The object of this study is the process of disposing of the upper stage body of a launch vehicle made of polyolefins by burning in the dense layers of the Earth's atmosphere during removal from Earth orbit. The task addressed was to determine the possibility of disposal of the upper stage bodies of launch vehicles made of polyolefins during deorbiting.

The mathematical model built makes it possible to take into account the effect of ballistic and aerothermodynamic aspects at the same time. The application of this model makes it possible to estimate the degree of disposal of the upper stage bodies of launch vehicles made of polyolefins in the Earth's atmosphere at the stage of scientific research. In turn, this makes it possible to rationally choose the design parameters of materials for launch vehicle bodies, taking into account the disposal phase in the dense layers of the atmosphere, as well as rationally select the initial parameters for deorbiting orbits. This makes it possible to maximize the level of disposal and minimize the probability of debris falling on uninhabited areas of the Earth.

The results of the study showed that launch vehicle bodies made of polymer materials such as polyethylene and polypropylene could burn up in the atmospheric part of the trajectory by 90–100 %, depending on the mass-dimensional characteristics and the type of orbit. In turn, increasing the ellipticity of the orbit makes it possible to increase the steepness of the entry of the upper body of the launch vehicle into the dense layers of the atmosphere, and hence, to increase the heat flows that contribute to the combustion of the body. With this in mind, methodological recommendations have been compiled for choosing orbits of the necessary ellipticity, taking into account the place of fall of fragments of the upper bodies of carrier rockets that did not burn up in the atmosphere

Keywords: disposal of the launch vehicle body made of polyolefins, mathematical model of deorbiting, influence of heat flows on the heating of the body, atmospheric section of trajectory, extra-atmospheric section of the trajectory

UDC 629.7

DOI 10.15587/1729-4061.2025.319437

ESTIMATING THE DEGREE OF DISPOSAL OF A LAUNCH VEHICLE CASING MADE FROM POLYOLEFINS IN THE EARTH'S ATMOSPHERE

Mykola Dron'
Doctor of Technical Sciences, Professor
Department of Rocket and Space and Innovative Technologies*

Erik Lapkhanov
Corresponding author
Doctor of Philosophy, Senior Researcher
Department of System Analysis and Control Problems
Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and the State Space Agency of Ukraine
Leshko-Popelya str., 15, Dnipro, Ukraine, 49600
E-mail: ericksaavedralim@gmail.com

Aleksandr Golubek
Doctor of Technical Sciences, Professor
Department of Cyber Security and Computer-Integrated Technologies*

Andrii Dreus
Doctor of Technical Sciences, Scientific Consultant
Promin Aerospace
H. Skovorody str., 5A, Kyiv, Ukraine, 04070

Olena Kositsyna
PhD, Associate Professor
Department of Analytical Chemistry and Chemical Technology*

Ludmila Dubovik
Senior Researcher
Research Institute of Energy Efficient Technologies and Materials Science*

*Oles Honchar Dnipro National University
Nauky ave., 72, Dnipro, Ukraine, 49010

Received 06.10.2024
Received in revised form 03.12.2024
Accepted 20.12.2024
Published 05.02.2025

How to Cite: *Dron', M., Lapkhanov, E., Golubek, A., Dreus, A., Kositsyna, O., Dubovik, L. (2025). Estimating the degree of disposal of a launch vehicle casing made from polyolefins in the earth's atmosphere. Eastern-European Journal of Enterprise Technologies, 1 (1 (133)), 33–43. https://doi.org/10.15587/1729-4061.2025.319437*

1. Introduction

The use of composite and polymer materials in the rocket and space industry is a rather promising direction. The main advantages of their application include:

1) weight reduction by 20–40 % compared to the use of metal structures [1];

2) preservation of strength properties, as in metal structures [2], as well as, under certain conditions, their improvement;

3) lower energy costs for production compared to metal alloys;

4) reducing the cost of manufacturing objects of rocket-comic equipment.

All this leads to a steady increase in the number of devices, nodes, and assemblies for objects of rocket and space technology, made with the use of composite and polymer materials, over the last decades [3]. The advantages of polymer materials are explained by their properties, which could be represented in the form of the following comparative table with other analogous materials [4]. Thus, according to [4], the main advantage of using polymer materials is lower density with similar, and in some cases, greater strength. In comparison with the AMG6 alloy, the density of polyolefins is more than two times lower, with titanium alloy – by more than four times, with steel – by more than seven times. However, the disadvantage of polymer materials is a significant decrease in strength properties under conditions of increasing temperature.

Thus, according to [1–4], it could be concluded that polymer-based composite materials have better strength properties than metal-based alloys. This led to their introduction into the components and assemblies of modern rockets and satellites. However, the production of composite materials is a rather complex and expensive process. Given this, paper [4] analyzed the possibility of using polyolefins as alternative materials for the manufacture of shells of autophagic rockets. Among such materials, polyolefins such as UHMWPE, PE-X, and PP are singled out.

In addition, works [5–7] put forward a hypothesis and carried out a scientific justification [4, 8–11] of the possibility of using polymer materials of the polyolefin type for the manufacture of hulls of launch vehicles of the ultralight class. These materials are more accessible and cheaper than composite materials, which is a significant advantage when resources are limited. According to the recommendations of the International Convention on the Non-Proliferation of Space Debris, the upper stages bodies (USBs) of LVs must be removed from target orbits. One of the widespread directions of this process is removal to remote areas of the Earth's surface. Under these conditions, part of LV UBs burns in the dense layers of the atmosphere, with the drop of some refractory parts to the Earth's surface.

All of this renders relevance to research aimed at minimizing the parts of LV UBs with a polymer casing, which in the process of deorbiting could reach the surface of the Earth, with the minimization of the size of the fall areas. Particular attention should be paid to the construction of a generalized mathematical model of thermodynamic processes in LV UBs from the polymeric casing during deorbiting. Its application makes it possible to assess the degree of disposal of LV UBs in the process of removal to remote areas of the Earth's surface at the stage of scientific research.

2. Literature review and problem statement

In [4], an in-depth analysis of the physical-chemical characteristics of polyolefins was carried out in view of the possibility of application in rocket and space technology (RST). It is shown that materials such as UHMWPE, PE-X, PP are promising for the manufacture of casings of autophagic rockets. However, no studies on the influence of resistance force of the Earth's atmosphere on the integrity of structures, their heating, and ablation have been conducted.

In turn, in earlier studies, ground-based experimental testing of the autophagic propulsion system of LVs under various operating modes was carried out [7]. The justification of feasibility of using polypropylene as a fuel component of autophagic LVs was carried out. Also, it is stated that the strength characteristics of polypropylene are suitable for the manufacture of a thin casing shell. However, these tests were conducted for other types of materials, and the main focus was on the analysis of their use as fuel for autophagic LV. In addition, the question of analysis of the heating of LV body in the dense layers of the atmosphere was not considered.

In further studies [9], analysis of features of the aerodynamic heating of the surface of LV bodies made of thermoplastic polyolefins – polyethylene and polypropylene – was carried out. As a result of experimental and theoretical studies, it was determined that these materials meet the conditions of heat resistance during movement in the atmospheric section of the flight path during launch into orbit. In turn, during the movement of LV UB in the dense layers of the atmosphere in the section of the trajectory of deorbiting, its velocities are significantly higher than the trajectories of removal. Given this, the influence of thermal factors on the strength characteristics of LV UB would increase significantly. However, no analysis of the heat resistance of such materials on the removal path was carried out, which does not make it possible to determine the degree of their disposal.

