DOI: 10.13009/EUCASS2019-220

Optimization of allocation of areas for the falling of the worked-off stages boosters of the launch vehicle based on zoning and classification of the existing impact areas of Baikonur cosmodrome

[1]B.T. Suimenbayev, [2]V.I. Trushlyakov, [3]Zh.K.Zhubatov, [1]G.T. Yermoldina,
[1]Zh.B. Suimenbayeva, [1]A.M. Bapyshev
[1]Institute of Information and Computing Technologies, Almaty, Kazakhstan
125, Pushkin Street, 050010, Almaty, Kazakhstan, bts49@mail.ru
[2]Omsk State Technical University, Omsk, Russia
11, Mira Avenue, 644050, Omsk, Russia, vatrushlyakov@yandex.ru
[3]Republican state enterprise "Scientific-Research Center "Garysh-Ekologiya"
191, Abay Avenue, 050046, Almaty, Kazakhstan, zh.zhubatov@mail.ru

Abstract

The analysis of the mechanical, chemical and pyrogenic effects of the Baikonur cosmodrome on the environment showed the presence of technogenic specific impact of the worked off first stages (WS) on the ecosystems of the impact areas (IA). The authors proposed the concept of the controlled descent of the worked-off stages of the launch vehicles with liquid rocket engines (LRE) in the recommended sections of areas with stable characteristics of the ecosystem of the considered impact area at simultaneous saving energetically optimum launch scenario of the launch vehicle. The results on development of the modernized information-analytical system (IAS-IA) aimed at the information interaction of the IA databases (DB) with the applied technology, scheme and design solutions directed to an exception of residual fuel on the basis of methods of the control theory, game theory and solutions, experiment planning theory, time series regression analysis are presented.

1. Introduction

The operation of the launch vehicles (LV) with liquid rocket engines (LRE) is associated with a negative impact on the environment, which especially appears in the impact areas of the WS, due to the presence of specific properties of this vehicle: the presence of multi-stage and unused residues of liquid fuel in the tanks and fuel lines. The first property of a launch vehicle with LRE leads to the need to allocate significant areas on the surface of the Earth for areas where the lower WS fall, and for orbital WS this leads to littering of the near-Earth space with large-sized potentially explosive space debris. In addition, ensuring the fall of the WS in already designated impact areas leads to a decrease in the output mass of the payload of the LV into the orbits of operation. The second property of the LV with LRE leads to the increase in the likelihood of explosions and fires in the ground areas where the WS falls, chemical contamination of soils and water sources. All these occurrences take place in the impact areas of the Baikonur cosmodrome. Further development of LVs with LREs, for example, in the USA, goes in the direction of saving lower WS for their reuse, which leads to a sharp decrease in the area of the impact areas. It should be noted that the existing impact areas in the USA, EU, Japan, India are located in the waters of the World Ocean, where issues with the allocation of impact areas are less acute than in Russia and Kazakhstan.

The ecological safety of operating of the impact areas of the worked-off stages is one of the main strategic objectives, the ultimate goal of which is to protect public health, preserve biodiversity, prevent pollution, ensure the sustainable functioning of ecological systems, and reproduce and rationally use of natural resources.

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The impact of the LV launches as one of the types of the technogenic impact on the ecosystems of the impact areas has a number of specific features that make it fundamentally different from the other types of economic activity. This is due to the irregular periodicity of the launches, transboundary pollution, as well as the multi-vector impact on virtually all components of the geosphere - the Earth's surface, the atmospheric surface layer, the ozone layer, the ionosphere, near-earth space.

The long-term monitoring of the ecological consequences of the LV launches in the impact area indicates a negative technogenic load on ecosystems, their vulnerability and long-term recovery. During the continuous exploitation of the impact areas of the worked-off stages, natural complexes with soil contours contaminated with rocket fuel components (RFC) and their transformation products were formed. Even in the old places of fall of the separating parts of the launch vehicles, after 10–15 years, rocket fuel components are found in concentrations that exceed the maximum permissible concentrations (MPC) many times over.

The worked-off first steps are separated at altitudes of 60-90 km. The stage speed at the entry into the dense layers of the atmosphere is insufficient for its destruction, which may occur as a result of aerodynamic overloads or due to an explosion when the tanks are overheated with the fuel residues. In the case of the fall of the first stages, containing the RFC residues, an explosion is possible when hitting the ground, as a result of which the fragments of the stage fly away from the place of fall, and the combustion products and unreacted fuel residues enter the atmosphere and soil [1]. The rocket fuel components, remaining in insignificant volumes in the structural elements, are spilled on the soil and evaporate into the atmosphere. In some cases, spillage ignition may occur. Thus, when the first stages fall, the soil and vegetation cover is disturbed, the surface layer of the atmosphere, soil, vegetation is contaminated with residues of RFC and their combustion and transformation products, as well as vegetation cover ignites and the territory becomes littered with the stage fragments.

