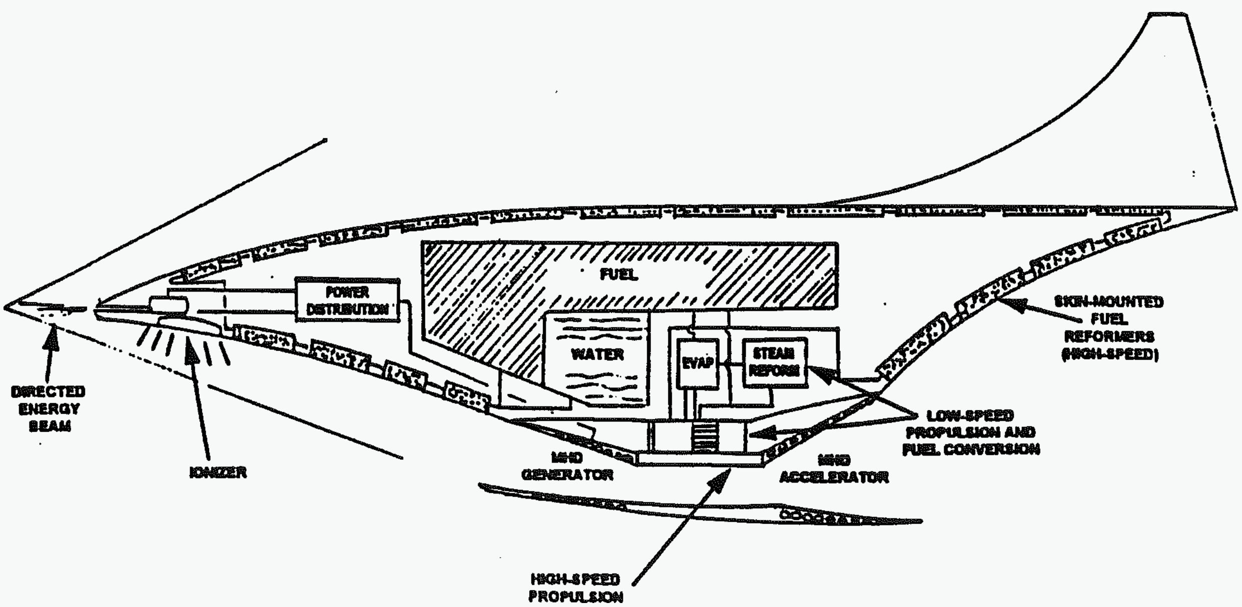


Figure 1. AJAX Hypersonic Vehicle Concept

While the overall concept includes all of the features shown in Fig. 1, it should be emphasized that different aerospace vehicle applications could feature different combinations of the AJAX technology components. For example, a high Mach number cruise vehicle could utilize the advantages of the hydrocarbon fuel reforming system without using either the MGD inlet or nonequilibrium plasma generation aspects of the overall concept, while the MGD inlet control approach could be used with a “conventional” cryogenic-fuel hypersonic vehicle, and the nonequilibrium plasma flow control technology may have considerable applicability to Mach 2-3 military and commercial aircraft. In the following paragraphs we will review the MGD and plasma technologies briefly . We will then address the use of hydrocarbon fuels, perhaps the nearest-term of these technologies, in more detail.

1. MGD Energy Extraction from the Inlet Airstream

As is generally the case with the AJAX technologies, more than one objective is accomplished with this concept. Since the extraction of energy from a flowfield using a properlydesigned MGD generator decelerates the flow, this energy extraction method also can be used to perform the inlet compression process required for a scramjet engine cycle. In principle, then, this approach can be used to provide the wide range of inlet contraction ratios necessary to operate a scramjet engine over a wide range of Mach numbers without the mechanical complication and weight inherent in a variable-geometry inlet. If the weight of the magnets and other electrical devices necessary for the MGD generator in a hypersonic vehicle application is comparable to the weight of a mechanically-variable inlet, then the power generation capability is effectively free.

The power produced by an MGD generator for a one-dimensional flow is given by

$$P = \sigma v^2 B^2 k(1-k)$$

where k is the load factor which lies between 0 and 1, representing the limits of pure open and pure closed circuits, v is the one-dimensional velocity perpendicular to the magnetic field, B is the magnetic induction strength, and σ is the electrical conductivity. For an electrical conductivity of 10 mho/m, typical of an unseeded plasma at 5000°K and 1 atm. (conditions consistent with boundary layer flow at a freestream Mach number of 14), with magnetic induction strengths from 0.5 to 2 Tesla, and a load factor of 0.5, up to 250 MW can be produced.