In [10], the issue of designing the structure and ballistic parameters for an ultralight LV of variable length was considered in order to ensure acceptable thermal loads on the body structure in the atmospheric part of the trajectory. The fundamental possibility of using polyolefins as structural materials and fuel for the casing is substantiated. It is shown that in order to ensure an acceptable thermal regime of the structure, it is necessary to use thermal insulation from polymeric Teflon coating. But the influence of thermal regimes in the process of cessation of existence was not considered. This is explained by the fact that the polyolefin components in the case of the use of autophagic LV serve as fuel for DU and do not require disposal in the dense layers of the atmosphere.

In turn, in work [11], the authors conducted a study aimed at evaluating the possibility of using a variable-length LV from a lightweight polymer body to launch a payload on a suborbital trajectory. It is shown that polyolefin housings could withstand thermal loads well in the atmospheric part of the trajectory of the launch of LV into orbit. However, the aspects of removing the bodies of such rockets from orbit were not considered.

Thus, in a series of studies [4, 7–11], a comprehensive justification of the expediency of using polyolefins for the production of tanks for autophagic LVs and ultra-light LVs was carried out. However, the emphasis in those works is at the analysis of effectiveness of the use of polyolefins as fuel components and the analysis of heat resistance of these materials on the trajectories for launching the payload into orbits. Deorbiting and disposal processes were not considered since the main goal was research on providing reliable LVs with structural components from polyolefins for launching spacecraft into orbits.

Another example of the use of polymers for spacecraft is research on the possibility of applying inorganic polymers as components for designing optical systems for Earth remote sensing satellites [12]. The results of the study showed that geopolymers meet the minimum requirements for the stability of physical properties under the conditions of the initial impact of the space environment, namely in vacuum and when heated. However, no analysis of the physical properties of these materials during the movement of space vehicles in the dense layers of the atmosphere was considered. This is explained by the fact that in the phase of active operation, these optical systems are intended for use when moving in the rarefied upper atmosphere of the Earth.

In turn, when designing aerodynamic systems for deorbiting the class 1U, 2U, 3U cube sats, polymer materials such as Kapton were also used [13]. An inflatable mini aerostat, a packaging and unfolding device, as well as an electronic control unit for an inflatable aerodynamic diversion system have been developed. But no study of combustion in the Earth's atmosphere was conducted. This could be explained by the fact that ultra-small spacecraft would in any case burn up when moving in dense layers of the atmosphere, taking into account their size, mass, and types of component materials. This is explained by the fact that such film materials are quite exposed to the factors of the space environment in low Earth orbits [14] and burn quite easily in dense layers of the atmosphere. Taking this into account, the analysis of the degree of disposal of aerodynamic diversion systems from such materials may not be carried out.

Another approach to using composite materials is the design of fiber-reinforced composites in aerospace engineering [15]. In the case of applying such structures in combination with the above-mentioned polyolefins, the resistance of such materials to the factors of the space environment may increase. Given this, the disposal of LV casings made of such materials in the dense layers of the atmosphere could be a challenging task and require the selection of special deorbiting trajectories.

Thus, our review of the literature [4, 7–15] demonstrates that the use of polymer materials, especially polyolefins, has a sufficiently high level of scientific and practical development in the world and in Ukraine. Thus, it could be concluded that Ukraine is also one of the leaders in the application of polymeric materials in general and polyolefins in particular in the field of RST.

However, one of the unsolved problems related to designing LVs from polymer materials is the task of their disposal after the mission is completed. This issue is being solved by many leading RST organizations in order to combat the pollution of the Earth's orbit [16]. A likely method to solve it is to deorbit spent LV UBs from the target orbits with subsequent combustion in the dense layers of the Earth's atmosphere. Under these conditions, the task of ensuring LV UB destruction with subsequent combustion of its debris under the action of mechanical and aerothermodynamic loads of the atmospheric section of the trajectory is becoming more urgent. On the other hand, deorbiting process should ensure that the minimum amount of debris reaches the Earth's surface at the predefined parameters for the specified drop area.

In the world literature, the task to deorbit objects from space equipment, taking into account their drop to the Earth's surface, is called re-entry [17–19]. Thus, in work [17], a mathematical model was built, and methodology was devised for determining the scatter of coordinates for the spacecraft re-entry fall regions at controlled deorbiting. The use of the Kalman filter made it possible to increase the accuracy of determining the area of the possible re-entry region of the space vehicle. However, in the classic tasks of removing spacecraft from orbit using re-entry missions, special protective thermal shields and devices for braking satellites in the lower atmosphere are designed. This is explained by the fact that in such missions the main goal is not disposal but preservation of the structure of the spacecraft for its further use after repair and restoration on Earth. Taking into account that the main purpose of deorbiting LV UB from polyolefins into the dense layers of the atmosphere is disposal, and its movement in the atmospheric part of the trajectory is uncontrollable, the approach from [17] cannot be fully applied. In turn, works [18, 19] argue about the expediency of choosing the optimal trajectories of the removal of space vehicles taking into account the movement in the extra-atmospheric sections of the trajectory. The application of methods, optimization and algorithms of statistical analysis of multiple Monte Carlo tests showed the possibility of choosing the optimal parameters of the re-entry trajectory. However, all those methods were considered for spacecraft without taking into account the degree of combustion in the atmosphere and the change in their mass as a result.

Based on our review of the literature [4–19], it could be concluded that the approach to designing polyolefin casings is new. Taking into account the detailed scientific and theoretical substation of this approach [4, 7–15] regarding the issue of development of LV casings from polyolefins and their strength at the start-up stage, the issues of disposal assessments after the end of operation remained unresolved. The mains reasons why the task to assess the degree of disposal of the carrier rocket body made of polyolefins in the Earth's atmosphere remains unsolved are as follows:

– this class of LVs is new for rocket and space technology and has been developed only in recent decades along with the spread of demand for cheapening the process of launching payloads into near-Earth orbits [4, 7–15];

– the task of assessing the degree of disposal of the LV casing is multidisciplinary and multifaceted, which relates to the simultaneous solution of complex scientific problems of ballistics at hypersonic speeds, aerodynamics, heat and mass transfer, strength, materials science, etc.;

– the complexity and high cost of conducting experimental work.

This is exactly what is observed in the considered sources. For the most part, they are aimed at solving one problem: design, ballistics, materials science, etc. Or to solve the task to dispose of objects of rocket and space technology of a different class (which are built using classic materials such as steel, aluminum, etc.) by deorbiting them to uninhabited regions of the Earth [17–19].

Taking into account our review of the literature and the growing interest in the construction of LV UB casings from polyolefins, there is a task to determine the possibility of their disposal at the end of the period of active operation. To solve this problem, it is necessary to analyze the possibility of combustion of LV UB from a polymer material (polyolefin) in the process of deorbiting into the dense layers of the Earth's atmosphere. Under such conditions, there is a task to build mathematical models and algorithms to analyze the degree of disposal of polymer bodies along the passive part of the trajectory.

3. The aim and objectives of the study

The purpose of our work is to determine the possibility of disposal of LV casing made of polyolefins during deorbiting to remote areas of the Earth's surface. This will make it possible to estimate the degree of disposal of LV UBs by burning in the dense layers of the atmosphere at the system level of design and at the stage of conceptual design.