At present, the prospects for the development of rocket production are aimed at rescue, methods of return, and controlled descent of the worked-off first stages of the launch vehicle [2-7].

The proposed project considers the evolutionary concept of reducing the technogenic impact of the WS in the impact areas of the Baikonur cosmodrome based on the parallel implementation of two basic directions of reducing the technogenic impact of the WS in the impact areas:

- determining the optimal sites for the WS fall in the selected zones of the impact areas with the greatest resistance to technogenic impact, respectively, the minimum cost of work on restoring the soil grounds of the site of the WS fall to its original state; (A)
- controlled descent of the WS after separation from the launch vehicle in the designated site of the fall with an accuracy not exceeding the size of the selected optimal site (B). To solve problems related to direction A, it is proposed to create an additional information and analytical system of the impact area (IAS_{IA}), which is a part of the ecological monitoring system of the Baikonur cosmodrome (EMSC). To solve problems related to direction B, possible design solutions are proposed based on the evaporation of the unused liquid fuel residues in the WS tanks, ensuring its fire-explosion safety, and using the resulting vapor-gas mixtures for the controlled WS descent while moving on the descent trajectory to the optimum site located in a dedicated impact area zone.

2. Ecological state of the impact areas of the worked-off stages

According to the lease agreement of the Baikonur complex on the territory of Kazakhstan, 22 zones of fall with 46 impact areas of separating LV parts with a total area of 41,364.7 22 sq.km in Kyzylorda, Karaganda, Kostanay, Akmola, North Kazakhstan, East Kazakhstan, Pavlodar regions were allocated [18]. In addition, in accordance with [9], an additional allocation of a land area of 5.8 thousand hectares in the Kostanay region is envisaged as a new area of fall of separating parts of the Soyuz-2 LV when launching from the Baikonur cosmodrome to the north direction. In this regard, the problem of ensuring the ecological safety of the territories of the impact areas of the LV worked-off stages is becoming increasingly important due to the increasing requirements of national environmental legislation and public claims.

The main factors of technogenic load in the impact areas are [10]:

- mechanical pollution by the WS and their fragments (destruction of the structure and the subsequent dispersion of parts);
- chemical contamination by spills of the unused liquid RFC residues and its transformation products);
- pyrogen-thermal effects (fires, explosions).

Chemical contamination with the liquid RFC residues, leading to a high probability of fires, is associated with a high containment of the guaranteed unused fuel, which is the most aggressive factor of exposure. The magnitude of liquid residues of RFC for various types of LV can reach up to 3% of the initial charge of RFC and more.

Contamination of soil by RFC leads to significant physico-chemical transformations, expressed in a change in the microelement composition of the soil, its air and redox regimes. Groundwater and surface water are the successors of RFC and its decomposition and transformation products. When RFC gets into water, it is oxidized by oxygen contained

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in water, as well as active decomposition under the influence of solar radiation and in the presence of chemically active impurities.

Chemical contamination of soil profiles and groundwater depends on the concentration of pollutants on the surface, and the more the water load during detoxification of contaminated soils, the more toxic compounds (products of chemical transformation of the fuel) penetrate the soil. So, when the spillage enters the podzolic soil two months later after neutralization of the contaminated area, unsymmetrical dimethylhydrazine (UDMH) and its oxidation products can penetrate to a depth of 5-70 cm. The high filtration capacity of the sand contributes to its deeper penetration, clayey soils impede the deep migration of combustible substances.

Accumulation of RFC by plants depends on a complex of factors: the family of plants, the geochemical conditions of their habitats, the proximity of sources of technogenic pollutants, the amount of RFC that has delivered to the surface of the soil and plants. Low concentrations of RFC have no significant effect on the cytomorphological structure of plants. The effect of large concentrations cause morphological and anatomical changes in plants [1].

The main factors that has a negative impact on the environment, especially on animals, are pyrogenic and thermal disturbances of the plant and soil cover of the IA, arising from the WS fall. The fires initiated by the fall of the LV WS destroy the food supply and in this connection contribute to the extinction of phytophagous mammals, insectivorous reptiles and granivorous insect-eating birds, as well as the destruction of entomofauna and invertebrates. The practice of the LV operation has shown that deflagration and fires, damage of the vegetation cover due to the WS fall occur mainly in the impact areas of the spent boosters of the first WS with oxygen-kerosene main liquid rocket engines (LRE) [12].

The most likely causes of fires are liquid residues of RPC in the WS tanks, which ignite when the fuel compartments of the WS are destroyed at the moment of impact on the ground surface in the IA.

The probability of occurrence of fires depends on the position of a particular area in the altitude-belt spectrum of the territory (length of the snow covered period), the nature of the underlying substrates, the angle of inclination and exposure, which largely determine the redistribution of precipitation over the territory; the nature of its own vegetation (the presence or absence of rags, its height, density, the possibility of "drying out".

