Reviewing paper:

The Task of Replacing American Orbiter by Small Space Plane *

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Following the recommendation of admiral Hal Gehman, the chairman of CAIB (Columbia Accident Investigation Board), to replace the USA shuttle as soon as possible, the NASA issued the Orbiter Space Plane Requirement Level 1 and organized a Design Review concerning the proposals of The Boeing Company on one hand and of the group Locheed Martin, Northrop Grumman and Orbital Sciences Corporation on the other hand. The general tendency is to design a vehicle mainly oriented to the transportation of the ISS crew as well as for evacuation and rescue operation when necessary. This vehicle would be named CTV (Crew Transport Vehicle). It should be of a reasonable size, should be capable to make a lateral shift during its descent from the orbit and should be able to choose the location of its landing inside limits.
The many problems resulting from the small size of the CTV are known: aerodynamic attitude control at very low density-rarified gas-altitudes, molecular recombination in dissociated air, center of gravity location and equipment outfitting, increased local heatfluxes, etc. The solution of which is not assured at the present state of art.

Keywords: *Orbital Space Plane, re-entry, effect of aerodynamic shape, effect of aerothermal heating, size effect.*

1. INTRODUCTION

The publication of the American Commission investigating the Columbus shuttle disaster (CAIB) was followed by its chairman admiral Hal Gehman statement : "It is in the interest of the nation to replace the Space Shuttle as soon as possible".

His suggestion was accepted and the first efforts concerning the *OSP (Orbital Space Plane)* could be formulated as " *What to do and how to replace the existing space planes-orbiters with a new transporter space vehicle?"*. Based on the tactical and technical requirements prepared for OSP and at a specially organized workshop, NASA has evaluated concepts prepared by two competiting groups: The Boeing Company on one hand and the group Lockheed Martin, Northrop Grumman and Orbital Sciences Corporation on the other hand.

Four concepts were presented and evaluated: ballistic capsule (Fig. 1), lifting body (Fig. 2), sharp body (Fig. 3) and wing body (Figs 4 and 5). The capsule configuration was considered because of great experience obtained from numerous space programs with human crews and its simple balancing during the re-entry from the orbit as well as simplicity of its manufacturing and integration with the rocket-carriers. The two disadvantages of this configuration are:
1° The descent trajectory from the orbit remains in the same plane;
2° The low aerodynamic finesse $C_L / C_D \approx 0,2$ (C_L - lift coefficient, C_D-drag coefficient) is insufficient to provide an adequate protection to the crew from stress characterized for the pure ballistic descent from the orbit. The advantage of capsule configuration lies in the capability to transport the material essential for the functioning of the space station (containers with experimental materials, food, drinks, astronaut's suits and etc.) and by using the automatic guidance and docking to the station. Following the unloading of the cargo, the capsule is used to remove the waste products from the station and burn it with the capsule when entering dense stratospheric layers.

The concepts of the other three configurations are aimed to improve the aerodynamic finesse of the plane : reducing the loading factor and ability to descent outside the trajectory plane. This enables landing at different recovery airfields. The main purpose of such a flying vehicle will be the transportation of astronauts while the essential cargo (space station equipment, spare parts and etc.) will be limited by both mass and volume. In the case of emergency evacuation of the space station, this vehicle could accommodate the total of 7 astronauts. This is the reason why it is called CTV

Received: February 2003, accepted: September 2004.

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* The text of the paper represents in the most part the translation of the corresponding text of the same author published in Serbian, in "Tehnika", No 2, 2004, ref. [5].

(Crew Transport Vehicle). Lifting to orbit this specific type of small orbiter should be realized using the existing rocket-carriers. The concept, design, fabrication and maintenance of such category of space vehicles contain many specific difficulties that should be taken into account. These are discussed in some detail in this paper.