To achieve the goal, the following tasks have been set:

– to build a generalized mathematical model that takes into account the effect of ballistic and aerothermodynamic aspects, to estimate the degree of disposal of the body of LV UB made of polyolefins in the Earth's atmosphere at the stage of scientific research;

– to analyze the degree of combustion of polymeric LV UB in the dense layers of the Earth's atmosphere;

– to compile methodological recommendations for ensuring the environmental safety of the removal of polymeric LV UB from Earth orbit.

4. The study materials and methods

The object of our study is the process of disposal of the casing of LV UB made of polyolefins by burning in the dense layers of the Earth's atmosphere when deorbiting from Earth orbit.

The main hypothesis of the study assumes that the disposal of the casing of LV UB from polyolefins occurs through its combustion in the dense layers of the Earth's atmosphere at aerodynamic heating during deorbiting.

The following assumptions are adopted in the work:

1) LV UB is a material point of variable mass that moves under the action of the Earth's gravity and the aerodynamic resistance of the Earth's atmosphere;

2) the midsection area and the average coefficient of the atmosphere drag are unchanged;

3) the melting process is uniform; it occurs linearly with layer-by-layer propagation in the material;

4) Earth is general terrestrial ellipsoid WGS-84;

5) the gravitational potential of the Earth is EGM 2008; the influence of the 2nd, 3rd, and 4th zonal harmonics is taken into account;

6) Earth's atmosphere. GOST 4401–81. Standard atmosphere. Parameters for dense layers. NRLMSISE-00 is upper.

The expediency of the introduced abstraction is due to the reduction of computing costs and the simplification of the mathematical apparatus of the model of aerothermodynamic processes in LV UB for its integration with ballistics models. In turn, it is expected that the use of such a mathematical apparatus will allow for quick assessments of the possibility of disposal of the casings of LV UB made of polymeric materials in the dense layers of the atmosphere with reasonable accuracy. This is required at the system design level and at the conceptual design stage.

The work uses general scientific and special research methods:

– methods of system analysis and synthesis for the construction of a mathematical model with the simultaneous application of models of heat flows in the atmospheric and extra-atmospheric sections of LV UB trajectory and ballistics models;

– method of synergistic approach for integration of heat flow models and a model of LV UB movement;

– a method of mathematical modeling and computer simulation to analyze the process of deorbiting LV UB from polymeric materials with subsequent burning in the upper atmosphere.

5. Results of investigating the process of disposal of the upper body of a launch vehicle from polymer materials in a dense atmosphere

5. 1. A generalized mathematical model for estimating the degree of disposal of the launch vehicle body

The following coordinate systems were introduced [20–22]:

a) geocentric inertial coordinate system (GICS) at the epoch J2000.0 OXYZ. The origin of this right orthogonal coordinate system O is located at the center of mass of the Earth, the OZ axis is directed towards the north pole J2000.0, the OX axis lies in the plane of the equator and is directed to the point of the true vernal equinox, the OY axis completes the system to the right;

b) WGS-84 $O_gX_gY_gZ_g$ coordinate system. Non-inertial right orthogonal coordinate system with origin at the center of mass of the Earth O_g. The O_gX_g axis lies in the plane of the equator and is directed toward the intersection of the equator with the WGS-84 zero meridian, the O_gZ_g axis is directed along the axis of the Earth's daily rotation in the direction of the north pole, and the O_gY_g axis completes the system to the right.

It is proposed to divide the process of deorbiting the polymeric LV UB upper body into two phases:

1) motion in the upper rarefied atmosphere (free molecular interaction);

2) movement in the dense layers of the atmosphere, complete or partial combustion of the casing with the possible drop of debris to the Earth's surface.

In the first phase, the height of LV UB trajectory gradually decreases. At the same time, the absolute speed and density of the atmosphere increase. In the second phase, gradual aerothermodynamic heating of the casing occurs with the transition of the aggregate state of the casing material to a liquid or gaseous state.

Taking this into account, it is advisable to use a mathematical model in kinematic parameters according to the following principle [23]:

$$\begin{aligned}
&\frac{dV_X}{dt} = G_X + A_X,\\
&\frac{dV_Y}{dt} = G_Y + A_Y,\\
&\frac{dV_Z}{dt} = G_Z + A_Z,\\
&\frac{dX}{dt} = V_X,\\
&\frac{dY}{dt} = V_Y,\\
&\frac{dZ}{dt} = V_Z,\\
&\frac{dm}{dt} = -\dot{m}_M,
\end{aligned} \tag{1}$$

where V_X, V_Y, V_Z are the projections of the speed of movement of the upper body of LV made of polymeric materials onto the axes of the GICS coordinate system; X, Y, Z – values of the current coordinates of the movement of the upper body of LV from polymeric materials in the GICS reference system; t – deorbiting time; G_X, G_Y, G_Z – projections of accelerations of gravitational disturbances onto the axes of the GICS coordinate system; A_X, A_Y, A_Z – projections of accelerations of aerodynamic disturbances onto the axes of the GICS coordinate system; m is the mass of LV UB; $\dot{m}_M$ is the speed of mass removal of the casing of LV UB.

Projections of the current position vector onto the axes of the WGS-84 coordinate system are determined according to the following ratios:

$$\begin{bmatrix} X_g \\ Y_g \\ Z_g \end{bmatrix} = M_{X_g \leftarrow X} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \tag{2}$$

where $M_{X_g \leftarrow X}$ is the transition matrix from GICS to the WGS-84 coordinate system, which is determined according to recommendations from [23].

The acceleration of the Earth's gravity is determined from the following equations:

$$\begin{bmatrix} G_X \\ G_Y \\ G_Z \end{bmatrix} = \frac{g_R}{R}\begin{bmatrix} X \\ Y \\ X \end{bmatrix} + g_\omega \begin{bmatrix} i_X \\ i_Y \\ i_Z \end{bmatrix}, \quad (3)$$

$$g_r = -\frac{\mu}{R^2}\left\{\begin{array}{l} 1+\frac{3}{2}\frac{a_E^2}{R^2}C_{2,0}\left(5\sin^2\varphi_E-1\right)+ \\ +\frac{5}{2}\frac{a_E^3}{R^3}C_{3,0}\sin\varphi_E\left(7\sin^2\varphi_E-3\right)+ \\ +\frac{15}{8}\frac{a_E^4}{R^4}C_{4,0}\left[7\sin^2\varphi_E\left(3\sin^2\varphi_E-2\right)+1\right] \end{array}\right\}, \quad (4)$$

$$g_\omega = \frac{\mu}{R^2}\left\{\begin{array}{l} 3\frac{a_E^2}{R^2}C_{2,0}\sin\varphi_E+ \\ +\frac{3}{2}\frac{a_E^3}{R^3}C_{3,0}\left(5\sin^2\varphi_E-1\right)+ \\ +\frac{5}{2}\frac{a_E^4}{R^4}C_{4,0}\sin\varphi_E\left(7\sin^2\varphi_E-3\right) \end{array}\right\}, \quad (5)$$

$$R = \sqrt{X_g^2+Y_g^2+Z_g^2},$$

$$\sin\varphi_E = \frac{Z_g}{R},$$

$$\begin{bmatrix} i_X \\ i_Y \\ i_Z \end{bmatrix} = M^T_{X_g \leftarrow X}\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},$$

where μ is the gravitational constant of the Earth; a_E is the semimajor axis of the general terrestrial ellipsoid.