2.1 Evaluation parameters

Analysis of the nature of the WS fall of the separating parts of the LV in the assigned impact areas showed that the anthropogenic impact of rocket and space activities in the impact areas is local, differs for individual sections in intensity and density of the territorial distribution, and the landing of the first-stage tanks leads to the collapse of the structure, spill of the RFC residues, the occurrence of fires and, as a consequence, requires large expenditures on the complete elimination of technogenic consequences. Consequently, the determination of optimal areas for the WS fall in the selected zones of the IA with the greatest resistance to the technogenic impact should be based on the following provisions:

1) limiting the area of dispersion and the pattern of the spread of the WS fragments of the worked-off boosters of the first stages of modern LV by the calculated ellipsoid to clarify the area of anthropogenic impact;
2) the use of GIS technologies and the use of cartographic material to create a data set of information and analytical system of impact areas (IAS_{IA});
3) determination of estimated geological and geomorphological, hydrographic indicators of bioproductivity;
4) determination of seasonality and climatic conditions;
7) a description of economic activities in the impact areas of the worked-off stages and in adjacent territories;
8) determination of ecological (economic) damage;
9) determination of a set of estimated indicators and their threshold values, fixing the belonging of the zones to acceptable for the predicted aiming points, which will allow the selection of the desired zones.

As is known, the vulnerability and stability of a biogeocoenosis in the impact areas as a result of the action of negative anthropogenic factors is determined by the state of its main components — the ecotope (soil, climate, water) and biotope (vegetation).

Therefore, for the implementation of the first direction, the factors that determine the sustainability of the IA to the technogenic impact are considered: a) fire safety of vegetation and associated meteorological conditions; b) the condition of the soil cover, including the suppression of the fertility and the degradation of the soil cover; c) the state of vegetation.

2.1.1 Fire safety criteria

Fire hazard is determined by such fire and technical characteristics as combustibility; flammability; flame propagation velocity over the surface; smoke forming ability; toxicity [4-5].

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Resistance of ecosystems to pyrogenic effects is determined primarily by their ability to ignite and flammability. The formation of a combustible medium is caused by the presence in it of a sufficient amount of a combustible substance - plant biomass, which has various rates of combustion [16].

The risk of fire is determined by a complex of interconnected meteorological elements (precipitation, air humidity, its temperature, etc.).

A period from the moment of a descent of snow cover to the onset of stable rainy autumn weather or the formation of snow cover is considered to be fire hazardous. The risk of fires increases from the northeast of this area to the southwest following the increase in aridity of the climate. During the fire hazardous season, periods of fire highs are distinguished when the number of fires exceeds their average number.

It should be noted that the air temperature is determined at a level of 2 m above the ground. In the lower, near-surface layer of air, the temperature can reach substantially large values. Heating of the soil surface during the daytime is great - the average maximum surface temperature ranges from 48^0C to 59^0C in July, the absolute maximum reaches 76^0C.

2.1.2 Criteria for soil cover evaluation

The soil cover includes dozens of soil varieties with different physicochemical properties. Therefore, in order to simplify the work of collecting information and processing it, well-known reference data are used using the soil map of the region.

For assessing and grading the allocation of each site, it seems appropriate to determine soil bonitet [17]. Soil bonitation of the impact area should be carried out according to the standard soil bonitation techniques. The bonitet score of each soil variety is calculated from the percentage of humus in the half-meter layer, and correction factors are introduced for all other properties. The bonitet scale thus obtained is superimposed on the soil map.

Due to the instability of the soil to the mechanical load on the territory as a result of the impact of heavy fragments on the ground, mainly propulsion systems and fuel-pumping units, funnels of different dimensions are formed — 1-20 m in diameter, 0.3-1.5 m deep [1, 18]. As indicators of the resilience of the surface layer and the complexity of its destruction to determine the allowable load to the mechanical impact, accounting of mechanical properties of rocks on a scale of strength is used.

2.1.3 Criteria for evaluation of a vegetable cover

The potential of vegetation in the self-purification of ecosystems involved in the redistribution and accumulation of RFC depends on a combination of factors such as the type of the plant community, the geochemical conditions of their habitat, proximity to sources of chemical contamination of RFC, the amount of pollutants entering the surface of the vegetation, floristic composition and structure [19].

The response of vegetation to the technogenic effect of LV launches is expressed in the evaluation of the resistance of plant communities [1, 20]. The potential stability of plant communities is determined by the ecological and biological properties of the plants themselves [1, 19]. Restoration of some communities occurs relatively quickly. At the same time, individual communities are characterized by the low annual growth of the phytomass, their self-healing requires a longer period. A distinctive feature of all communities is their poor resistance to fires and, consequently, a long succession period of recovery.

