Aerothermodynamics calculation of thermal destruction of “Fregat” upper stage at descent in the Earth’s atmosphere

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The engineering calculation method has been developed for investigation of the process of thermal destruction of “Fregat” upper stage at deorbiting and descent into the Earth’s atmosphere. The results of calculation of its descent trajectory and characteristics of aerodynamic heating are presented. Within the framework of the thermodynamic approach, the authors investigated the process of pressure increase in the tanks due to heating and evaporation of the liquid phase of fuel. Stresses in the shells, the height and the energy equivalent of explosive destruction of tanks were calculated depending on the degree of their filling with remains of the components of liquid fuel.

Keywords: upper stage “Fregat”, atmosphere of the Earth, the trajectory of descent, aerodynamic heating, fuel tanks, vapor pressure, stresses in the shells.

Introduction

Currently, following the requirements of environmental legislation in many countries, much attention is paid to the assessment of the impact of rocket and space technology on the environment. The negative consequences of space-rocket activity are anthropogenic and chemical contamination of lands in the areas, where parts separating after the apparatus launch fall, and toxic residues of liquid rocket fuels are dumped, as well as destructive effect of the structural elements of rocket and space technology at their reaching the Earth’s surface.

To meet the challenges of payloads orbiting along with the carrier-rockets the upper stages are used. They function as interorbital tugs, providing spacecraft (SC) moving from reference to the target orbits, their orientation and direction to departure and interplanetary trajectory.

Among such upper stages there is “Fregat” (USF) developed in the Lavochkin RPU and used as a unified upper stage of rocket carriers of medium and heavy class. The possibility of multiple actuation of a cruise propulsion system and a flexible control system based on onboard computer provide USF with ample opportunities for distributing the loads among different target orbits. USF allows orientation and stabilization of the head unit in the active and passive parts.
of the trajectory and orbiting spacecraft into high, geostationary, geosynchronous transfer and polar sun-synchronous orbits.

The first launch of USF as part of the carrier rocket “Soyuz” was successfully implemented in February 2000 according to the flight test program. Over the past period, USF was launched 32 times and showed absolute reliability [1]. Application of USF and its modifications can solve the previously inaccessible problems on the masses and orbits of the distributed loads and increases the competitiveness of Russia in the international market of space services. In particular, in addition to launching Russian and foreign spacecraft from the Russian cosmodromes, USF within the rocket-carrier “Soyuz” is used for launches from Kourou in French Guiana to deploy a satellite navigation system “Galileo”, and to launch other spacecraft.

After the completion of USF mission in near Earth space its removal from the working orbit and the controllable entry into the Earth’s atmosphere are provided for sinking in the preset area. During descent USF is exposed to aerodynamic heating, and as a result a significant part of its elements is burnt in the atmosphere, and some part may reach the Earth’s surface.

To predict the possible areas of chemical contamination and falling of incombustible parts of USF we must know the parameters of the initial phase of its thermal destruction: the height and nature of the damage, the list of fragments, velocity and mass of the fragments after initial destruction of USF, their trajectory angles, etc. These data are used as a baseline for calculating the trajectory parameters, further changes in the mass of individual fragments and the velocity of falling of incombustible parts of USF on the Earth’s surface.

The process of USF destruction depends on many factors and may occur under different scenarios. The worst of them is explosive destruction, which leads to an undesirable increase of the area of USF fragments dispersion. This, in particular, results from the inevitable presence of residues of the components of liquid fuel in the USF tanks. With their evaporation due to heating the pressure increases, and stresses in the tanks may exceed the tensile strength of the shell material, resulting in possible destruction of tanks, mixing and the explosive reaction of high-energy components of fuel and oxidizer.

The objective of the present work is to develop the engineering calculation method for studying the process of thermal destruction of USF and to determine the trajectory parameters at the time of destruction due to aerodynamic heating of the fuel tanks at deorbiting and descent into the Earth’s atmosphere.

**Main characteristics of USF**

The constructive basis of USF is a block of tanks of cruise propulsion system [1, 2] performed in the form of six jointly welded metallic spheres of equal diameter (see Fig. 1) made of alloy AlMg-6. Four of them are used as fuel tanks (in twos for fuel and oxidizer), and two — as module sections. USF dimensions are: height is 1.6 m and diameter (described) is ~ 3.36 m. Diameter of fuel tanks is ~ 1.36 m, volume is ~ 1.306 m$^3$, the shell with thickness $\Delta = 1.85 \times 10^{-3}$ m made of aluminum alloy. Maximum weight of USF filled with fuel is ~ 6780 kg, and dry one is ~ 941.5 kg. Cruise propulsion system of USF runs on toxic autoignite fuel components “fuel ADMH — oxidant NT”.

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*Fig. 1. “Fregat” upper stage appearance.*