Geodetic coordinates (latitude B, longitude L, and height above the WGS-84 h_g ellipsoid) are calculated using WGS-84 coordinates according to [24].

The density of the atmosphere ρ_A in the section of the upper atmosphere is calculated according to the NRLMSISE-00 standard, in the section of the dense atmosphere – according to GOST 4401–81. Standard atmosphere. Parameters, as functions of flight altitude h_g.

The acceleration of the drag force of the Earth's atmosphere is found from the following equations:

$$\begin{bmatrix} A_X \\ A_Y \\ A_Z \end{bmatrix} = -\frac{C_X S_M}{2m}\rho_A V_r \begin{bmatrix} V_{rX} \\ V_{rY} \\ V_{rZ} \end{bmatrix}, \quad (6)$$

$$\begin{bmatrix} V_{rX} \\ V_{rY} \\ V_{rY} \end{bmatrix} = \begin{bmatrix} V_X \\ V_Y \\ V_Z \end{bmatrix} - \omega_E \begin{bmatrix} i_Y Z - i_Z Y \\ i_Z X - i_X Z \\ i_X Y - i_Y X \end{bmatrix}, \quad (7)$$

$$V_r = \sqrt{V_{rX}^2+V_{rY}^2+V_{rZ}^2},$$

where C_X is the average coefficient of aerodynamic resistance of the atmosphere; S_M is the midsection area; ω_E is the angular velocity of the Earth's daily rotation.

Heat flows affecting the LV body could be divided into two types:

1) heating caused by thermal radiation;

2) aerodynamic heating during movement in dense layers of the atmosphere.

Mathematical models of heating from thermal radiation during the movement of space vehicles in near-Earth orbits are given in [25]. For generalized estimates, it is advisable to also use the assumption given in [26], conditionally dividing the surface of LV UB casing into illuminated by the Sun and non-illuminated. Thus, the differential equations for determining the temperature of the illuminated and non-illuminated part of the surface of LV UB casing take the following form:

$$m_{sn}C_k\frac{dT_{sn}}{dt} = E_s\alpha_k A_{solsn} + E_a\alpha_k A_{albsn} + \\ + E_p\varepsilon_k A_{plansn} - \sigma\varepsilon_k A_{sn}T_{sn}^4,$$

$$m_{sh}C_k\frac{dT_{sh}}{dt} = E_a\alpha_k A_{albsh} + E_p\varepsilon_k A_{plansh} - \sigma\varepsilon_k A_{sn}T_{sh}^4, \quad (8)$$

where m_{sn} is the mass of the illuminated part of LV UB casing; m_{sh} is the mass of the non-illuminated part of LV UB casing; C_k is the heat capacity of the polymer material from which LV UB is made; T_{sn} is the temperature of the surface of the illuminated part of LV UB casing; T_{sh} is the temperature of the surface of the non-illuminated part of the casing of LV UB; ε_k is the degree of blackness of the material of LV UB; A_{sn} is the area of the entire surface of LV UB casing; α_n is the absorption coefficient (absorbability) of the polymer material from which the upper LV body is made; A_{solsn}, A_{ablsn}, A_{plansn}, A_{ablsh}, A_{plansh} – calculated surface areas of LV UB casing receiving solar radiation, albedo radiation, and planetary radiation on illuminated and non-illuminated parts, respectively; E_s, E_a, E_p are the values of the radiation fluxes of the Sun's radiation, the Earth's albedo, and planetary radiation.

Taking into account the non-oriented movement of LV UB during deorbiting, it is suggested to assume that, on average, half of the surface of the casing is on the illuminated part, and the other half of the surface is on the unilluminated part. Taking this into account, it is advisable to take the average value of the temperature of the illuminated and non-illuminated parts to estimate the temperature of the surface of LV UB casing from thermal radiation:

$$T_k = \frac{T_{sn}+T_{sh}}{2}, \quad (9)$$

where T_k is the average value of the temperature of the surface of LV UB casing from thermal radiation.

The next thermal factor is aerodynamic heating when moving in dense layers of the atmosphere (altitude below 100–150 km). For general evaluations, methodologies for determining aerodynamic heating according to [27] are used as follows:

$$\frac{dQ_{air}}{dt} = \frac{1}{2}C_H\rho_A V_r^3 S_M, \quad (10)$$

where Q_{air} is the amount of heat released during the aerodynamic heating of the LV casing; C_H is a dimensionless thermal conductivity coefficient.

When adapting (10), the following equation was used to estimate the rate of mass removal during combustion:

$$\dot{m}_M = \frac{Q_{air}S_x^{air}}{H_n}, \quad (11)$$

where S_x^{air} is the surface area of LV UB casing, which is heated due to aerodynamic friction; H_n is the heat of phase transformation.

Considering that we assume that melting occurs uniformly in the direction opposite to the movement of the heated surface of the casing with gradual burning of material layers, the following ratio holds:

$$dm = \rho_m S_x^{air} \cdot d\xi, \tag{12}$$

where ξ is the wall thickness of LV UB casing; ρ_m is the density of the material from which the casing of LV UB is made.

Taking into account (11), equation (12) could be reduced to the type of differentiation of the parameter ξ by time, as follows:

$$\frac{d\xi}{dt} = \frac{Q_{air}}{\rho_m H_n}. \tag{13}$$

In turn, for estimation calculations when determining Q_{air}, it is advisable to use the reduced analytical expression for aerodynamic heating:

$$Q_{air} = \frac{4.6 \cdot 10^7}{\sqrt{\xi}} \left(\frac{\rho_A}{\rho_0}\right)^{\frac{1}{2}} \cdot \left(\frac{V_r}{V_{1k}}\right)^3, \tag{14}$$

where ρ_0 is the density of the atmosphere at sea level; V_{1k} is the value of the first cosmic velocity.

Thus, a generalized mathematical model has been built for estimating the possibility of disposal of LV UB in the dense layers of the Earth's atmosphere by burning. The model includes a ballistics module based on differential equations (1), models of heat flows in the extra-atmospheric part of the trajectory (8), and aerodynamic heating in the dense layers of the atmosphere (10) to (14).

5. 2. Results of determining the degree of combustion of the upper body of a launch vehicle by burning in dense layers of the atmosphere

In order to carry out evaluations, it is suggested to consider the possibility of disposal of LV UB whose casing is made of polyolefins. The weight and size characteristics of these hypothetical bodies are proposed to be taken from the characteristics of the kick stage and the second stage of the Electron rocket by the New Zealand aerospace company Rocket Lab [28].

The following objects were adopted to model the process of the termination of the existence of LV UBs:

1. The kick stage of the ultra-light class LV. The mass is 40 kg, the surface area is 0.85 m^2, the average value of the coefficient of aerodynamic drag on the trajectory at an altitude above 170 km is 2.12, at an altitude below 170 km it is 0.5.

2. The second stage of LV of the ultra-light class. Weight – 250 kg; the midsection area is 2.83 m^2, the average value of the drag coefficient on the trajectory at an altitude above 170 km is 2.12, at an altitude below 170 km – 0.5.

The process of deorbiting from low Earth orbits of two types is considered: close to circular with eccentricity less than 0.005, and small elliptical.