To assess the resistance of phytocenoses to a specific technogenic impact, it is proposed to take into account the following parameters: a) density indicators (structure) of the plant community; b) projective cover (the ratio of the area in the landscape); c) phytomass.

2.2 Assessment of the economic costs of ecosystem restoration

The methodology for assessing ecological damage is based on the consistent implementation of the two main procedures: the determination of negative ecological changes and the identifications of its economic equivalent, i.e. the cost of the ecological damage [10].

According to the methodology for determining the payment for environmental pollution, the ecological damage is estimated according to the basic regulatory fees for emissions and discharges of pollutants. The amount of payment for the environment pollution in the impact area for each case of a standard WS fall is determined by the specific impact conditions: a fall with or without destruction, with or without spillage of fuel, volumes of spillage on the ground, discharge into water bodies, emission into the atmosphere, etc.

The total costs of the ecological support for launches and compensation of the ecological damage include the following expenses: charge for the environmental pollution, conducting ecological monitoring, clean-up of the territory, compensation for the decrease in agricultural production productivity and health care spending [10].

For example, in terms of the charge for the environmental pollution, the unit costs for waste disposal (in 1996 prices) were:

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- for kerosene T-1 (toxic waste class IV) - 70,000 rubles / ton;
- for asymmetric dimethyl hydrazine (toxic waste class I) - 490000 rubles / ton.

In the case of cleaning the area, including the collection, detoxification and disposal of residues of RPC and WS fragments, neutralization of the spillage, the costs of eliminating the consequences increase significantly.

For all impacts, sufficiently large payments to environmental authorities are provided. In 1995 prices, the cost of conducting controls in the RP amounted to ~ 107 million rubles per launch [10, 21]. In case that WS fragments get into the settlement, the consequences of all these impacts are more critical, require more rapid measures to eliminate their consequences and, possibly, evacuate the population and carry out various payments for material and moral damage [22].

The ecological and economic costs for the impact areas of separated stages for the LV Proton type can range from ~ 3% to ~ 35% of the launch cost (based on the launch cost, estimated at ~ 300 million rubles in prices up to August 17, 1998), and these costs significantly depend on the possible payment options for the environmental pollution and environmental management [10]. For LVs like Zenit and Soyuz, using kerosene T-1 as fuel, costs can range from 2 to 21 million dollars per launch in 2017-2018 prices [22].

Thus, the assessment of the economic costs in the impact areas for carrying out measures to minimize the technogenic consequences of the WS impact is a prerequisite and requires consideration when allocating an operational-territorial unit (OTU).

3. Description of the existing IAS- EMSC and justification of the IAS$_{IA}$ creation

3.1 Description of the existing IAS- EMSC

One of the key points in ensuring the ecological safety of rocket and space activities is the organization of the ecological monitoring system of the cosmodrome (EMSC) [10, 23].

The information support of the EMSC is presented by the developed databases of ecological data and is implemented by means of geo-information systems related to the modeling and visualization of geographic space and the solution of spatial problems. The main task of the IAS-EMSC is the formation of operational information and analytical assessment of the emerging extreme situations (accidents, spillages, etc.) and the making of operational and early decisions on the localization and liquidation (compensation) of ecological damage from the Baikonur cosmodrome activity. In the structure of IAS- EMSC, the following subsystems are distinguished: preparation of initial data for archiving and documentation; planning, accounting and control, analysis and regulation; mathematical and geoinformation modeling; information processing, analysis and decision making; regulatory support.

The existing IAS of the Baikonur Cosmodrome (IAS$_{BC}$) is aimed at monitoring, assessing the state of the territories, tracking flights and making management decisions to eliminate the consequences.

The capabilities of IAS- EMSC are mainly focused on the monitoring and analysis of chemical pollution of the territories of the impact areas. The main advantages of the current IAS are: cartographic support, populated database, monitoring of pollution over time, multilateral identification of impact factors, operating with GIS tools related to modeling and visualization of the geographic space and solving spatial problems.

The visual location of the IAS- EMSC subsystem is represented by the territorial location of the surveyed key areas and the creation of vector layers that have fields filled with information in the structure: IA number, coordinates of the place and dates of the fall, coordinates of sampling points, maximum MPC values, excess of standard indicators, used methodology of physical and chemical diagnostics, etc. The main parameters of resistance in the developed system of criteria of potential resistance to technogenic impact are indicators of chemical contamination, physical-chemical transformation of the RFC, biodiversity reduction and vegetation condition at the organism and ecosystem levels [6].

The upgraded IAS proposed for implementation includes monitoring of pyrogen-thermal and mechanical effects and is aimed at informational interaction of the database with the applied technological, schematic and design solutions aimed at eliminating fuel residues, reducing ecological load and chemical pollution of ecosystems by rocket fuel components and a corresponding reduction in impact areas, and collecting data on the economic value and measures taken to neutralize spilled fuel and restoring damaged grounds after receiving LV WS.