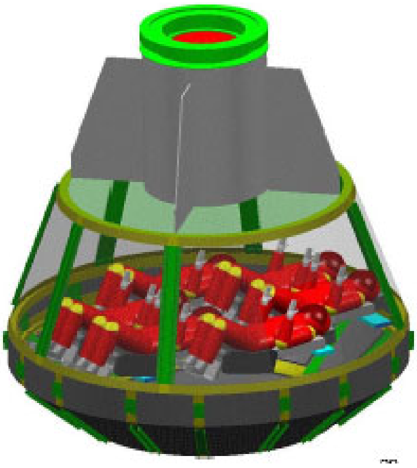

Figure 1. Balistic capsule

NASA Dryden Flight Research Center Photo Collection
http://www.dfrc.nasa.gov/gallery/photo/index.html
NASA Photo: EC99-44921-1 Date: 1999

X-33 artist concept - 1999

Figure 2. Lifting body

Figure 3. Sharp body

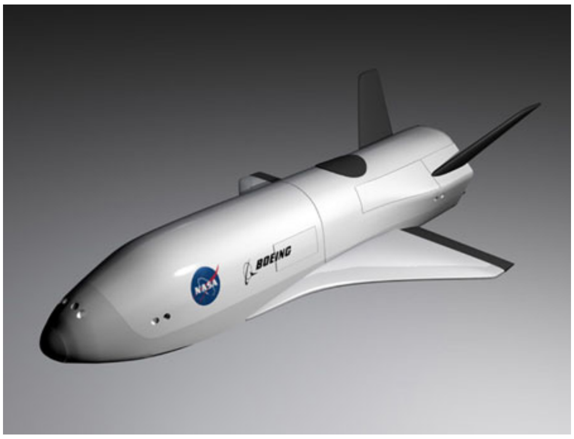

Figure 4. Wing body

Figure 5. Wing body

2. EXISTING EXPERIENCE

In all phases of flight, the experience with vehicles using the lift surfaces is limited to the American Shuttle Orbiter and the Russian orbiter Buran. Numerous studies, tests in aerodynamic tunnels and laboratories enabled to establish and improve different mathematical models in all forms of activities of the system and subsystems. It could be concluded that there is an ample knowledge for the design of such a vehicle.

The question arises as to whether the accumulated knowledge and experience could be applied to ongoing different pre-projects for CTV vehicle? If we consider the concept of the vehicle itself, the answer is no : in a wide and multidimensional domains of parameters controlling the flight of an orbiter returning from the orbit, the American Space Shuttle and Russian Buran have very similar combination of important parameters and their similarity is not only in aerodynamic form but also in the nature of the material used for their construction.

Outside this domain that can be called a singular point, the rest is "terra incognita". Bearing in mind that the present tendency is in the construction and realization of winged vehicles substantially of smaller size, what other difficulties the reduction of the vehicle dimensions could cause that have not been solved by what has been already achieved and what should be realized?

3. PERFORMANCE AND FLIGHT REQUIREMENTS

Minimal requirements that a CTV vehicle should meet are :

- Lateral shift in respect to orbital plane : > 1000 km,
- Stability (or moderate instability) around the three axes of the vehicle,
- Landing speed not greater than 110 m/sec (396 km/h),
- Capability to land on airfield tarmac < 3500 m,

Heating of the load structure in accordance with the characteristics of materials approved for the space use.

The requirement for the lateral shift in respect to the orbital plane can be satisfied only if the space vehicle has the wings whose lift combined with the fuselage lift exceeds considerably the vehicle drag in hypersonic as well as supersonic and subsonic flight regimes.

The lateral shift is very important factor for the safety of crew and vehicle : the crew can decide where is the most convenient location to land and not obliged to follow the descent trajectory in the orbital plane. In case of emergency, the space station can be abandoned without risk to land anywhere and under any conditions. However, this means that the aerodynamic characteristics have to secure adequate lift/drag ratio in a range of Mach numbers and to counteract many phenomena encountered during the descent from the orbit that, in turn, become very important issue for small vehicles. Here we shall discuss the most important aspects.

4. RE-ENTRY. AERODYNAMICS AND AEROTHERMAL PHENOMENA

The safe re-entry from the orbit requires a total control of the space vehicle around its three axes. The initial control is realized by small liquid fuel rockets where their thrusts provide the correction moments around the main vehicle axes. Although the aerodynamic rudders are activated early in the re-entry, their stabilizing action becomes more and more pronounced as the air density increases. The combined action of rocket jets and aerodynamic rudders can be prolonged even during the re-entry into the dense atmospheric layers and, a priori, to the landing as long as the fuel load permits.