The initial parameters of an orbit that is close to circular:
– the semi-major axis of the orbit: 6853227 m;
– orbital eccentricity: 0.0008;
– inclination of the orbit: 97.4 degrees;
– right ascension of the ascending node of the orbit: 353.731 degrees;
– perigee argument of the orbit: 357.035 degrees;
– orbit latitude argument: 0.0 degrees.

The following results were obtained as a result of simulating the trajectory of the motion of LV UB made of polyolefins for the given initial conditions using model (1) to (14).

Our results demonstrate that the time of deorbiting the LV UB made of polymer materials in the form of a kick module was approximately 260.5 days, at an initial orbit height of 485 km (Fig. 1). The temperature of LV UB varied: for the illuminated part of the casing – in the range of 280–333 K, for the non-illuminated side of the casing – in the range of 228–240 K (Fig. 2). This temperature is maintained until entering the dense layers of the atmosphere. After entering the dense layers of the atmosphere (Fig. 3), the temperature due to aerodynamic heating increases by orders of magnitude and the melting process occurs (Fig. 4). The results of simulating the deorbiting of a 40-kg LV UB showed that upon entering the dense layers of the atmosphere, the melting process of the LV UB casing begins (Fig. 3, 4). At a height of 1 km above the Earth's surface, the mass of LV UB was 9 kg, which is 23 % of the initial mass. Given this, we can say that the kick module made of polymeric materials is recycled by more than 75 %. Estimates of the possible place of fall of the kick module have been carried out. Thus, unburnt debris weighing about 10 kg ceased to exist in the Pacific Ocean (Fig. 5). Such debris does not pose a danger to residents, animals, and an environmental threat to this region.

Regarding the second stage, the results of deorbiting and disposal are shown in Fig. 6, 7.

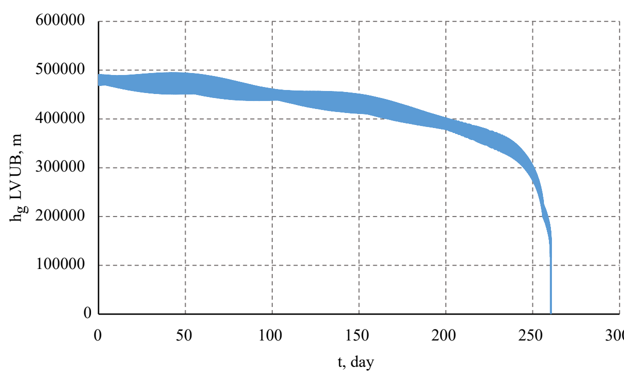

Fig. 1. Dependence of flight altitude of the upper stage of launch vehicle on the time of deorbiting an orbit close to circular

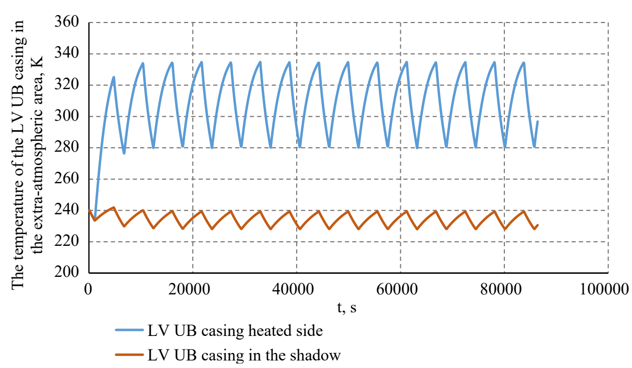

Fig. 2. Temperature dependence of the upper stage of launch vehicle casing on the time of deorbiting during movement in the extra-atmospheric section of a near-circular orbit for 24 hours

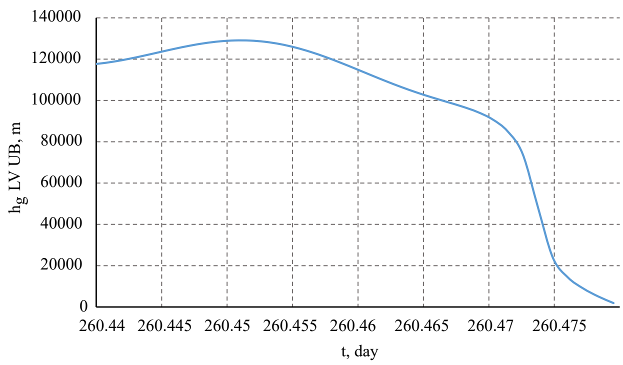

Fig. 3. Dependence of flight altitude of the upper stage of launch vehicle on the time of deorbiting from a near-circular orbit at the movement section in the dense layers of the atmosphere

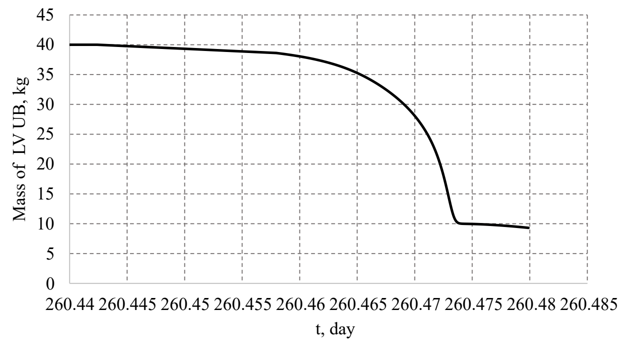

Fig. 4. Dependence of mass of the upper stage of launch vehicle on the time of deorbiting from a near-circular orbit at the section of motion in the dense layers of the atmosphere

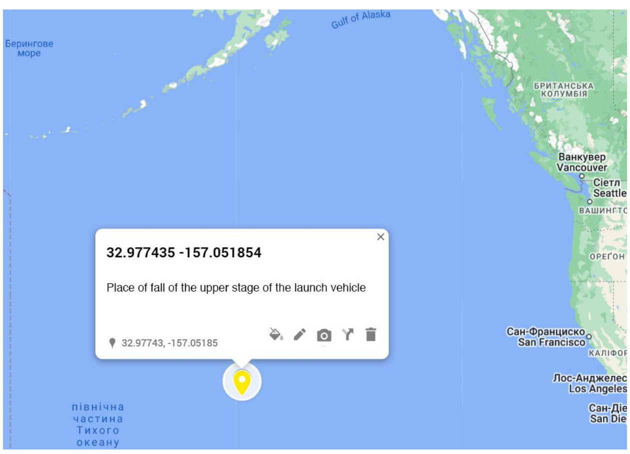

Fig. 5. Geodetic coordinates of the point of termination of the upper stage of launch vehicle after deorbiting from a near-circular orbit

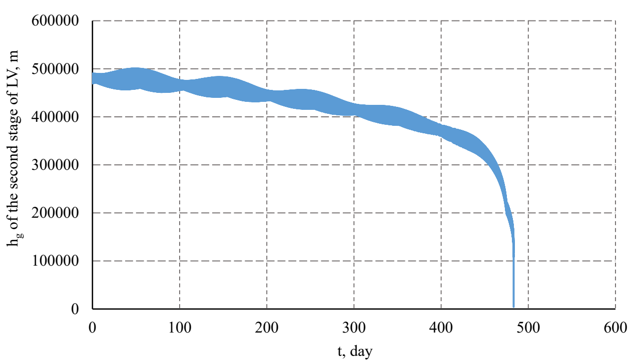

Fig. 6. Dependence of flight altitude of the second stage on the time of deorbiting from a near-circular orbit