3.2 Justification for the creation of IAS$_{IA}$

The process of selecting the optimal sites for the WS fall into the selected IA zones is proposed to be based on the existing EMSC system with the introduction of the developed *IAS$_{IA}$*, which should analyze data on the soil and vegetation cover, terrain, availability of water sources, meteorological parameters; to classify homogeneous groups of biogeocenosis objects; specify the area of impact of standard WS falls.

IAS$_{IA}$ should perform the following functions:

- accounting of information about lithogenic basis, relief, types of soil (subsystem "Soils");

DOI: 10.13009/EUCASS2019-220

- preparation of information on the state of vegetation on the basis of archival cartographic data and satellite images (subsystem "Vegetation");
- preparation of information on seasonality and climate data analysis (subsystem “Meteofactors”);
- analysis of fire safety reference data on flammability and ignition parameters (“Fire safety” subsystem);
- accounting and economic evaluation of measures to eliminate the consequences of WS falls in the impact areas;
- classification of homogeneous groups of objects and analysis of the results of impact area zoning.

4. Development of IAS of the impact area (IAS$_{IA}$)

Based on the analysis carried out, the formulation of the task of creating an IAS$_{IA}$ WS can be formulated as follows:

1. Justification of the choice of landing sites of WS, which will limit the area itself and monitor the impact of rocket and space technology on the IA environment, as well as minimize the costs of eliminating the effects of anthropogenic impact at each launch of the launch vehicle.
2. It is advisable to determine the aiming points of worked-off stages that are resistant to anthropogenic loads in the alienated impact areas within the framework of the EMSC, which provides local monitoring of high-risk objects (objects of space centers, impact areas, territories that adjacent to the impact areas, areas along the launch routes). The choice of the predicted points of the LV WS fall is supposed to be made on the basis of zoning of this IA.
3. For the most effective organization of the ecological monitoring and assessment of the introduction of technologies and schematic and design solutions for controlled descent of the first stages of the launch vehicle, it is proposed to consider the information integration of the main systems - EMSC, design decision making systems (DDMS) by the LV developer and the worked off stage [24].
4. Within the framework of the IAS$_{IA}$ being created, the integration and coordination of the activities of organizations and departments involved in the ecological monitoring of the territories of the WS fall areas, as well as the LV developers, should be carried out. For example, the proposed system IAS$_{IA}$ in terms of ecological monitoring is focused on the use of heterogeneous information about the state of the environment (soil, flora, fauna, rivers and atmosphere); and information and analytical system of launch vehicle (IAS$_{LV)}$ is aimed at introducing technologies and design solutions and providing tactical and technical characteristics of the launch vehicle.

The main purpose of creating an IAS$_{LV}$ is to predict aiming points, to compare the predicted coordinates of the points of falling with the coordinates of the allowed falling zone, to estimate the amount of fuel residues and to make recommendations on adjusting the falling points of the LV WS.

4.1 Structure of the IAS$_{LV}$

The functional structure of the modernized IAS (IAS-M) includes:

IAS$_{BC}$ - the existing IAS of the cosmodrome
IAS$_{IA}$- additionally created by the IAS of the impact area of the WS
IAS$_{LV}$ - existing IAS for LV design
IAS - additionally created IAS to formulate recommendations for the LV design with improved ecological characteristics.

IAS$_{IA}$ is designed to generate data when developing promising launch vehicles in the area of landing of WS. Functionally IAS$_{IA}$ solves the following tasks:

a) from the received data on the upcoming LV launch from the *IAS$_{LV}$* (the initial aiming point of the WS fall in the assigned IA $R_{in}(x_i, y_i)$ the optimal aiming point at which the payload mass inserted to the specified orbit is maximal, dividing the area of the IA by N sections with Si areas (i = 1, ... N), so that $\sum_{i=1}^{N} S_i = S_{\sum}$;

b) in the chosen N areas, N possible predictable coordinates of the points of fall of the WS are selected;

c) distances $\Delta R_i = R_{opt}(x, y) - R_{pr}(x_i, y_i)$ are estimated for assessing the possibility of WS maneuvering by shifting the point of fall of the WS to these values and transmitted to the *IAS$_{LV}$*;

d) on the basis of the passport of this IA, the ecological damage $E_i[R_i(x_i, y_i)]$ from falling into this i-th section and, accordingly, the cost of restoration works, is calculated the each predicted point of fall $R_i(x_i, y_i)$;

e) the received information is transmitted to the *IAS$_{LV}$* for the calculation of the LV movement control programs in the active section of the launch trajectory and the WS control programs in the descent section to the selected point, which is determined from the analysis of the data array $\{C_i^{sa}[R_i(x_i, y_i)\}$ the estimation of the ballistic capabilities of the ABDS for maneuvering by changing the coordinates of the point of the fall by a
$\Delta R_i = R_{opt}(x, y) - R_{pr}(x_i, y_i)$ value.