The dependence on v^2 and B^2 is evident from these results, implying that at the relatively low ionization levels obtainable without seeding, a large magnet is required in the AJAX design, and suggesting that the magnetic system weight will be a key issue with respect to design feasibility.

2. Nonequilibrium Plasma Effects

There is an extensive literature surrounding the observations of gasdynamic phenomena in nonequilibrium plasmas. Much of this literature, some of which is summarized in Ref. 2, derives from experimental work done at the A. F. Ioffe Physicotechnical Institute in St. Petersburg. These experiments were done in two ballistic facilities-a light gas gun capable of accelerating projectiles to 6 km/sec, and a powder gun capable of 2.5 km/sec. Many of the results described in the literature were obtained at 2 km/sec, which in air at the 1200°K experiment conditions corresponds to about M=2.9. The experiments involved a variety of projectile shapes. Schlieren photography and shadowgraphs clearly show the absence of a bow shock in front of spherical and conical projectiles at this flight condition in a glow discharge plasma, and in the case of a stepped-cylinder projectile, the shocks from each of the steps, which coalesce in the classic manner in air, no longer coalesce in the glow discharge. The elimination of the shock wave occurs at a certain plasma intensity; for plasmas at lower intensities the shock strength is reduced but it is still apparent. The interpretation of the effect is that the effective speed of sound in the excited plasma is increased relative to that in normal air at the same temperature. This is indicated by observing the shock standoff distance for a sphere as a function of sphere velocity in the plasma and comparing it to that measured in air, as is shown in Fig. 2. For both the plasma, curve 1, and normal air, curve 2, the shock standoff distance decreases with increasing velocity. However, the distance is always greater for the plasma, indicating that the acoustic velocity is considerably higher in the plasma than in air, These results can be used to infer the effective acoustic velocity, as is shown in Fig. 3; for this condition in air the speed of sound is 720 m/sec.