During the initial descent the air molecules break down, ("dissociated gas"), small size vehicles can cause serious difficulties in the control of its optimal positioning in respect to the speed vector. In this zone the air is so thin that despite high speed the Reynolds number is very low and consequently the boundary layer is very thick. The shape of the shock wave and aerodynamics coefficients are not affected by the aerodynamics of the vehicle surrounded with the thick boundary layer (proportionally thicker for the small vehicle in comparison to the American Orbiter and Buran). The use of rocket jets for maintaining the vehicle position in space is essential but their efficiency (for their location within the vehicle and means for regulating their flow) is not assured. The moments created by jets thrust around the vehicle axis are known (small vehicle, small moments) but the dominant force generated by the jets depends on the intensity of interaction between the exhaust jets and the flow of dissociated gas in the thick boundary layer. This phenomenon can even cause the appearance of local shock waves and thus change the global aerodynamic forces and moments. It is unlikely that phenomenon can cause divergence.

Aerodynamic tunnels, developed and specifically suited for the fundamental research, are unlikely to provide the valuable results. The lack of "industrial" aerodynamic tunnels is a very serious problem. In small working sections of the research aerodynamic tunnels, where the size of a model for small winged flying body of size of European Hermes does not exceed 1:100, whereas the nitrogen flow simulating the effect of the rocket jet in hypersonic stream should correspond to 1:10 000! Under these circumstances the question is what similarity criteria to be used? How to determine the vehicle behavior during the descent from the orbit at altitudes 120-40 km? How to make sure that the above mentioned phenomena will not cause loss of control of a small vehicle and thus to avoid chaotic tumbling during a free fall towards the Earth, its burning and death of crew? It should be borne in mind that during the first flight of Space Shuttle Columbia, the required body flap deflection, essential for longitudinal balancing of the vehicle, was insufficient even though it was determined by calculations and experiments carried out in the aerodynamic tunnels. Fortunately, the flight control designer was smart enough to secure the body flap deviation commonly used in the aviation that was found to be sufficient.

This incident substantiates again the fact that activities carried on Earth cannot be strictly used since the risk during the first flight would be enormous. The Russian have recognized this problem and the first and only flight of Buran was without a crew. The automatic guidance was functioning flawlessly even during the final phase of the descent. Results of many measurements helped to improve the calculation models that were used to analyze the "response" of a complex aerodynamic shape in flight. It should be pointed out that only the scale 1:1 gives reliable results. Different reduced size flying models are always attractive orders for the space industry, but, due to complex actions of many parameters and inability to select the aerodynamic similarity criteria, the use of reduced scale models provides no reliable improvement for calculation models used for the full size vehicle.

In addition to the above mentioned effect of the boundary layer, there is also a problem of dissociation. The dissociation of oxygen and nitrogen molecules in the zones with high temperatures, i.e. near the stagnation points reaches 7000 K, does not occur simultaneously nor under the same conditions ; this problem becomes even more important when associated with the "chemical kinetics". The change in gas state occurring behind the shock wave is not instantaneous :

different directions along an aerodynamic body "encounter" the dissociated gas with different R, c_v, c_p characteristics (R-gas constant, c_v-specific heat at constant volume, c_p-specific heat at constant pressure). In aerodynamic tunnels with high enthalpies the hot gas is introduced into the working section in the disassociated state, which represents only an approximation of the real phenomenon. In this case, difference in the orbiter size (where effects of this phenomenon were not measured but were considered) and one future small plane could play a very important role.

The interaction between aero thermal process and materials used to provide thermal protection of the plane as well as the heated structure (silicon-based ceramics, composites C-C) could, under given conditions, be a suitable catalyst leading to the re-composition of gas molecules and thus introduce the heat into the plane structure. Finally, transition from laminar into turbulent boundary layer leads to the interaction between the shock wave and the boundary layer, and separation and re-attachment of the boundary layer in the hypersonic flow around the complex-shape body. The small size rises questions for which there are no readily available answers.

In summary, in order to design space vehicle with substantially smaller dimensions than that of the American Orbiter and Russian Buran, a number of activities from the aerodynamic point view should be imposed on both fundamental research aimed at understanding the mechanisms of observed phenomena and on the aerodynamic design and shape optimization of the plane itself.

5. EFFECT OF AERODYNAMIC SHAPE

One essential problem that is caused by the small size of the plane is the need to strictly adhere to the accepted and optimized aerodynamic shape.

