# ADVANCED AEROSPACE SYSTEMS WITH INTERCONTINENTAL AND GLOBAL RANGE OF FLIGHT

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## Abstract

*The study of possible prospects for the development of reusable high-speed vehicles with intercontinental and global range of flight has been carried out on the basis of a complex system analysis.*

*Three main classes of long-range vehicles are considered:*

- *high-speed vehicles with long-range cruising flight in atmosphere;*
- *suborbital high-speed vehicles;*
- *orbital high-speed vehicles.*

*The problems of passenger and payload transportation, monitoring of the Earth surface, the use of the vehicles in the interests of the Ministry for Emergency Situations and struggle against terrorism are discussed.*

*Main possible characteristics of typical high-speed vehicles of three classes, the problems of their development, manufacture and operation are revealed on the conceptual level.*

*The key problems of a high-speed vehicle with a scramjet designed for a long-range cruising flight in atmosphere are as follows:*

- *providing high lift/drag ratio;*
- *achieving high level of specific impulse of scramjet;*
- *providing considerable relative vehicle fuel load.*

*Such vehicles may be realized only when highly efficient structures and thermal protection of high-speed vehicles are created.*

*One of the main factors speeding up the development of high-speed vehicles is a significant reduction of flight time (by times) for long range as compared with current subsonic cargo-passenger aircraft. This is very important for businessmen and tourists who can "appreciate the time". The first step is design of experimental vehicles-demonstrators.*

## Symbols and abbreviations

HSV – high-speed vehicles
$K_{hyp}$ – hypersonic aerodynamic efficiency (lift/drag ratio)
$I_{sp}$ – specific impulse of engine
$\overline{G}_f$ - relative vehicle fuel load
*ASS* – aerospace system
*MASS* – Russian multipurpose aerospace system of Design Buerau "Molnia"
*ASSH* – aerospace system with horizontal start
*ASSV* - aerospace system with vertical start (like Space Shuttle or Energia-Buran)
*ASA* – aerospace aircraft
*HA* – hypersonic aircraft
*HV* – hypersonic vehicle
*HBA* – hypersonic business aircraft
*HPA* – hypersonic passenger aircraft
*HCV* – hypersonic cruising vehicle
*HP* – hypersonic plane
*RBCC*, *TBCC* – rocket-based combined cycle, turbine-based combined cycle of engine
*TAV* – trans-atmospheric vehicle
*LNG* – liquefied natural gas
*ACC* – advanced carbon-carbon
*IAF* – Congress of Int. Astronautical Federation
$T_{service}$ – entry into service
*OPSS* – orbital plane "Space Shuttle"
OPEB – orbital plane "Energia-Buran"
$N_p$ – amount of passengers
RRB – return rocket booster

## 1 Introduction

For the past 50 years after the flight of the first astronaut of the Earth Yuri Gagarin and, especially in the last years, the projects of high-speed multipurpose vehicles are being developed more intensively. Primarily it concerns experimental vehicles to validate new hypersonic technologies, create full scale highly efficient launchers and hypersonic cargo-passenger vehicles [1]-[4], [6]-[14], [17]-[25]. The aeronautical and space technologies are evolving so rapidly that, according to the forecasts of domestic and foreign specialists, up to 2040–2050 years scheduled passenger transportation to intercontinental and global ranges and to near-earth orbits are anticipated [5], [15]. Different standard operations in atmosphere and near space performed on commercial basis and in the interests of national needs (nation’s economy, science, Ministry for emergency situations, Defense etc.) are possible.

In this connection the formulation of the problem on developing high-speed vehicles (ASSH, ASSV, ASA, HA, HBA, HV, and others) possessing new capabilities, as compared with current available aeronautical and rocket-space transportation means, becomes urgent.

