ANNALES
UNIVERSITATIS MARIAE CURIE-SKŁODOWSKA
LUBLIN — POLONIA

VOL. XLIII/XLIV, 32 SECTIO AAA 1988/1989

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Politechnika Warszawska

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Air-breathing Space Boosters

The rocket propulsion is now the only useful propulsion system to deliver the man made objects to space. In the contemporary rockets basically chemical rockets propulsion is used. Most of the chemical rocket propellants consist of fuel and oxidizer. Usually 2,5 - 6 parts of oxidizer to one part of fuel (by mass) make the propellant. So 70 - 85% of propellant (by mass) consist of oxidizer. If the propulsion system can use the atmospheric air as an oxidizer, the mass of space transportation system can be significantly reduced. For this reason many countries start to develop the Aerospaceplane. However the development of the propulsion system for the Aerospaceplane is a challenging task, since such system should work from zero velocity on ground to the hypersonic velocity in the space frontier.

More simple and less costly will be application of the air-breathing propulsion to boosters only, and use only in the velocity range where this system is most efficient and still relativity simple. From the other side, it should be notice that the space boosters make 60 - 80% of the total mass of space transportation system, and many of these boosters accelerate rocket only to the velocity of 1,25 - 2,5 km/s. To accelerate Space Shuttle to about 1,5 km/s (part of this velocity is the rotational velocity of Earth, at KSC ~ 0,4 km km/s) nearly 70% of its take off mass is spent (after booster separation). Advanced Ariane-5 will use up to 80% of its total mass to accelerate to about 2,2 km/s (~6,5 M).

In average space transportation system about 70% of its total mass is use to accelerate the vehicle to less than 2 km/s. At least 70% of the booster mass consist of oxidize. So the very simple calculation shows that the application of the air-breathing propulsion to the space booster can easily decrease the gross mass of the launch system by 50% or more.

In this paper the simple analysis of the space boosters using air-breathing propulsion will be presented.

THE AIR-BREATHING PROPULSION SYSTEM.

For the small velocity most effective is turbo propulsion. This kind of propulsion is very effectively used in all jet planes, but a direct applications of civilian or military jet engines for the space booster will not be appropriate. The main demands for space booster turbo engines are quite different than for these used in civil or military transportation. In space boosters, engines have to work for a few minutes and should have high thrust to weight ratio (T/W). Fuel efficiency is less important. Typical recent military engine with afterburning has the T/W of about 100 N/kg, but specially designed lift engines can have this ratio more than twice higher [1]. It can be easily assumed that for space applications such engines will have the T/W of about 200 N/kg or more.

As it was mentioned before, for space booster application turbo engine will be of different design than the classical one. The schematic diagram of such engine is shown on the Fig.1. It consist of the few stages compressor (two or three stages should be sufficient), turbine, combustion chamber and exhaust nozzle. Hydrogen will be the best fuel for such engine.

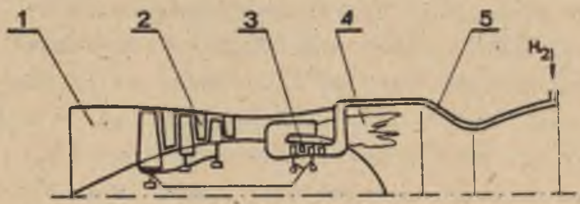

Fig.1. Schematic diagram of turboexpander engine.
1-inlet, 2-compressor, 3-turbine, 4-combustion chamber, 5- regeneratively cooled nozzle.

During engine work the hydrogen fuel will be fed first to cool the nozzle and combustion chamber. Than the hot gaseous hydrogen will be expanded through the turbine which drive a few stages compressor. Compressor supplied the air (oxidizer) to the engine and the expanding hydrogen (from the turbine) is burning in the combustion chamber with the air supplied by the compressor. Hot combustion products are expanding through the supersonic nozzle giving necessary thrust. To start such engine a short impulse from gas generator (to speedup turbo-compressor) is only necessary.

The efficiency of such engine will be increased with the flight velocity, since the compression ratio will be increased due to the dynamic compression in the engines diffusor. For the relatively high Mach number, dynamic compression in diffusor may be sufficient, so the turbo-compressor will start to windmill and the hot gaseous fuel will be fed directly to the combustion chamber and the engine will work as the ramjet engine. Such system can be effectively used up to velocity of $3 \div 4$ M. For higher velocity air flow through windmilling compressor can create bigger pressure losses so the bypass ramjet or scramjet should be used.