4.2 IAS$_{IA}$ functionality

As follows from Fig. 1, it is possible to ensure the fall of the WS into areas with significantly different landscape conditions. At the same time, it is assumed that an ABDS is installed on the WS, which provides control of the WS movement on the descent trajectory. As a result of this control, the accuracy of the WS fall is similar to the landing accuracy of the Falcon-9 LV WS when landing at a cosmodrome or a floating barge.

It is assumed that the autonomous on-board descent system (ABDS) development and its installation on Russian LV, in accordance with the proposed concept is objectively necessary, since the existing concept of design and operation of Russian LV with LPE does not satisfy a number of modern requirements. This follows from the analysis of the development of the trend of world rocket construction [10, 24, 4, 5, 7], in particular, the continuous increase in the requirements for environmental safety by both international and Russian legislation, increasing competition in the market of launch vehicles.

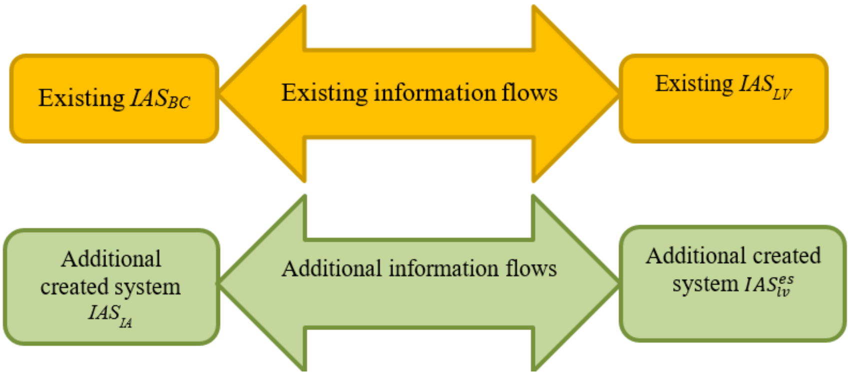


Figure 1: The general schematic diagram of information flows between
IAS_{BC}, IAS_{LV} IAS_{IA}, IAS_{LV}^{ES}

IAS_{LV}, which is part of the overall system for the design and exploitation of a launch vehicle, functionally provides:

a) the possibility of changing the predicted coordinates of the point of fall of WS to the other recommended points in the impact area, where the ecological consequences due to the characteristics of the impact area [1, 10] will be significantly less;

b) options for changing the coordinates of the points of fall of the WS, for example, by changing the pitch program, yawing on the active section of the LV launching phase [2] or by an additional autonomous on-board descent system installed on the WS [3], to implement the WS maneuver into other possible points of fall in the same designated impact area, but with more acceptable characteristics;

c) use of the energy optimal pitch program and the corresponding predicted optimal point of fall of the WS, while this point of fall must be in the R-neighborhood from the energy-optimal point of fall of the WS; The R-neighborhood is determined by the energy capabilities of the ABDS, the time of passive WS flight from the moment of separation from the LV to the moment of contact of the surface of the impact area.

In addition to the information received from the IAS_{IA}, which is necessary to improve the ecological safety of LV, the IAS_{LV} works on:

a) minimization of fuel residues in tanks after cutting-off of the main liquid propulsion engine;

b) assessment of the ABDS ballistic capabilities for the WS maneuvering on the trajectory of descent;

c) estimation of the possible spillages of residual fuel components from collapsed fuel tanks and WS lines in the predicted WS point of fall;

d) probability estimation of the WS explosion and the expected zone of fragment dispersion, etc.

IAS_{LV}^{ES} is an element of the existing IAS_{LV} which includes information and analytical models of the LV, starting with the stage of formation of tactical and technical and technical tasks, including the choice of design and construction parameters for LV, design and construction, technological, production documentation including for testing at all stages of fabrication of the material part in the manufacturer), operational documentation (for work on the technical and launch complexes of LV), network schedules of the work plan for the various phases of the LV life cycle.

IAS_{LV}^{ES} development within the framework of the concept of improving the ecological safety of LV with the main LPE in the impact areas of the WS provides for the use of information from the IAS_{IA} in several directions:

a) to change the program for controlling the movement of the launch vehicle at the launching phase (changing the points of aiming for the WS fall: the optimum point, an acceptable point from the condition of minimizing ecological damage, which is achieved by the adjusting the existing techniques for calculating LV launch programs);

b) to develop control of the WS movement with the ABDS use while moving along the trajectory of descent to the selected point on the territory of the WS impact area;

c) for the ABDS creation, which requires to complete a full cycle of its development with the assessment of the impact of the ABDS inclusion in the LV onboard equipment on the tactical and technical characteristics, reliability, operational properties and LV functioning;

d) determination of the ballistic capabilities of the ABDS for the displacement implementation of the coordinates of the WS point of fall by the value $\Delta R_i = R_{opt}(x, y) - R_{pr}(x_i, y_i)\ \ \Delta R_i$.