These capabilities are as follows:

- reduction of endurance of flight to intercontinental and global ranges to 1–3 hours [6], [7], [22];
- significant reduction of operational costs and total expenses in case of a number of flights during a day as compared to the costs of a single flight of a subsonic aircraft per day;
- expansion of capabilities of prompt cargoes delivery to places difficult of access, as well as monitoring of the Earth surface, assistance in emergency situations, struggle against terrorism, narcotic crops control, etc. [8].
- increase of reliability, safety, maneuverability and flexibility when using the wings and aviation principles of operation (for example, flight cancellation and recovery of the crew and reusable equipment).

The vehicles performing long-range flights in atmosphere (HA and HV) and aerospace suborbital and orbital vehicles (ASS and ASA) are singled out of a large number of different projects of high-speed vehicles.

## 2 Hypersonic aircrafts (HA)

As it is known, experimental hypersonic aircraft X-15 (USA, 1958–1968) performed 199 flights speeding up to $M_{max} = 6$ (1967) and reaching the altitude of $H_{max} = 108$ km (1963). The average cost of flight was approximately 600 thousand dollars.

In 70-ies the works on a hypersonic aircraft (HA) were carried out in some foreign countries [2], [6], [12], [14], [18], [19], [23], [24] as well as time in TsAGI and in the Tupolev’s design bureau [10] (Fig. 1), (Table 1).

The factors promoting the acceleration of the process of HA development currently are as follows:

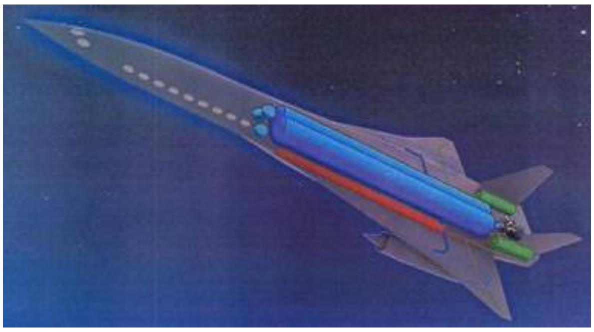
- design of the Ramjet and development of the Scramjet in some countries (USA, Japan, Russia, ESA, Australia and others);
- development of HA projects (England, France, Russia, Japan, USA);
- reaching the cruising speed in atmosphere of M = 6, 10 (demonstrators Russia IGLA, USA X-43, X-51);
- advancement of a number of hypersonic flight technologies such as thermal protection with $T_w = 1800–2200$°C (HERMES, ACC), titanium alloys of rapid crystallization (Inconel, $T_{w\,max} = 1100$°C, design level 980°C, X-15), metallic tiles for external surface of the vehicle, etc.;
- development of hybrid propulsion systems (RBCC, TBCC) with a high specific impulse ($I_{sp} = 2200–4000$ s at M = 6);
- providing minimum sonic boom of HA due to a significant increase of cruising altitude (up to H = 30–35km) in a special operating regime of a hybrid powerplant, considerable reduction of wing loading (from 350 kg/m$^2$ to 120 kg/m$^2$), decreasing HA “dry mass” due to the use of composite materials and special layout of HA with minimal sonic boom during

launching boost (long nose part of HA, rear arrangement of the wing);

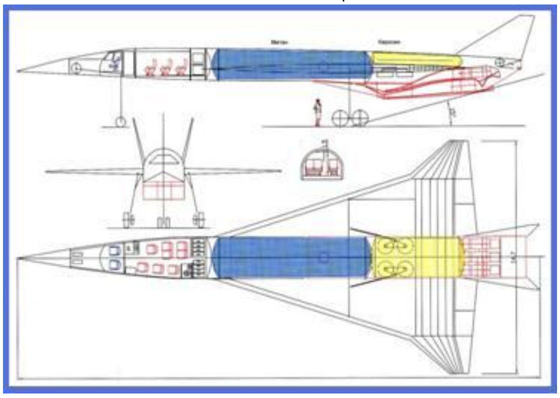
- development of new cycles of the engine providing saving of fuel and structural mass of the tanks due to the use of oxygen from air instead of onboard reserve (A. Bond in UK, see

HPA LAPCAT-A2 (England, FRG)
$M$=5; $G_{st}$=400 t; $N_p$=300

HPA ZEHST (EADS, Germany, Japan) $M$=4,6;
$G_{st}$=400 t; $N_p$=50-100; $T_{dem}$–2020 г.; $T_{service}$–2050.