The variation of the specific thrust (specific impulse) for different kinds of engines as a function of Mach number is shown on Fig.2. The hydrogen fueled turboexpander engine of relatively low compression ratio will have specific thrust of about 45 kN·s/kg. From Mach ~ 3 ramjet engine will be sufficiently effective, while for the Mach > 6 ramjet with supersonic combustion so - called scramjet will be most efficient. One can easily find that all air - breathing engines are nearly of an order more efficient than rocket engine. So the use of such engines, at least for the space boosters should be very desirable [2] [3].

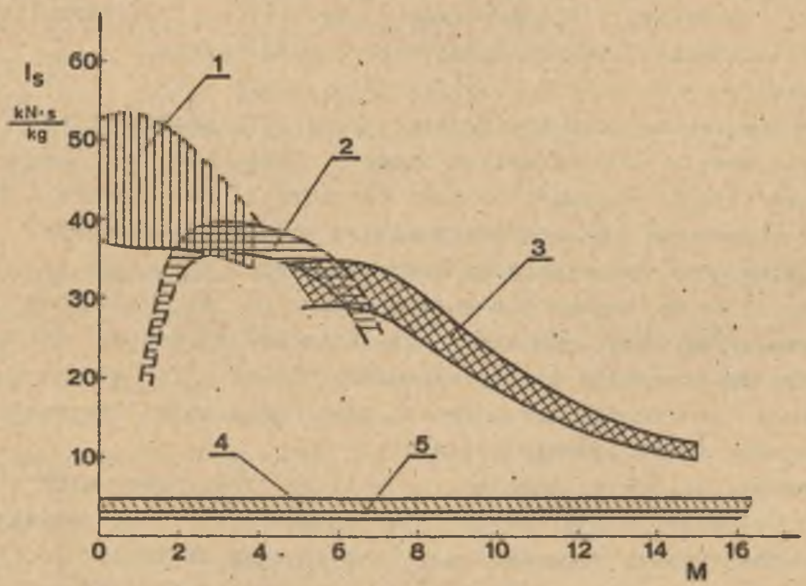

Fig.2. Specific thrust (specific impulse) of the different engines:1-turboexpander, 2-ramjet, 3-scramjet, 4-liquid propellant rocket, 5- solid propellant rocket.

As it can be find from the Fig.2, the air-breathing engine can be use nearly to orbital velocity. This is a reason for building of the Aerospaceplane. Such engine can be used effectively for the very high Mach numbers, but the developments of such engines will be very difficult and expensive. Aerospaceplans flying with the hypersonic velocity will be subjected to extensive thermal and pressure loads. This will complicate design and will increase costs of constructions and operations of such vehicles. More economically justify will be use of the air - breathing engine to relatively low velocities, so the more commonly used material and technologies can be used for engine and booster.

THE AIR-BREATHING BOOSTERS.

Let we consider the launch of a mass of 29 tons (payload similar to the maximum useful load of the Space Shuttle). The calculations results are presented in the Table 1. The booster weighting up to 45 ton will consists of 12 engines. Each engine with the diameter of 1,65 m will be placed around the fuel tank of 5,4 m diameter. All engines will have the common inlet and nozzle. The total thrust of 12 engines will be equal to about 4,5 MN. The boosters engines will work for about 120 s and will accelerate the vehicle to the velocity of 1200 m/s (about 4 M) at the altitude of 20 ÷ 25 km. Inertial velocity during booster separation will be 1500 m/s, if the launch will took place from the latitude of 28,5°. This is due to about 400 m/s component of Earth rotational velocity. For orbital insertion inertial vehicle velocity should be equal to 7800 m/s, so the additional 6300 m/s velocity increase should be made with the use of rocket propulsion. Calculations show that the rocket stage can accelerate the vehicle in the zero gravity and vacuum conditions to the $\Delta V \approx 7080$ m/s. Since the necessary velocity increase is equal to 6300 m/s, 780 m/s penalty for gravity and residual drag is sufficiently high.