If the first two items a), b) are realizable within the existing IAS_{LV}, then the implementation of positions c), d) will require certain costs and time for the ABDS creation.

In accordance with the formulated concept of improving the ecological safety of LV with the main LPE [2, 3], an additional ABDS development (Figure 2.4) will allow to realize the main part to ensure the specified indicators for the ecological safety of LV in the WS impact area:

- extraction of unused fuel residues in tanks and WS lines after cutting off the main LPE on the WS trajectory of descending based on the technology of their transfer from the gas-liquid phase to the gas-vapor mixture [26];
- use of energy resources in the recovered vapor-gas mixture from fuel tanks to solve the problem of controlled descent of the WS [24];
- development of algorithms for controlling the gas-reactive system [30], ensuring the WS descent at the specified point in the impact area from the condition of minimum costs for compensation of environmental damage $\{C_i^{sa}[R_i(x_i, y_i)\}$.

4.4 Implementation of M-IAS$_{IA}$

The execution of M-IAS$_{IA}$ is standard, carried out using geo-information software. The technological scheme includes the collection of data, their primary processing and archiving, the formation of cartographic material, and the solution of applied monitoring problems. Its main components are cartographic mapping, database management and spatial data analysis.

Developing IAS$_{IA}$ in the proposed context with the use of data on the characteristics of vegetation and the imposition of meteorological parameters provides an assessment of the state of the environment, taking into account the factor of fire safety of the territory and climatic features.

The resulting OTU system, which must be obtained as a result of ecological zoning, is denoted by the symbol S_n, where n is the set of OTU. Each OTU$_i$ will be obtained by dividing into sections with different landscape characteristics by the imposition of an irregular grid indicating the geographical coordinates in a digital format. The OTU system is a “mosaic” of areas with the same ecosystem composition, for which resistant indicators are defined.

As a set of characteristics of the ecosystem are:

- land-assessment information derived from the cadastral assessment (on soil fertility and technological properties). Soil quality is assessed by the method of soil assessing on the basic properties affecting the value of fertility;
- bioproductivity, species composition of vegetation;
- geological and geomorphological characteristics (hillyness and the presence of local depressions in the flat terrain, softness and flowability of the soil grounds suggest the advantage of transporting technogenic pollution over the processes of their accumulation, thereby ensuring resistance of the ecosystem to RFC pollution [1];
- seasonality and climatic conditions for monitoring the fire hazard and migration of toxic components of rocket fuel.

The calculation of the OTU boundaries gives us a matrix “object-attribute”, for which the resistance of the object is calculated (resistance index $r_i(i = 1, \dots, N)$ and the economic assessment of the cost of its restoration - the cost of the indicator - $c_i(i = 1, \dots, N)$. Next, a time series of OTU resistance is constructed $Z(i) = f(b, c),\ i = 1, \dots, N$. The indicators are bonitet of the soil type, vegetation, etc. OTU can be interpreted as a difference matrix “object - object "on a set of attributes.

The goal of the typological classification is to obtain stable OTU groups in the M-dimensional attribute space. After the typological classification, each class is interpreted, i.e. the ranges of the each indicator change on the OTU of this class are highlighted. By comparison, we find $Z(m) = \min \{Z(i)\}, i = 1, \dots, N$. For Z (m), determine the optimal coordinates of the aiming point of the separating parts (SP) $R_{un}(x, y)$, at which the mass of the payload of the boosted LV to the given orbit is maximum.

5. Optimization of the areas distribution for the fall of the LV WS on the example of the U-24 zone of the Baikonur cosmodrome

The implementation of the proposed method of allocating the optimal operational-territorial unit (OTU) is based on the existing IAS of the cosmodrome. The land plots act as an OTU S_i (i= 1, 2, 3 N), and four indicators are proposed as indicators characterizing possible damage from the fall of the worked-off stage into an allocated OTU: a) fire safety Q_f (flammability and combustibility), b) soil strength Q_s, c) bonite of soil type Q_{bi}, d) state of vegetation Q_V (projective cover, biomass, recovery period).

The selection of the optimal types of OTU provides the following sequence of actions.

1. A grid of N areas with S_i areas (i = 1, 2, 3 N) is superimposed on the research area. Each S_i site represents a "mosaic" of areas with a specific ecosystem composition. The dimensions of the S_i areas can be equal or different, which is determined by the characteristics of the selected fall region, the degree of its detail.

2. Based on the analysis of inventory data, physical-geographical and natural-resource maps, IA passports, remote sensing data, ecological impact assessment methods [1] form a database for assessing the values of the criteria entered.

3. Estimation of the values of the introduced criteria $Q_{fi}, Q_{si}, Q_{bi}, Q_{Vi}$ for each site with an area of S_i.