HBA (TsAGI)
$M$=5; $G_{st}$=40 t; $N_p$=6-8



HPA (Japan)
$M$=5; $N_p$=200-300; $L$=6000-11000 km

Fig.1. Hypersonic aircraft projects

Table 1

Hypersonic aircrafts of DB “Tupolev”

| Parameters | Type | | | | |
|---|---|---|---|---|---|
| | Tu-HPA | Tu-230 | Tu-260 | Tu-360 | Tu-2000 |
| Range, km | 8500–10000 | 8000–10000 | 12000 | 16000 | |
| Start mass, t | | 180 | 253 | 350 | 250–350 |
| Payload mass, t | | | 10 | 20 | 6–10 |
| Flight altitude, km | 28–32 | 25–27 | 29–30 | 30–33 | 200 |
| Mach number of flight | 5 | 4,0 | 6,0 | 6,0 | 28 |
| Project status | Projects | | | Proposals | |
| Time of development | 1958-1960 | 1983-1985 | 1985 | 1988 | 1990-1993 |
| Engines | Turbojet+Ramjet | Turbojet Д-80 | | | Scramjet |
| Flight time, hour | | 2,3 | 2,5 | 2,5–3,0 | 1,5 |
| Fuel | NLG | kerosene | $H_2$ | $H_2$ | $H_2$+ker. |
| Lift/Drag Ratio $K_{hyp}$ | | | 5,2–5,5 | | 2,5 |
| Fuselage diameter, m | | | 6,0 | 8,0 | |

also studies in this direction carried out in Japan);

- improvement of economic indices of HA as compared with subsonic aircraft.

In flight to a long range with increased speed and reduced required time of flight there appears a possibility of realizing two and more turnaround flights a day in comparison with a single flight of a subsonic passenger aircraft, T >10 hours. Due to the enlargement of the size and passenger capacity of HA (up to $N_p$ = 200–300), the radii of the blunt of the fuselage and wing nose increase and the level of aerodynamic heating reduces. Besides, it is possible to decrease the mass of HA considerably (galley, trolleys, catering, stewardesses, toilets, etc.) because of a short time of flight in comparison with a subsonic passenger aircraft (T < 2–3 hours) by analogy with a “low cost” technology for regional aircraft.

As the technologies of HA develop, its service life (reusability) and economic efficiency (the use of aircraft by businessmen and rich tourists for which “time is more expensive than money”) will increase.

A tendency to cheapen hypersonic flights may be justified by the comparison of the cost of one flight of X-15 (600 thousand dollars) and suborbital aerospace system $WK_2/SS_2$ (~100 thousand dollars), i.e. by 6 times.

The analysis of the influence of main parameters of HA concept on its characteristics (Figs. 2, 3) has been made on the basis of a complex multidisciplinary approach to the definition of a high-speed vehicle configuration.

However the reduction of the endurance of flight to long ranges results in the increase of hypersonic aircraft speed and makes the requirements to aerodynamics, structure and thermal protection more stringent (Fig. 3).

The equilibrium temperature of the high-speed vehicle surface may be within 700–2500°C and in order to provide operational capability of the structure different types of thermal protection (passive, active, hybrid) are used. They are capable of withstanding long heat flows, especially in nose parts of the vehicle and in the scramjet. In this case reliability, safety and reusability (service life) of HA are very important. Besides, a preliminary control of passenger health (cardiogram, blood pressure control, etc.) and new legalized norms and standards for hypersonic aircraft, orbital and suborbital vehicles, perhaps, will be necessary. It is shown [23] that in Russia it is possible to create a hypersonic business aircraft with flight range of L = 4500–5100 km (Fig. 1) depending on the level of technologies. Project elaborations of HA with M = 10 have been carried out too (Fig. 4).