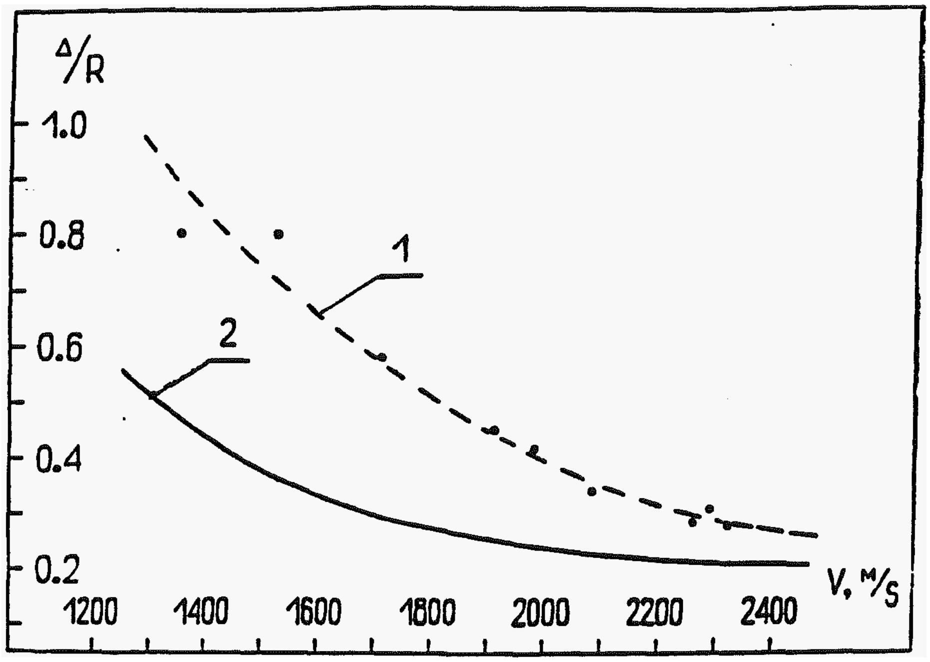


Figure 2 Effective Shock Standoff Distance for a Sphere

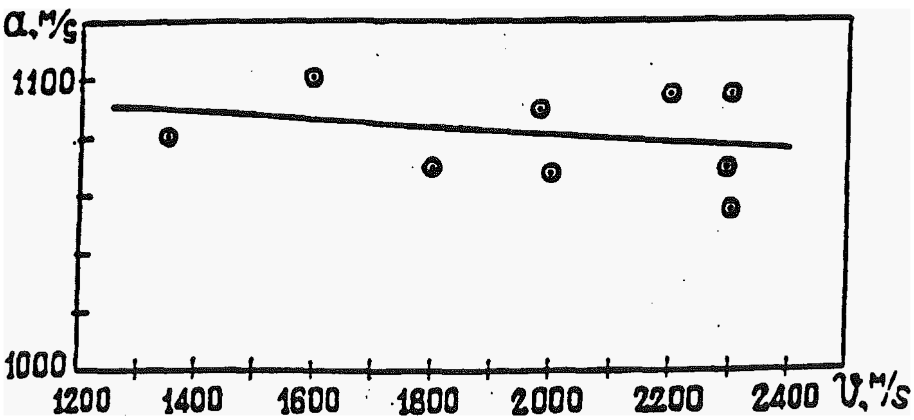


Figure 3 Effective Sound Speed in a Plasma

Both drag and heat transfer are strongly affected by the phenomenon. Heat transfer results were recently reported by Serov and Yavor(Ref. 3). In these experiments heat transfer effects were inferred from ablation rate results for a duralumin sphere coated with NaCl. The ablation rate was itself inferred from **sodium** concentration in the sphere wake, as measured *using* spectrointerferograms obtained using a two-beam interferometer. The results showed a factor of four reduction in heat transfer in the decaying plasma compared to in air at the same temperature.

3. Hydrocarbon Fuel Reforming and Thermal Management

The **use** of a hydrocarbon fuel is a key element in the overall AJAX concept as proposed by Fraishtadt. There are **a** variety of advantages that accrue if a hydrocarbon fuel *can* be successfully used in a hypersonic vehicle, some of which are listed in Table I. In particular, the **use** of hydrocarbon fuels allows all of the present fuels infrastructure to be used with advanced hypersonic vehicles, which *can* be a tremendous savings in **both** system cost and development time.

FEATURES	CRYOGENIC FUEL	REFORMED HYDROCARBON FUEL
SPECIFIC IMPULSE AT MACH 8	2500 sec	850 sec
DENSITY	0.07 gm/cc At speeds in excess of Mach 8, volumetric characteristics predominate over those related to mass, and the basic thrust is expended in overcoming drag.	0.73 gm/cc
BOILING TEMPERATURE	20°K	447°K
DESIGN REQUIREMENTS	•large tanks with high efficiency vacuum thermal insulation •special pipelines and hoses	•active thermal protection •additional tanks for water •water feed system.
NEED FOR NEW INFRASTRUCTURE	Construction of LH_2 feed systems. Cost of airport increased by factor of 2.	Fuel infrastructure already in place. Water treatment facilities required.
FLIGHT PREPARATION TIME	Two days	30-60 minutes
COST OF SERVICING	Cryogenic fuels servicing procedures	At the level of conventional aircraft.
ENVIRONMENTAL DAMAGE	LH2 is produced by means of energy intensive processes.	Same as for aviation-grade kerosene.
FIRE OR EXPLOSION HAZARD	Damage to the thermal shielding of the fuel compartment of the vehicle or storage tank can produce catastrophic result.	Years of aviation experience exists to reduce risks.
IN-FLIGHT REFUELING	Technically impossible in foreseeable future.	Techniques are available.
1 RATIO OF FUEL COSTS	160-300 times aviation kerosene	

Table 1 Comparison of Characteristics of Hydrogen and Hydrocarbon Fuels (After Fraishtadt)

The concept underlying this technology is one of "chemical regeneration of heat." It is necessary to make this distinction **because** in **both** the Russian and American literature on the subject of the **use** of hydrocarbon fuels in high speed vehicles, this concept is usually linked to another-"endothermic fuels"-which distorts and dilutes the essence of the resulting phenomena. If, in traditional applications, fuel is converted directly into heat in one stage by means of combustion, then in a device using the process of chemical regeneration of heat, the fuel energy conversion is divided into two stages. In the first stage, heat is removed from the surface of the vehicle by means of endothermic chemical reactions. The second stage is the burning of the products of the reaction, that is the converted fuel, having greater caloric capacity than the original fuel.

The application of chemical regeneration of heat aboard the vehicle in the AJAX concept means that the catalytic chemical reactors, in which the highly endothermic processes that result in the conversion of the initial kerosene fuel are carried out, are distributed in the most heat-stressed portions of the airframe and engine. The hydrogencontaining fuel mixture obtained as the result of the conversion process is directed into the combustion chamber. In this manner the usable portion of the aircraft's energy supply is increased by chemically recouping heat losses resulting from both the aerodynamic heating of the airframe in hypersonic flight and the operation of the power plants. At the same time the cooling capability of the fuel is increased by the means of both physical and chemical conversions (heating, vaporization, and endothermic reactions), and the active thermal protection of heat-stressed portions of the airframe is enhanced by the direct absorption of heat in a catalytic reaction process.