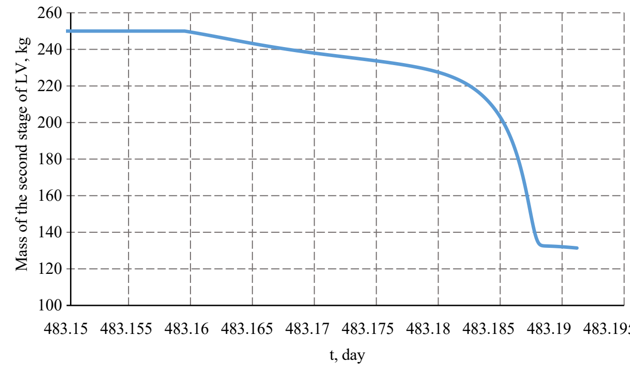

Fig. 7. Dependence of flight altitude of the second stage on the time of deorbiting from the circular orbit at the movement section in the dense layers of the atmosphere

From our results of simulating the motion of the second stage, it could be seen that the deorbiting time is significantly longer (almost 483 days) than that of the kick module, which is explained by the lower value of the ballistic coefficient. Also, the mass of the second stage at a height of 1 km above the Earth's surface was approximately 142 kg, which is 57 % of the initial mass of 250 kg. Given this, it could be concluded that the second stage of LV UB could be disposed of by 43 % when burned in the dense layers of the atmosphere when removed from near-circular orbits. Modeling of deorbiting showed that the second stage debris also ceased to exist in the Pacific Ocean at a considerable distance from the coastline.

Thus, taking into account the simulation results of deorbiting from near-circular orbits of UB and the second stage, which are made of polypropylene for the ultralight class LV, it could be concluded that:

1) it is possible to dispose of 75 % of the kick module weighing 40 kg;

2) it is possible to dispose of 43 % of the second stage, weighing 250 kg;

3) with the correct selection of the deorbiting trajectory and accurate prediction of the place of drop on uninhabited regions of the Earth, the debris of LV UB will not pose a threat to humanity and the ecology of the region.

Thus, when making similar casings of LV UBs from polyolefins and launching them into near-circular orbits, it is necessary to take into account and accurately predict the trajectories, taking into account the possible place of drop. Although these bodies could be disposed of up to 75 %, falling debris into densely populated regions could also pose a moderate threat level hazard. Given this, a second approach is proposed, which involves forming the ellipticity of the orbit of LV bodies to increase the steepness and speed of entry into the atmosphere. For example, for estimations of the degree of disposal of LV UBs, it is suggested to consider a low-elliptic orbit with the following initial parameters:

– the semi-major axis of the orbit: 6853227 m;

– orbital eccentricity: 0.055;

– orbital inclination: 50.4 degrees;

– longitude of the ascending node of the orbit: 125.731 degrees;

– perigee argument of the orbit: 60.035 degrees;

– orbit latitude argument: 0.0 degrees.

In turn, during the formation of small elliptical orbits for deorbiting the kick module and the second stage, the disposal results are significantly improved (Fig. 8).

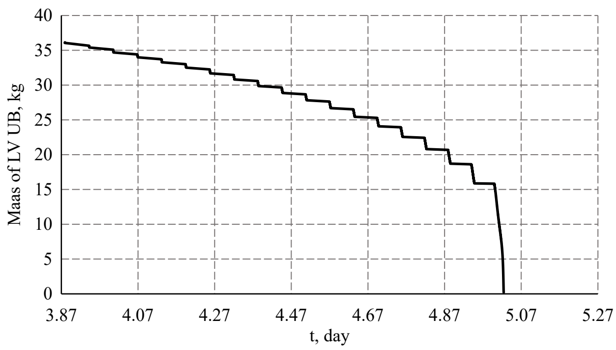

Fig. 8. Dependence of mass of the upper stage of launch vehicle on the time of deorbiting from the small elliptical orbit at the section of motion in the dense layers of the atmosphere

Thus, in low-elliptical orbits, the 40-kg LV UB completely burned up at an altitude of about 60–70 km. Given this, it could be asserted that during the formation of the necessary ellipticity of the orbit and the increase in the steepness and speed of the kick module's entry into the atmosphere, its polyolefin casing is completely disposed of.

In turn, for the maximum disposal of the second stage, it is necessary to increase the initial value of the eccentricity of this small elliptical orbit to 0.0558. The disposal dynamics of the second stage made of polyolefins are shown in Fig. 9.

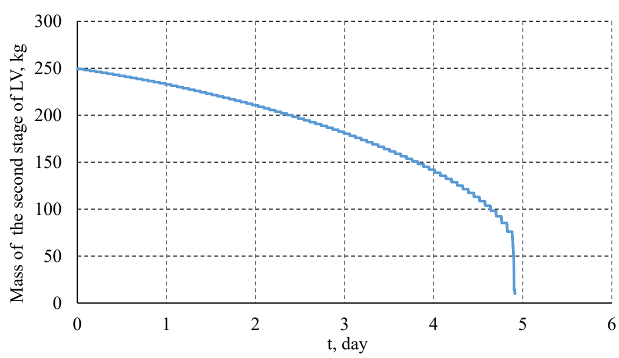

Fig. 9. Dependence of mass of the second stage on the time of deorbiting from a small elliptical orbit at the section of motion in dense layers of the atmosphere

Our results of simulating the disposal have shown that when forming a small elliptical orbit with an eccentricity in the range from 0.05 to 0.06, the speed at perigee increases. In turn, the perigee of the orbit first enters the dense layers of the atmosphere during deorbiting. Given this, with an increase in the speed of movement in the dense layers of the atmosphere, according to model (10) to (14), the heat flow of aerodynamic heating on the body of the LV body increases. The obtained effect accelerates the dynamics of the burning of LV body in the dense layers of the atmosphere, which is confirmed by the results of modeling (Fig. 8, 9). The second stage had a mass of 10 kg at an altitude of 500 m, which is 4 % of the initial mass of 250 kg (Fig. 9). According to the simulation results, the unburnt debris of the second stage when deorbiting from the low-elliptical orbit ceased to exist in the Atlantic Ocean outside the territorial waters of Brazil.

Our estimates of the dynamics of combustion of casings of the upper bodies of launch vehicle made of polymeric materials in the dense layers of the atmosphere when deorbiting from orbits of various dislocations make it possible to compile methodological recommendations for the disposal of such space objects.

5. 3. Compiling methodological recommendations for the disposal of bodies of launch vehicles made of polyolefins, taking into account environmental safety

The results of investigating the peculiarities of disposal of casings of LV UBs made of polymeric materials showed that the dynamics of burning the LV casing in the dense layers of the atmosphere are influenced by the following factors:

1) the shape of the orbit at the initial phase of deorbiting;
2) mass-dimensional characteristics;
3) thermal properties of the polymeric material.

Taking into account these factors, methodical principles were compiled for the disposal of LV UBs made from polymeric materials, taking into account environmental safety. The recycling algorithm takes the following form:

1) analysis of the structural characteristics of LV UBs (mass and dimensional characteristics, casing material, casing material properties);
2) analysis of the orbit of LV UB deorbiting before the start of deorbiting (type of orbit, location, initial prediction of the possible place of drop);
3) simulation of the process of deorbiting the LV UBs using a generalized mathematical model, which includes formulas and expressions (1) to (14), and determining the degree of disposal of the LV UB casing. The simulation includes the simulation of movement in the atmospheric and extra-atmospheric section of the trajectory, determination of the average temperature of the casing before entering the dense layers of the atmosphere, modeling of casing burning process when entering the dense layers of the atmosphere;
4) conducting assessments of the point of termination of the existence of the wreckage of LV UBs in the case of incomplete combustion of the casing;
5) correction of deorbiting orbit with a high probability of debris hitting densely populated regions of the Earth.