TABLE1. Data for the Booster-Rocket configuration

		Air-breathing Booster	Rocket
Net mass	kg	$35\cdot10^3$	$20-21\cdot10^3$
Propellant (Fuel) mass	kg	$10\cdot10^3$	$196-200\cdot10^3$
Payload mass	kg	$245\cdot10^3$	$25-29\cdot10^3$
Total mass	kg	$290\cdot10^3$	$245\cdot10^3$
Real ΔV	m/s	1000-1200	6300-6500
Final inertial velocity*	m/s	1300-1500	7800
Propellant (Fuel)		LH_2	LH_2/LOX

*Assuming Launch at 28.5°

Separation of the booster at the altitude of about 20- 25 km will be only dozen kilometers away from the launching pod, so the booster can be guided back to the launch area and recoverd by parachute. If necessary two or more turbo engines, in subsonic velocity, can be used to power back to the launch side, where it can be recovered.

The schematic view of such booster with the rocket is shown on the Fig.3. Acceleration of the vehicle to only Mach 4 and the extensive use of hydrogen fuel cooling capacity will allow to use conventional materials and technology to build such booster. All engines will have common inlet, with some controlled geometry, and common conical nozzle. Such nozzle will not need regulation since by principle it is automatically adjusted to the outside pressure. Aerodynamic control fins will be used during the boots and recovery phase of the booster flight.

It can be easily find out from the above analyses, that to launch 29 tons to Low Earth Orbit only 290 ton launch vehicle will be necessary. This can be compare to 590 ton Saturn 1B, which placed 18 tons in low Earth orbit (about 3% of launch mass), with 2770 ton Saturn 5, capable to place 130 ton in orbit (~ 4.7% of launch mass) or a 2050 ton space Shuttle able to place 29 ton in orbit (only about 1,5% of launch mass).

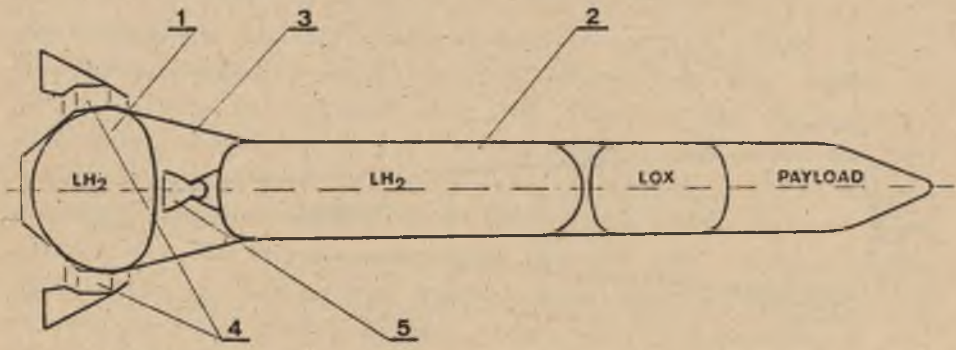

Fig.3. Schematic diagram of rocket with the air-breathing booster: 1-air-breathing booster, 2-rocket, 3-interstage, 4-turboexpander - ramjet engines, 5-rocket engine.

The proposed booster can place in the low Earths orbit about 10% of its launch mass, so it can be at least twice better than the best rocket launcher, and more 7 times better than the Space Shuttle. For the proposed Cargo Shuttle the air-breathing-rocked launcher will still have more than twice better performance.

In the above air-breathing booster bigger mass will be contributed to the turbine engines. The turbine engines are necessary to accelerate the vehicle from zero velocity, since the ramjet can be effectively used for the velocity higher than 2 M. For much higher Mach number turbo engine should be bypassed so the further acceleration will be possible by the direct application of ramjet propulsion to the rocket stage. Such stage will combine ramjet, scramjet and rocket propulsion (Ram--Rocket) and it is shown schematically on the Fig.4. Acceleration of this stage to the velocity of 1000-1200 m/s can be made by the same air-breathing booster as described above. Further acceleration will be made by ramjet-scramjet and than by rocket engine. Table 2 present the basic data for the such space launcher.