## 3 Suborbital systems

With the purpose of reducing time when flying to a specified long range, suborbital and orbital regimes of HSV flight (at first, staged systems such as ASSH, ASSV and further ASA with horizontal start, Fig. 5) may be used.

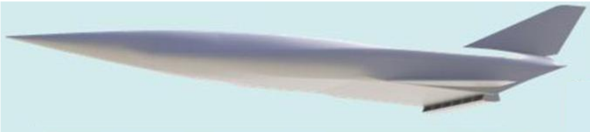
The flight profile may be purely aeroballistic (boost, orbit flight without entering the circular orbit and gliding) or the vehicle performs partially an orbital flight with a subsequent return on the Earth to a given airfield.

Last time suborbital tourist vehicles (two-staged) with a subsonic carrier-aircraft as the first stage and a rocket aircraft as the second stage are being developed. They are designed with the speed up to M = 3–5 and the altitude of 100–120 km of short duration (5–20 min). It is planned to get a certificate for such flights in NASA and perform them both in commercial and experimental goals with involving private and private-state capital.

The variants of domestic and foreign suborbital high-speed vehicles with horizontal start and landing are given in Fig. 5. The optimization of landing regime of standard aerospace plane X-37B, when it is dropped from the carrier-aircraft, may be taken as an example of an applied use of a suborbital high-speed vehicle with $WK_2$ as a carrier-aircraft.

It should be noted that orbital systems also may perform suborbital flights in meeting one of the two conditions:

- flight without enough fuel for vehicle to perform orbital operation;

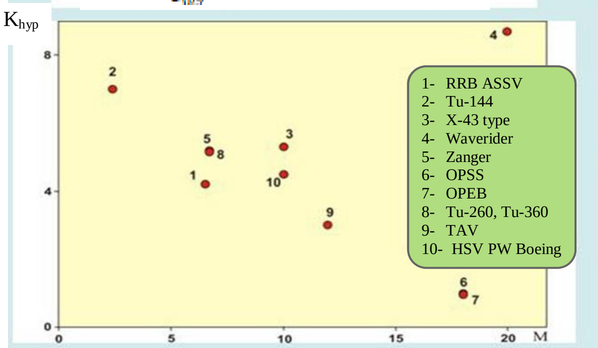


$$L_{\Sigma} = L_{bust} + L_{cr} + L_{gl}$$

$$L_{cr} = \frac{R}{r} \times \frac{V_{cr}}{1-\frac{V_{cr}^2}{gr}} I_{sp} K_{hyp} \ln \frac{1}{1-\bar{G}_{fcr}}$$

$$L_{gl} = \frac{R}{2} K_{hyp} \ln \frac{1}{1-\frac{V_{cr}^2}{gr}}$$

$$\bar{G}_{fcr} = \frac{1}{\bar{G}_{0cr}} \left(\bar{G}_{f\Sigma} - \bar{G}_{fbust} - \bar{G}_{fres}\right)$$




Hypersonic Lift/Drag Ratio HSV, $K_{hyp}$

| M / Publ. | 6 | 10 | 20 |
|---|---|---|---|
| $K_{hyp\ max}$ | 7 | 5-6 | 5-9 |
| $K_{hyp\ min}$ | 4,5-5 | 3,5-4 | 3,5 |
| IAF-42 | | | 8,7 ($L_v$~100m) |
| IAF-48 | 4,16 | | |

Specific Impulse Scramjet $I_{sp}$, s

| M / Publ. | 6 | 10 | 20 |
|---|---|---|---|
| IAF-39 (Japan) | 3800 | 2840 | 1250 |
| IAF-48 | 4300 | 2667 | |
| IAF-52 | 3700 | 2700 | 900 |
| Scramjet Tu-2000 | 4137 | 2036 | 1132-996 |
| $I_{sp\ min}$ | 3085 | 1902 | 1000 |
| $I_{sp\ max}$ | 4300 | 2840 | 1250 |