Thus, the methodological recommendations compiled allow us to evaluate the degree of disposal of casings of LV UBs made of polymeric materials. Also, this procedure makes it possible to assess the man-made threat by determining the possible place of drop of LV UB fragments that did not burn up in the atmosphere.

6. Discussion of results based on the construction of a generalized mathematical model for evaluating the disposal of the launch vehicle casing made of polyolefins no more

The synergistic application of the movement forecasting model (1) to (7) and the generalized models for estimating thermal factors (8) to (14) makes it possible to perform general assessments of the possibility of disposal of the polymeric casings of LV UBs in a dense atmosphere. This allows us to choose the initial parameters for the orbit of deorbiting such space objects in the case of using active means for cleaning the near-Earth space [16], taking into account the minimization of the environmental threat [29]. However, in contrast to [29], in which the degree of environmental impact from autophagy rocket fuel combustion is considered in the active area. In addition, the model built makes it possible to estimate the likely place of fall of unburnt fragments of LV. In turn, the choice of deorbiting trajectory taking into account the rational place of fall makes it possible to reduce the degree of environmental pollution of the inhabited regions of the Earth. Also, the application of models of melting (11) to (13) of materials due to aerodynamic heating (10), (14) made it possible to determine the degree of combustion of the casing of LV UB made of polyolefins in a dense atmosphere. Similar simplified mathematical models for estimating the heat flows of space vehicles subject to return from orbit to Earth are given in works [30, 31]. Thus, in work [30], with the use of general evaluation models of heat flows, evaluations of the combustion of the components of the construction of the artificial satellite of the Earth were carried out. Depending on the material of the structure, it was determined that the degree of disposal of this or that component during deorbiting of a satellite from near-circular orbits varies from 30 % to 100 %. The estimates obtained in this paper for the degree of disposal of the polyolefin casings of LVs when removed from near-circular orbits are also in this range. In turn, work [31] also proposed the use of simplified models for general estimates of heat flows during movement in dense layers of the atmosphere. The given interpolation formulas [31] are close to our generalized model (14). Given this, it could be concluded that the constructed generalized mathematical model for estimating the degree of disposal of LV UBs made from polyolefins is not abstract and has a sufficient number of analogous models. In addition, the proposed model makes it possible to reduce the calculation time for obtaining generalized estimates of aerodynamic heating and the degree of combustion of LV UB stages. Analogous models require more computing resources and are also difficult to integrate.

When conducting research, the mathematical model built has certain limitations regarding practical application. They are related to the fact that our model could be used only at the initial stages of designing such LV UBs to determine the degree of disposal of their casings in the process of ceasing existence. Such stages include the stages of conceptual scientific research, conceptual design, etc.

However, there remain a number of problematic aspects when applying this model for high-precision calculations of the melting process, which is associated with a number of assumptions accepted in our work. Thus, when performing high-precision calculations, a necessary condition is the presence of accurate values for the aerodynamic characteristics of LV UBs, which makes it possible to use accurate values of the aerodynamic drag coefficients. Also, taking into account the nonlinearity of heat flows in the material of LV UB casing, complex mathematical models with partial differential equations are necessary [32]. The disadvantage of using such models with partial differential equations is the complexity of their integration with ballistics equations (1). However, for the adequate application of the models given in [32], it is necessary to enter into the general complex mathematical model the model of angular non-oriented movement of LV stage for the accurate determination of the inhomogeneity of the heating of the casing along the entire trajectory of movement. However, it is impossible to precisely model the non-oriented angular motion of LV UB, taking into account the stochastic nature of disturbances of the space environment (for example: solar activity, deviation of the model gravitational potential from the real one) and information about its initial angular position.

This research might be advanced through the following:
– simulation of LV UB as a body of variable mass;
– consideration of aerothermodynamic processes;
– taking into account the influence of overload and temperature on the integrity of the structure;
– taking into account the impact of ablation process on the shape and aerodynamic characteristics;
– taking into account the probabilistic process of ablation and changes in strength characteristics.

7. Conclusions

1. A generalized mathematical model has been built for analyzing the disposal rate of upper bodies of launch vehicles made of polyolefins. Disposal is proposed by burning these casings in the dense layers of the atmosphere during deorbiting of the upper bodies of launch vehicles from near-Earth orbits. The mathematical model includes three submodules: a ballistics submodule, a submodule for determining heat flows in the extra-atmospheric part of the trajectory, and a submodule for aerothermodynamic processes in the dense layers of the atmosphere and estimates of the degree of melting. The use of a synergistic approach allowed us to combine all three submodules into a single mathematical model, in which all differential equations are integrated over time. That has made it possible to perform quick calculations of deorbiting time of the upper bodies of launch vehicles made of polymeric materials with the determination of the degree of their disposal in the dense layers of the atmosphere and the place of possible drop of debris that did not melt.

2. Estimated calculations of deorbiting time and the degree of disposal of the upper and second stages of the Electron ultra-light class launch vehicle when their bodies are made of polymer materials showed the following:
– when the stages of an ultralight class launch vehicle are deorbited from near-circular low Earth orbits, their casings melt in the dense layers of the atmosphere by 40–75 %;
– the degree of melting of casings of bodies of the launch vehicles during deorbiting depends on the structural features, mass-dimensional characteristics, and the material from which the casing is made;
– the formation of elliptical orbits makes it possible to increase the degree of melting the bodies of launch vehicles made of polyolefins in the dense layers of the atmosphere by 20–60 % due to the increase in their speed of entry into the dense layers of the atmosphere;
– the formation of low ellipticity of orbits with an eccentricity in the range from 0.05 to 0.08 gives a gain in reducing the time of deorbiting the bodies of launch vehicles by 3 times.

3. Methodical recommendations for the disposal of casings of the upper bodies of launch vehicles in the dense layers of the atmosphere have been compiled. We have shown the necessity of carrying out assessments of the place of drop of fragments of the casing of the upper bodies of launch vehicles during their incomplete combustion in the atmosphere in order to determine potential risks of an environmental and man-made nature. Thus, our methodological recommendations allow for a comprehensive analysis of the disposal of upper bodies launch vehicles made of polyolefin, taking into account the features of deorbiting trajectory, the degree of combustion in the atmosphere, and the determination of the place of possible debris drop. Such evaluations could make it possible to optimally choose the deorbiting trajectories for space objects whose casings are made of polyolefins when active deorbiting means are used.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The research was carried out within the framework of the project "Theoretical foundations for designing ultralight launch vehicles from polymeric materials" within the EU Framework Program for Research and Innovation "Horizon 2020", contract LV/12-2023 with the Ministry of Education and Science of Ukraine.