The plane is designed without the horizontal tail and this concept allows only slight shift in the center of gravity in order to secure the stability (or acceptable instability) around three axes over the entire range of Mach numbers. The plane inner should conform to not only the functional requirements imposed by the manned space mission but also to the installation of subsystems and payload in order to meet the required center of gravity. This requirement does not appear difficult to satisfy in the design stage but the reality is completely different ; the plane subsystems and their equipments have not only the mass but also a volume. This volume, increases by the need to provide room for electrical cables and connections, piping for distribution of different fluids, internal thermal insulation...etc. It can easily exceed the allowed space in the plane.

In the worst case, when the available space is accepted to barely comply with the requirements for distribution of mass and volume of equipments, the price paid for doing this is sacrificing the easy access to subsystem elements during maintenance and post flight inspections. Such a situation may require disassembling of one or two elements of any given subsystem to make access to the other subsystem elements requiring the replacement or repair. This is followed by the inevitable checking of the functioning of the mentioned subsystems as well as their incorporation into the plane system level. If the planning and cost for such an intervention are fixed and blocked, the reliability consequences and functional safety of the plane become extremely unacceptable.

In the case that it is inevitable to increase the plane size, this may lead to new difficulties :

- If it is essential to preserve the aerodynamics and thus required aerodynamic characteristics, increasing the size can only be realized in accordance with the homothetic principle that inevitably leads to an increase in the mass of the structure and of the thermal protection. This jeopardizes the compatibility of such plane with the rocket-carriers.
- If it is essential to increase the available volume (mainly in the fuselage). This requires shape changes which, in turn, affects the aerodynamic characteristics and definitely reduces the finesse and lateral shift and increases the already high landing speed. In doing so, the plane mass is increased but this consequence is rarely evaluated in terms of its real importance : experience has shown that the envisaged mass augmentation of a flying object is always inversely proportional to the optimism used to make the decisive changes.

6. EFFECT OF AEROTHERMAL HEATING

The heating of the plane structure and thermal protection represent considerable problem that are difficult to solve for a winged plane. The descent trajectory from the orbit cannot be of any form ; there is a law relating the flight altitude with the velocity along the trajectory in the domain :

$$0 < H < 120\,\text{km}$$

$$0,4 < v < 8\ \text{km/s}$$

The plot $H = f(v)$ with a zone of tolerance of the parameters discussed, represents the re-entry "corridor" which is somehow specific for any given plane. By flying in this corridor, the plane is not expected to loose either the control around three axes (small values of $\mathrm{d}H/\mathrm{d}v$) or to burn (high values of $\mathrm{d}H/\mathrm{d}v$). In the determined corridor the plane size plays decisive role : the smaller the plane the higher is the heating. This can even reach the limiting values beyond which the available technology is no longer applicable. This is because of the following reasons :

Size effect.

In the hypersonic part of the descending trajectory, the zones most exposed to aerothermal heating are those with high pressure coefficients C_p, especially the shock wave around the wing leading edge, the plane nose and the lower body part, that is the elements that contribute to the lift. In order to determine the order of magnitude, the leading edge can be approximated as a cylinder in a flow field perpendicular to its axis, whereas the body nose as a sphere. A number of tests in the "hot" aerodynamic tunnels lead to the conclusions that the size of upstream aerothermal flux depends on the radius of the cylinder or sphere : under the same experimental conditions, the smaller the radius the higher the aerothermal flux. This phenomenon is defined by the following relationship:

$$\Phi = \Phi' \sqrt{R'/R}$$

where Φ' is the flux measured on the calibrated body, R' is the radius of the calibrated body and R is the radius of the tested body.

Assuming that the leading edge radius of the small plane is nine times smaller than leading edge radius of the Orbiter, the upstream aerothermal flux at the wing leading edge of a small plane will be three times larger! One can ask a question, what would happen to leading edge knowing that the number of missions for the Orbiter wing leading edge was reduced from 100 to some 55 before the Columbia disaster? The temperature higher from the anticipated one was probably the main reason. It is also possible that the heat transfer from the leading edge to the metallic structure of Orbiter was smaller than estimated.

Mass Effect of the Plane Structure.