Relative Fuel $\bar{G}_{f\Sigma}$

| Concept / Parameter | NASP | ASA Tu-2000 | HPA M=10 TsAGI | ASA Rocket | ASA Star jet | ASA Boeing PW | ASA $O_2$+ $H_2$+ Ker | ASA in ASSH |
|---|---|---|---|---|---|---|---|---|
| Start weight, t | 180 | 210 250 | 240 | 680 | | 236 | 470 | 50 |
| Relative Fuel | 0,56 | 0,5-0,6 | 0,595 | 0,8 | 0,794 | 0,57 | 0,86 | 0,86 |

Fig. 2. Cruise flight of HSV in atmosphere

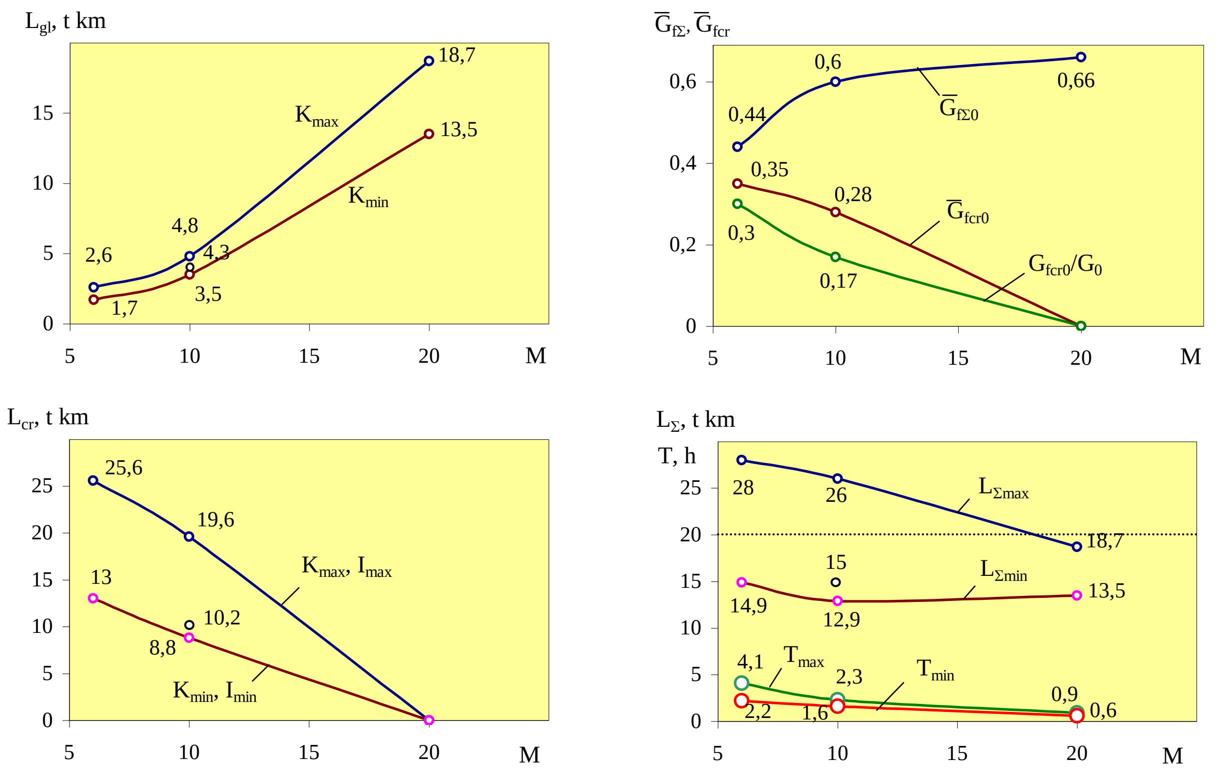



Fig. 3. Main characteristics of HSV of gliding and cruising types

- exceeding of payload mass as compared with design payload mass (orbital).