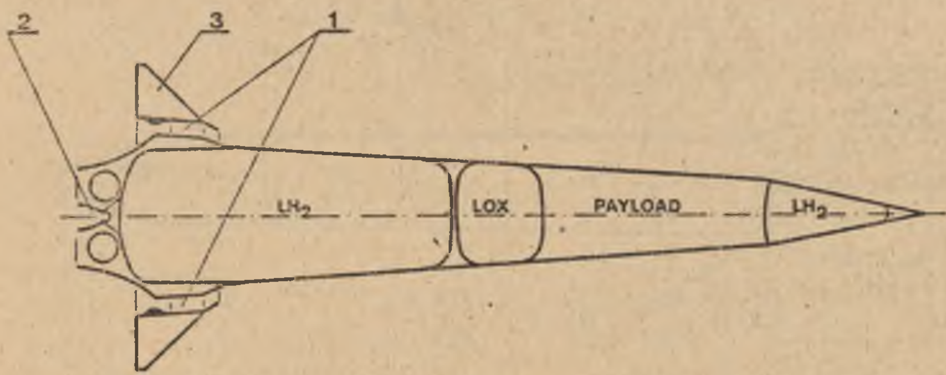

Fig. 4.Schematic diagram of the ram-rocket stage:
1-ramjet-scramjet engines, 2-rocket engines, 3-fines

TABLE 2. Data for the Booster-Ram-Rocket configuration

		Air- -Breathing Booster	Ram - Rocket	
			Ramjet	Rocket
Net mass	kg	$33 \cdot 10^3$	$10 \cdot 10^3$	$10 - 12 \cdot 10^3$
Propellant (Fuel) mass	kg	$12 \cdot 10^3$	$40 \cdot 10^3$	$125-135 \cdot 10^3$
Payload mass	kg	$245 \cdot 10^3$	$195 \cdot 10^3$	$48-60 \cdot 10^3$
Total mass	kg	$290 \cdot 10^3$	$245 \cdot 10^3$	$195 \cdot 10^3$
Real ΔV	m/s	1000-1200	2100-2500	3800-4400
Final Inertial velocity*	m/s	1300-1500	3400-4000	7800
Propellant (Fuel)		LH_2	LH_2	LH_2/LOX

*Assuming launch at 28.5°

After booster separation ramjet engine will accelerate the vehicle to the velocity of about 6 M, and than the engine working mode should be switch to the supersonic combustion so called scramjet. It is also possible that scramjet engine should be used just after separation of the booster. Scramjet can accelerate the vehicle to 10-12 M. Acceleration will take place at the altitude up to 40 km. For the such fast flight in the atmosphere some parts of the vehicle as well as the engine will be subjected to very intensive heating, so the extensive cooling should be assured. Hydrogen fuel carried in the nose cone tank can be used during the atmospheric acceleration for the vehicle body cooling. Evaporated and heated hydrogen will be eventually burn in engine. When the vehicle reach velocity of 10÷12 M the whole ramjet-scramjet engine will be separated. This engine as well as some fuel thanks and aerodynamic control fines (eventually a small wing) will be expendable. The front tank can still be used, for some time, as a nose cone which protect the payload. Nose tank can be seperated at higher altitude, so the higher payload can be delivered to the orbit. It is seen from Table 2, that in this case the useful load can be about 20% of the total launch weight. Such launch system can be very effective and relatively inexpensive.

CONCLUSIONS

It was shown, that the use of air-breathing engines in space launch vehicles can very effectively increase the mass of launched payload. Simple application of reusable turboexpander-ramjet engines in the booster stage can increase the useful load of space launcher at least twice, comparable to the traditional rockets. Further significant increase is possible by the application of ramjet-scramjet propulsion, to speedup the launcher to hypersonic velocity during the atmospheric flight.

The applications of relatively simple air-breathing engine to power space launcher during atmospheric flight is very promising goal, since the specific impulse obtained by these engine is about an order of magnitude higher than of rocket engine. Disadvantage of these engines are relatively small thrust to weight ratio and the big variation of thrust with velocity and altitude. Also intensive heating during relatively long atmospheric flight create additional problems which should be solved.

There are many possible choices of the future shape of air-breathing propulsion, but evidently this kind of propulsion will dominate in space launchers of next century. The first visible air-breathing space launcher is the West Germany Sänger project. The development of USA Aerospaceplane NASP and the other project studied in Europe and Japan are the steps to extensive use of the air-breathing propulsion as a very economical way of space transportation. The presented suggestions are the one which can easily benefit the use of air-breathing engines in the future space transportation systems.

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