Since the anticipated plane has a small mass, the mass of this structure will also be small. However, this structure plays a very important role in the overall thermal balance of the plane as a "heat sink" and the temperature can reach and even exceed the critical values of the material used. For instance, the maximum temperature of the metallic structure of the Orbiter, at critical point is 165°C (this is in agreement with allowable values for the alloys at this location). This temperature is reached ½ hour after landing and is due to thermal inertia of the Orbiter structure. However, according to certain estimates for the European orbiter Hermes, its "warm" structure, composed of resin BMI and fibers C, reaches the temperature of 200°C at the altitude of 20 000 m, at the entry of the plane into turbulent stratospheric layers. As far as the temperature of the wing leading edge is concerned at thermally the most sensitive location, it was somewhat reduced due to the changes in the wing plane shape.

There is no doubt that the critical point in the development of winged space vehicles is the lack of materials resistant to very high temperatures as well as the complete technology for the production, control and repair of such vehicles. Development of such technology should be the goal in itself : any attempt to initiate its development in parallel with development of the space vehicle should be avoided by all means. This is because in such a situation the results obtained will be incomplete, many important parameters will not be elucidated, program restrictions (planning, finance) will be placed at the front thus depriving complete certification of the technology used. All half-reached decisions will be costly, if not immediately, then certainly later. Following the disaster, the investigating commission will have to determine the list of what had not been done and what should have been done, what had been ignored and what should not have been ignored.

7. CONCLUSION

From the technical point of view, the development and certification of a small winged space vehicle represents an important and interesting challenge, particularly for the technical teams that have to learn and to carry out. The progress can be achieved only by acquiring new knowledge and experience as well as eliminating the barriers in front of the anticipated goal. Penetration the "terra incognita" and illuminating the "dark areas" is a dream of all researchers and engineers. Such a noble dream merits to be respected.

The romantic vision must go along with a more pragmatic and practical activities of the space industry. Design offices and many laboratories has to be supported continually by large programs (since such complex structure cannot live on a day to day activities). The capacities should be maintained not only in the knowledge but also in the manpower whose existence has to be assured.

When discussing the development of a small space plane as a replacement for the three remaining American Orbiters, this endeavor would be more expensive because :

The development period should be at least 8 years provided that the technology of materials resistant to high temperatures and having specified mechanical characteristics are developed and certified.

The use of such a space vehicle will be limited to Earth orbits ; this type of space vehicle would not be of any interest for missions towards other planets with low or without atmosphere.

The maintenance of the space station ISS, which is destined to remain for many years as the only station in the Earth orbit, will require significantly fewer missions than originally planned 10 – 15 years ago. This because despite all the efforts no economically viable activity was identified that would attract new and expensive investments for the connection with Earth. Today the Russian capsule "Soyuz" is the only available connection between Earth and ISS ; in few years it will be replaced by another one with larger capacity and better adapted for the transportation of astronauts. Concerning the material supply, this role is already fulfilled by the Russian automatic capsule "Progress" and this situation will most likely remain in the future.

Our conclusion is that the fate of a small space winged vehicle CTV (Crew Transport Vehicle) is doomed. It is bad for the aerodynamics, for lateral shift and landing to airports and also, for the culture and habits of transport aviation, which somehow wanted to move into the space.

In the future, the newly developed capsules could be used to send astronauts and supplies to other planets. Anyhow, the main investor, Uncle Sam, is turning his back to the space station ISS and is aiming at the Moon and the planet Mars.

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ПИТАЊЕ ЗАМЕНЕ АМЕРИЧКОГ ОРБИТЕРА ЈЕДНОМ МАЛОМ СВЕМИРСКОМ ЛЕТИЛИЦОМ

Ненад В. Хрисафовић

У раду је дат научни и стручни осврт на тренутно стање и перспективе орбиталног транспорта и снабдевања Међународне орбиталне станице који су настали после катастрофе првог свемирског орбитера ”Колумбија”. У раду су анализирана четири могућа концепта орбиталних летелица: 1- балистичка капсула (ballistic capsule), 2- узгонско тело (lifting body), 3- оштро узгонско тело (sharp body) и 4- једна крилата летелица (wing body) са главним проблемима који се јављају при повратку из орбите, укључујући проблеме аеродинамичког загревања, ефекте размере летелице и аеродинамичког облика орбиталних летелица.