Among the many possible endothermic reactions converting hydrocarbons, steam reforming was chosen for the AJAX application. The choice was made according to several criteria, including the heat of the reaction, the temperature and the rate at which it takes place, the resulting increase in heat capacity, and the quantity of hydrogen produced. The heat of the reaction has a considerable influence on the amount of heat absorbed by the thermochemical reaction. Consider the steam conversion of methane in stoichiometric proportions, involving 0.47 kg/kg mixture methane and 0.53 kg/kg water. The cooling capacity of an apparatus using this reaction is made up of four parts: the preheating, vaporization and superheating of water and methane, and the heat of the reaction. For this reaction, the physical cooling capacity over the range from t=0° C to t=727°C is 3.3 MJ/kg of mixture. The heat of reaction is 6.6 MJ/kg of mixture, yielding a total cooling capacity of 9.9 MJ/kg of mixture. This compares very favorably with the physical cooling capacity of methane over the range t=110°K to t=920°K of 3 MJ/kg, and also with hydrogen over the range t=20°K to t=850°K at 12 MJ/kg.

The specific form which the steam conversion reaction takes depends on the conditions under which it is carried out, including temperature, pressure, and ratio of water to hydrocarbon, among others. At high temperatures (t>1000°C) the reaction produces practically nothing but hydrogen and carbon monoxide, while at temperatures below 400°C the output of products is strongly inclined to the formation of methane and carbon dioxide. Unfortunately, the dissociation process for hydrocarbons is complicated by unwanted reactions for the formation of free carbon (coke) which leads to carbon deposition on the catalytic reactors. It is possible to compute thermodynamically the minimum critical ratio of water to carbon below which, in equilibrium, carbon will always be formed, but in practice systems are often not in equilibrium, and the deposition of coke depends to a significant degree on the reaction in progress which, in turn, is influenced by such individual properties as the catalyst composition and the nature of the hydrocarbon. Here characteristics of the catalyst such as its selectivity begin to play a not-insignificant role. Improvement of the catalyst's selectivity by, for example, addition of an alkali that promotes carbon gasification will allow the thermodynamicallydetermined boundaries to be approached. Another measure is to avoid temperature drops which speed up the cokeforming reactions. Thus intensification of heat exchange on the reaction surface has extreme significance and wide use in the AJAX thermal protection concept.

Further, research on the rate of coke deposition on the surfaces of nickel-containing catalysts has shown that it is reduced in the order ethylene >benzene >heptane >hexane >butane

>methane, and the ratio of C/H is reduced in the methane molecule. Thus if the raw material is methane, carbon deposit formation is not a critical problem. From this comes the conclusion that it is necessary to organize the process of dissociation of the initial liquid hydrocarbon in such a manner that in the most crucial, largest surface area, and most inaccessible places, the conversion would involve gaseous methane. Such an arrangement is possible when using a two stage system for the steam conversion of liquid hydrocarbons. In such a system the process occurs in two steps. First, liquid hydrocarbons are gasified at low temperature (t=300-450°C) via the reaction

$$C_nH_m + (n\text{-}m/4)H_2O \rightarrow (n/2+m/8)CH_4 + (n/2 - m/8)CO_2$$

The thermal effect in the given range of temperature is just changing its sign from exo- to endo- depending on the composition of the initial raw material and the parameters of the process. Because of the relatively low temperature of the process it is necessary to use a highly active catalyst with a large value of surface area divided by weight. In the second step, the products of gasification are transformed according to the reactions

$$C_nH_m + nH_2O \rightarrow nCO + (n+m/2)H_2$$
$$CH_4 + H_2O \rightleftarrows CO + 3H_2$$
$$CO + H_2O \rightleftarrows CO_2 + H_2$$

in a high temperature (t=700-900°C) conversion step. This organization of the working process has several advantages compared to a single-step process. Rather than producing vaporized liquid hydrocarbons, high temperature conversion produces a gaseous mixture of methane that is stable to supercritical coke formation, carbon dioxide, and a small amount of hydrogen, damping the cracking reaction. As a result the danger of coking the catalyst is substantially reduced. This approach also makes it possible to reduce the excess water vapor in the conversion process and approach stoichiometry with respect to the initial components.