It is possible to realize suborbital trajectories of long range if the speed relative to

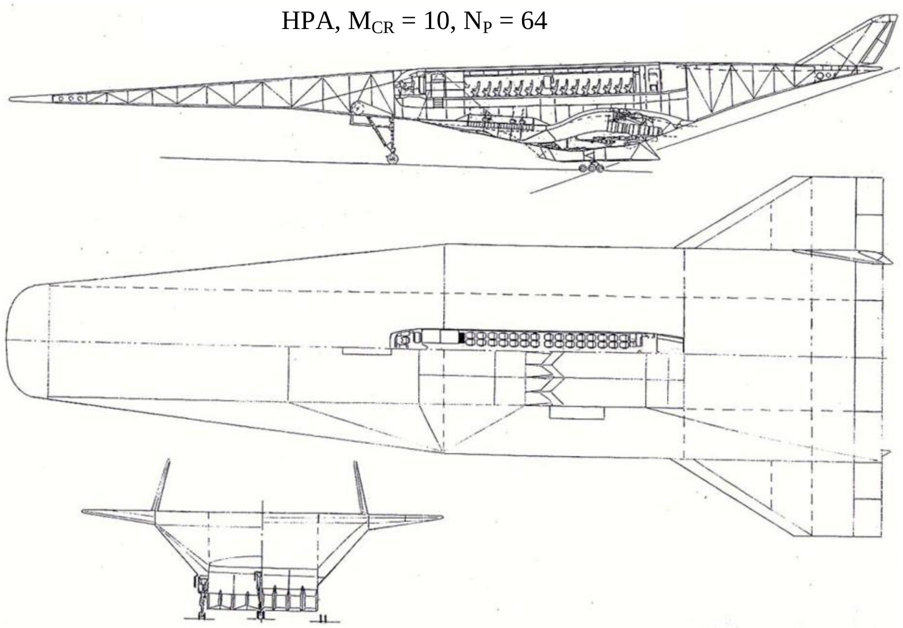



Fig.4. Hypersonic passenger aircraft (TsAGI)

$V_{orb}$ reduces by some dozens meters per second and more.

The evolutionary exploration of global atmosphere and near space will be implemented, probably, by means of gradual increase of the speed of suborbital tourist high-speed vehicles.

## 4 Orbital high-speed vehicles

The well-known projects of single-staged HSV entering the orbit: Sanger (1927–1934-ies, Germany), NASP (70–90-ies, USA), Tu-2000 (90–ies, Russia) had not been realized because of the non-readiness of key technologies, shortage of financing, wars and crisis. The most elaborated project passing through all stages of preliminary design and inter-departmental expert examination is a project of reusable aerospace system MASS (Fig. 5). Here is shown the other more promising by terms and cost TsAGI's proposal on the development of ASS on the basis of the subsonic aircraft IL-76 and ASA with the mass of 50 tons, passenger capacity of 5–8 passengers and liquid-propellant rocket engines designed for suborbital ranges (Fig. 5). The development of different types of reusable space systems with vertical start in the world (Space Shuttle, "Energia-Buran", ASSV consisting of Atlas 5 and ASA X-37B, etc.) may also lead to the creation of winged upper stages of ASSV with suborbital and orbital regimes of flight in the nearest future.

With the availability of an orbital path of flight, a specified long range may be achieved both in "plane" motion (boost-launch-orbital path of flight-recovery from orbit without roll) and in orbital vehicle descent in atmosphere with roll. The value of range is controlled both by the point of orbital departure and by aerodynamic regime of descent (a combination of angle of attack and roll programs).

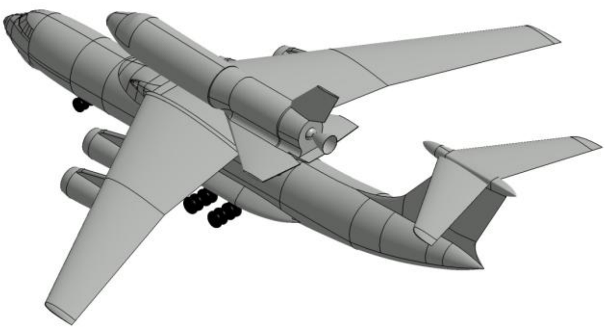
An important advantage of winged orbital vehicles is the possibility of not only launching to orbit but also recovery of payloads of large mass and dimensions. These may be artificial earth satellites, units and subassemblies which are aimed at providing transport maintenance of space stations and aircraft. Winged orbital vehicles will perform operations connected with assembly on the orbit, removal of space debris, return of satellites for repair on the Earth, as well as provide operations on space manufacture of unique materials on the orbit, functioning of solar power stations and orbital complexes intended for flights to other planets.