Data availability

All data are available, either in numerical or graphical form, in the main text of the manuscript.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

References

1. Brunner, A. J. (2020). Fracture mechanics of polymer composites in aerospace applications. Polymer Composites in the Aerospace Industry, 195–252. https://doi.org/10.1016/b978-0-08-102679-3.00008-3
2. NjugunaNjuguna, J., Pielichowski, K. (2004). Polymer Nanocomposites for Aerospace Applications: Characterization. Advanced Engineering Materials, 6 (4), 204–210. https://doi.org/10.1002/adem.200305110
3. Henson, G. (2018). Materials for Launch Vehicle Structures. Aerospace Materials and Applications, 435–504. https://doi.org/10.2514/5.9781624104893.0435.0504
4. Dron', M. M., Kositsyna, O. S., Dreus, A. Yu. (2023). Prospects of using polyolefins as alternative structural materials for ultralight launch vehicle. Journal of Chemistry and Technologies, 31 (4), 845–853. https://doi.org/10.15421/jchemtech.v31i4.289212
5. Yemets, V., Sanin, F., Dzhur, Y., Masliany, M., Kostritsyn, O., Minteev, G. (2009). Single-stage small satellite launcher with combustible tank of polyethylene. Acta Astronautica, 64 (1), 28–32. https://doi.org/10.1016/j.actaastro.2008.06.015
6. Yemets, V., Sanin, F., Masliany, M., Kostritsyn, O., Minteev, G. (2010). Is the combustible inertial pico launch vehicle feasible? JBIS – Journal of the British Interplanetary Society, 63 (7), 249–259.
7. Yemets, V., Dron, M., Yemets, T., Kostritsyn, O. (2015). The infinite staging rocket – A progress to realization. Proceedings of the International Astronautical Congress, IAC, 12, 9118–9124.
8. Yemets, V., Dron', M., Pashkov, A. (2020). Autophage Engines: Method to Preset Gravity Load of Solid Rockets. Journal of Spacecraft and Rockets, 57 (2), 309–318. https://doi.org/10.2514/1.a34597
9. Dreus, A. Yu., Dron, M. M., Dubovik, L. G., Strembovsky, V. V. (2023). Assessment of the possibility of using polymers in the bodies of promising launch vehicles based on the heat resistance factor. Kosmìčna Nauka ì Tehnologìâ, 29 (6), 03–12. https://doi.org/10.15407/knit2023.06.003
10. Dreus, A., Yemets, V., Dron, M., Yemets, M., Golubek, A. (2021). A simulation of the thermal environment of a plastic body of a new type of launch vehicle at the atmospheric phase of the trajectory. Aircraft Engineering and Aerospace Technology, 94 (4), 505–514. https://doi.org/10.1108/aeat-04-2021-0100
11. Golubek, A., Aleksieienko, S., Dron, M., Dreus, A. (2024). Assessing the possibility of using a variable-length launch vehicle with a polymer body for orbiting payload. Eastern-European Journal of Enterprise Technologies, 3 (7 (129)), 63–72. https://doi.org/10.15587/1729-4061.2024.306225
12. Cesul, B. T. (2008). Inorganic Polymers for Space Applications. 22nd Annual AIAA/USU Conference on Small Satellites Content. Available at: https://digitalcommons.usu.edu/cgi/viewcontent.cgi?article=1388&context=smallsat
13. Roddy, M. A., Huang, A. (2016). Development of a solid-state inflation balloon for aerodynamic drag assisted deorbit of CubeSats. Engineering, Environmental Science, Physics.
14. Grossman, E., Gouzman, I. (2003). Space environment effects on polymers in low earth orbit. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 208, 48–57. https://doi.org/10.1016/s0168-583x(03)00640-2
15. Kondratiev, A., Potapov, O., Tsaritsynskyi, A., Nabokina, T. (2021). Optimal Design of Composite Shelled Sandwich Structures with a Honeycomb Filler. Advances in Design, Simulation and Manufacturing IV, 546–555. https://doi.org/10.1007/978-3-030-77719-7_54
16. Alpatov, A. P. (2018). Kosmichne smittia: aspekty problemy. Tekhnichna mekhanika, 1, 30–47.
17. Fedele, A., Omar, S., Cantoni, S., Savino, R., Bevilacqua, R. (2021). Precise re-entry and landing of propellantless spacecraft. Advances in Space Research, 68 (11), 4336–4358. https://doi.org/10.1016/j.asr.2021.09.029
18. Nocerino, A., Notaro, I., Morani, G., Poderico, M., D'Amato, E., Blasi, L. et al. (2023). Trajectory control algorithms for the de-orbiting and Re-entry of the MISTRAL satellite. Acta Astronautica, 203, 392–406. https://doi.org/10.1016/j.actaastro.2022.12.010
19. Gaglio, E., Bevilacqua, R. (2023). Time Optimal Drag-Based Targeted De-Orbiting for Low Earth Orbit. Acta Astronautica, 207, 316–330. https://doi.org/10.1016/j.actaastro.2023.03.011
20. Markley, F. L., Crassidis, J. L. (2014). Fundamentals of Spacecraft Attitude Determination and Control. Springer New York. https://doi.org/10.1007/978-1-4939-0802-8

21. Kaplan, G. H. (2005). The IAU Resolutions on Astronomical Reference Systems, Time Scales, and Earth Rotation Models (Draft 4). Defense Technical Information Center. https://doi.org/10.21236/ada434096
22. Petit, G., Luzum, B. (2010). IERS Conventions. IERS Technical Note No. 36. IERS Conventions Centre, 179.
23. Golubek, A. V., Tatarevskiy, K. E., Filippenko, I. M., (2020). Apriornaya ocenka tochnosti vyvedeniya kosmicheskih apparatov s BINS. Dnepr: LIRA, 187.
24. Zbruckiy, A. V., Ganzha, A. P. (2011). Navigaciya kosmicheskogo apparata distancionnogo zondirovaniya Zemli po semke zemnoy poverhnosti. Kyiv: NTUU "KPI", 160.
25. Fortescue, P., Swinerd, G., Stark, J. (Eds.) (2011). Spacecraft Systems Engineering. John Wiley & Sons. https://doi.org/10.1002/9781119971009
26. Lapkhanov, E., Palii, O., Golubek, A. (2022). Determining the degree of effect of heat flows on the deformation of the shell of a space inflatable platform with a payload. Eastern-European Journal of Enterprise Technologies, 5 (1 (119)), 6–16. https://doi.org/10.15587/1729-4061.2022.266161
27. Allen, J. (1964). The aerodynamic heating of atmosphere entry vehicles – a review. NASA, Ames Research Center Moffett Field, California, 44.
28. Payload user guide. Electron. Available at: https://www.rocketlabusa.com/assets/Uploads/Electron-Payload-User-Guide-7.0.pdf
29. Kositsyna, O. S., Dron', M. M., Yemets, V. V. (2020). The environmental impact assessment of emission from space launches: the promising propellants components selection. Journal of Chemistry and Technologies, 28 (2), 186–193. https://doi.org/10.15421/082020
30. Park, S.-H., Mischler, S., Leyland, P. (2021). Re-entry analysis of critical components and materials for design-for-demise techniques. Advances in Space Research, 68 (1), 1–24. https://doi.org/10.1016/j.asr.2021.03.019
31. Park, S.-H., Neeb, D., Plyushchev, G., Leyland, P., Gülhan, A. (2021). A study on heat flux predictions for re-entry flight analysis. Acta Astronautica, 187, 271–280. https://doi.org/10.1016/j.actaastro.2021.06.025
32. Tyurenkova, V. V., Smirnova, M. N. (2016). Material combustion in oxidant flows: Self-similar solutions. Acta Astronautica, 120, 129–137. https://doi.org/10.1016/j.actaastro.2015.11.033