The inclusion of a chemical reactor within an aircraft skin contour brings up a set of special requirements on the catalysts and the endothermic process itself. Airborne catalysts must satisfy many special requirements, including high heat conductivity, high thermal-cycle strength, stability with respect to impact loads and vibration, and the ability to operate under large-magnitude, transient heat fluxes. To satisfy these requirements requires new catalyst technology, the basis for which is highly porous metal mesh materials. The catalytic material and promotional additives are applied on a secondary porous metal-ceramic secondary support, which is in turn attached to the surface of a Ni-Cr matrix. Specifications of this catalyst are as follows:

Component	% of total mass
Ni-Cr matrix	*50-59*
Metal-ceramic coating (Cr_3C_2, Cr_2O_3, NiO)	**45-35**
Catalyst phase (Ni)	**4-5**
Promotional additives (BaO, MgO)	**2-1**

Other characteristics

Hydraulic resistance, Pa/M	10^4
Specific surface area, m^2/gm	15

Catalytic activity

Degree of methane conversion, %

For $H_2O/C = 2$	$w = 2000\ hr^{-1}$	
	t= 600°C	*64%*
	t=800 °C	99.5%

Loss of activity after 100 hours of life testing was less than 1%.

Currently, work at Leninetz has been focused on the development of matrix- and planar-type catalysts appropriate for aircraft applications. This work has involved study of the heat and mass transfer process in these catalysts. In contrast to processes in industrial reactors where heat and mass are conveyed to the catalyst granules via the reagent flow, in catalytic heat exchangers the diffusion mechanism of mass transport combines with heat transfer along the structural coating via thermal conductivity. The latter mechanism can turn out to be the slowest, damping the process of catalytic conversion. Microporous coatings with a thickness of 10^{-4} to 10^{-5} mm, pore diameter of 10^{-4} to 10^{-6} mm, and heat conductivity of at least 1W/m°K were found to be the most effective. All newly-developed catalysts were subjected to tests at standard conditions on specially created laboratory test stands, to determine the catalysts' activity and behavior under conditions imposed by a reacting environment at high temperature. These investigations have resulted in the development of a series of thermochemical reactor constructions based on planar catalysts (type I) and matrix catalysts (type II) having the following technical specifications:

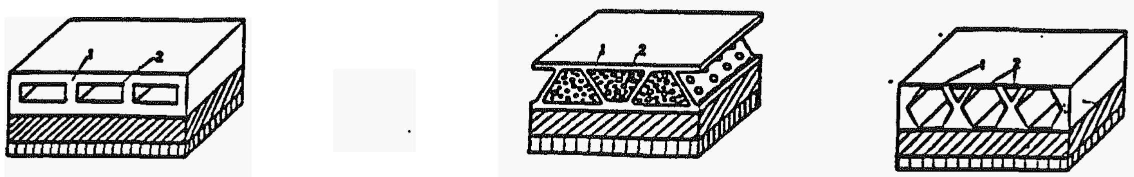
	Type I	Type II
Heat flux density, MW/m^2	up to 1	up to 2
Average flow speed, m/s	10-60	1-10
Hydraulic resistance, Pa/m	10	2.10
Operational temperature, °C	400-1000	400-1000
Pressure, Pa	up to 5.105	5.105
Height of flat reactor, mm	2-5	5-15
Weight/sq. m		
high temperature steel, kg	<18	<24
composite material, kg	<10	<16

Sketches of several variants of these thermochemical reactors are shown in Fig, 4.

gap model of reactor with catalytic covering $q=0.1\text{-}0.5\ MW/m^2$

panel-reactor with block catalyst $q=0.1\text{-}1.0\ MW/m^2$

panel-reactor from composite material $q=0.1\text{-}10\ MW/m^2$



1. Steel E1841
2. Ni/Al_2O_3

1. Steel EI841
2. HPHM, Ni/Cr_3C_2

1. silicon carbide
2. Ni/SiC

Figure 4. Thermochemical Reactor Variants

III SUMMARY AND STATUS

With the **AJAX** concept, the Leninetz organization has described a synergistic group of technologies which could point the way to a new direction in hypersonic flight. The key to a 11 of these technologies is eliminating wasted energy. Given the margins inherent in hypersonics, this is a worthy and necessary goal. However, much more work needs to be done to establish the feasibility of these technologies in a hypersonic vehicle system. Fortunately, while in **AJAX** they operate synergistically, they can all be developed individually, allowing a stepping-stone approach to their development. Such a stepping-stone development process could use one or more of the several hypersonic testbeds which are currently planned or under development around the world.

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