To realize these tasks it is necessary to use the demonstrators of key technologies providing time and costs reduction in creating highly efficient high-speed vehicles (Fig. 6).

Suborbital ASSH (USA) incorporating subsonic carrier-aircraft $WK_2$ and ASA-Space Ship2 $N_p$=2-8

Suborbital ASSH C-XXI with carrier-aircraft "Geophisics" (Myasischev experimental plant) $G_{ASA}$=3,5 t; $N_p$=2; $M$=4-5

Suborbital ASSH (TsAGI) incorporating Il-76 + ASA with rocket engine $G_{ASA}$=50 t; $G_{st}$=210 t; $N_p$=8-12; $M$=22; $L$=16000 km



Orbital ASSH MASS (DB "Molnia" $G_{ASA}$=27 t; $G_{st}$=625 t

Fig. 5. Suborbital and orbital aerospace systems with horizontal start

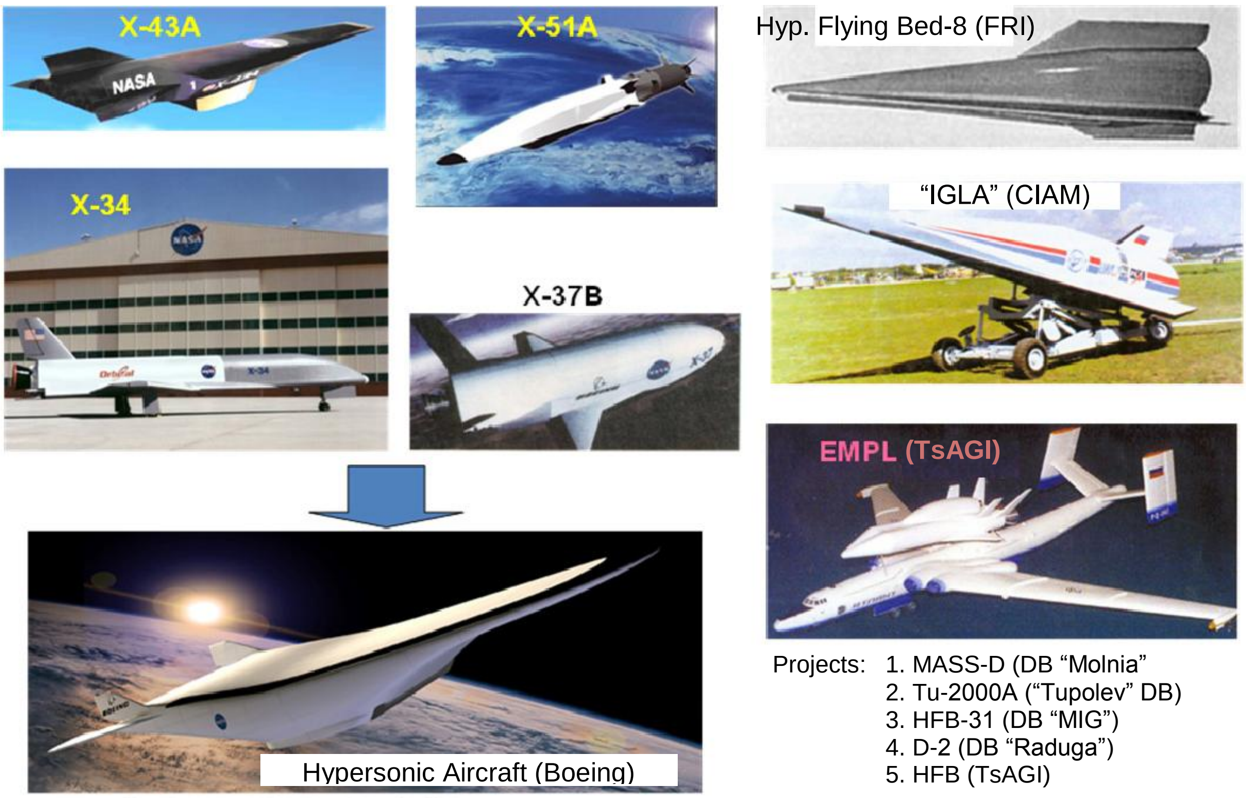



Fig. 6. Experimental studies of HSV

Table 2

Comparison of catastrophic launches for expendable rockets and reusable aerospace systems

| Systems | Heavy expendable foreign rocket systems | Russian expendable rocket systems | Summary amount of launches/catastrophes (expendable rockets) | Reusable aerospace systems (vertical and horizontal starts) | Summary amount of reusable launches/ catastrophes |
|---|---|---|---|---|---|
| Time period | 2000-2010 (10 years) | 2000-2010 (10 years) | | 1981-2011 (30 years) | |
| Launches/ catastrophes | 88/2 | 94/5 | 182/7 | SS EB Peg. X-37B 135/2 + 1 + 38 + 2 | 176/2 |
| Catastrophes | | | ~4% | | ~1% |
| Payload weight/ Start weight | 2–3% | | | 0,75–3,5% (ASSV) | |

An interesting comparison of the data of expendable launchers and reusable systems built in the world has shown that for a similar sample of the number of starts of heavy expendable launchers during 10 years and ASSV and ASSH for 30 years the incident rate of the reusable systems is approximately by 3-4 times lower than that of expendable vehicles, while an expected weight efficiency ($m_{pl}/m_{start}$) is higher [22], [24]. At the same time this is possible to reduce the regions of fall (or with their absence) and to increase economic efficiency of reusable systems as compared with expendable launchers.

It is evident that in spite of the increased complexity of reusable systems and time of development, their advantages will be revealed thanks to thorough mastering the vehicles and owing to the experience accumulated by aviation in development and operation of different types of aircrafts.

## 5 Conclusions

1. Flight endurance for modern subsonic and supersonic cargo-passenger aircraft designed for long range (L>10000–15000 km) exceeds 8–20 hours.
2. Long range of flight (L>10000–15000 km) may be realized by three types of high-speed vehicles:
   – HSV cruising in atmosphere (hypersonic aircraft, hypersonic vehicle);
   – suborbital (ASS, ASA);
   – orbital (ASS, ASA).
   
   In this case the endurance of HSV may reduce up to 1–1.5 hour, which is important for quick traffic activity, monitoring of the Earth surface in case of nature and technogenic catastrophes in the world, as well as for the struggle against terrorism and for the needs of the Ministry for emergency situations.
3. The requirements for advanced aerospace systems are as follows:
   – high level of technologies;
   integrated multidisciplinary methods for design;
   – reliable verification of all onboard systems and HSV characteristics by ground and flight tests of key technologies in wind tunnels, on specialized test rigs and on scaled and full-scale demonstrators;
   – high aerodynamic characteristics of HSV configuration (up to $K_{hyp}$ = 5–7 at M = 10);
   – significant increase in scramjet characteristics (to $I_{sp}$ ~ 2500–3000 s at M = 10);
   – reduction of high cost caused by the ASS carrier-aircraft and ASA scramjet;
   – lowering the risk due to the uncertainty of characteristics of HSV scramjet, structure, thermal protection and equipment.
   
   Suborbital ASS and ASA using liquid-propellant rocket engines have minimum time and risks of development.
4. Advanced ASS, ASA and hypersonic aircraft make it possible to considerably widen the spectrum of tasks being solved, to speed up exploration of the Earth atmosphere and near space providing high-speed cargo-passenger transportation, monitoring of the Earth surface and interests of the Ministry for emergency situations.

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