3.1 Determination of fire safety criteria Q_{fi}

The fire safety of each site of the Q_{fi} territory is composed of the indicators of the flammability potential $\Delta\Pi_{\Gamma i}$ (kJ/mol) and the combustibility Q_{bi} (kW/m^2) of the dominant plant community [6]:

$$Q_{fi} = m_{1i}\Delta\Pi_{\Gamma i} + m_{2i}Q_{bi} \tag{1}$$

where m_1 [(kJ/mol)$^{-1}$], m_2 [(kW/m^2)$^{-1}$] are weight dimensional coefficients, which are determined for a specific selected area and are determined in accordance with the methodology, for example, [5].

To estimate the cost of C_{Si} funds required to restore the allocated area of OTU S_i from damage caused by fire, the indicator Q_{fi} (1) is multiplied by the value of the cost coefficient C_{fi}, which is determined in accordance with [1]

$$C_{Si} = Q_{fi}C_{fi} \tag{2}$$

3.2 To estimate the value of the Q_{si} criterion on the basis of the well-known scale [10], the percentage ratio of rock strength is determined with the determination of the weight coefficient of each rock k_{ni} and an average value is given

$$Q_{si(average)} = k_{1i}Q_{p1} + k_{2i}Q_{p2} + k_{3i}Q_{p3} + \cdots + k_{Mi}\,Q_{pn} \tag{3}$$

where M is the number of rocks counted in the S_i-th allocated area.

In accordance with [1], the estimated cost of C_{Si} is determined and, accordingly, the estimated cost of repairing damage is calculated by the Q_{si} criterion:

$$C_{Q_{pi}} = C_{pi}\sum k_{ni}Q_{kni} \tag{4}$$

3.3 The Q_{bi} criterion is evaluated by analogy with (2), (4), and the assessment of the cost of repairing damage according to the Q_{bi} criterion is:

$$C_{Q_{bi}} = C_{bni}\sum k_{bni}\,Q_{bni} \tag{5}$$

3.4 The evaluation of the criterion Q_{Vi} ,characterizing the state of vegetation cover, is an account of the phytomass Q_{vmi} (cwt/ha) and the projective cover Q_{ppri} (in %):

$$Q_{Vi} = n_{Vi}Q_{vmi}Q_{ppri} \tag{6}$$

where n_{Vi} [(cwt/ha)$^{-1}$] is a weight coefficient by analogy (1) and is determined in accordance with [6].

An additional criterion, v_{ri}, is the rate of ecosystem restoration (in points) after mechanical or pyrogenic impact, is introduced as the monitoring survey materials accumulate [6]. Accordingly, the cost of repairing damage by criterion Q_v, by analogy with (2), (4), (5), can be written in the form:

$$C_{Vi} = n_{Vi}Q_{vmi}v_{ri}C_{nvi} \tag{7}$$

4. The total indicator of the cost of recovery of damage $C_{\Sigma i}$ in the designated OTU by the S_i area from the effects of the above facts is the sum of the values (2), (4), (5), (7):

$$C_{\sum i} = C_{Si} + C_{Q_{pi}} + C_{Qbi} + C_{Vi} \tag{8}$$

5. The choice of the optimal zone S_{iopt}^{ws} for fall of WS is performed from the condition $min\ C_{\Sigma i}$ (9)

The algorithm for zoning of impact areas of the worked -off stages based on the extraction of nuclei is as follows:

1. Specify the area of impact of the worked-off stage on the environment. The area of impact of standard processes of the LV operation on the environment has to be obviously known, i.e. the specified impact area is zoned - dispersion ellipsoid.
2. On the ellipsoid, the boundaries of which are given by calculation, the inventory data and taxation data, physical-geographical and natural resource maps, aerospace remote sensing data are superimposed, form a set of values of natural and technogenic zoning attributes.
3. Carry out the identification of objects, which consists in establishing a one-to-one correspondence between the objects of the external table of attribute features of the analysis and the objects of the vector map layer
4. Based on spatial data analysis, class cores are isolated and a "similarity" matrix is obtained to determine the attribute space.
5. The evaluation scale is calculated on a set of natural and technogenic attributes.
6. Find typical OTU and classify them according to previously developed reliable classification features.
7. Conduct a detailed classification, taking into account the terrain, fire resistance, land use schemes and climatic conditions to exclude the migration of rocket fuel components and fires.
8. On the basis of the classification carried out, areas acceptable for target points, in which conditions for biological reproduction are absent, are distinguished.
9. Visualize and document the classification results in the form of maps and text descriptions.

As a result of the regionalization carried out and the identification of the typical OTU, a specific scheme is obtained for the allocation of potential target points, organization, mode of operation, and impact areas of adverse anthropogenic impact (Figure 2). Such an approach allows minimizing costs when conducting monitoring studies and making recommendations on design solutions.

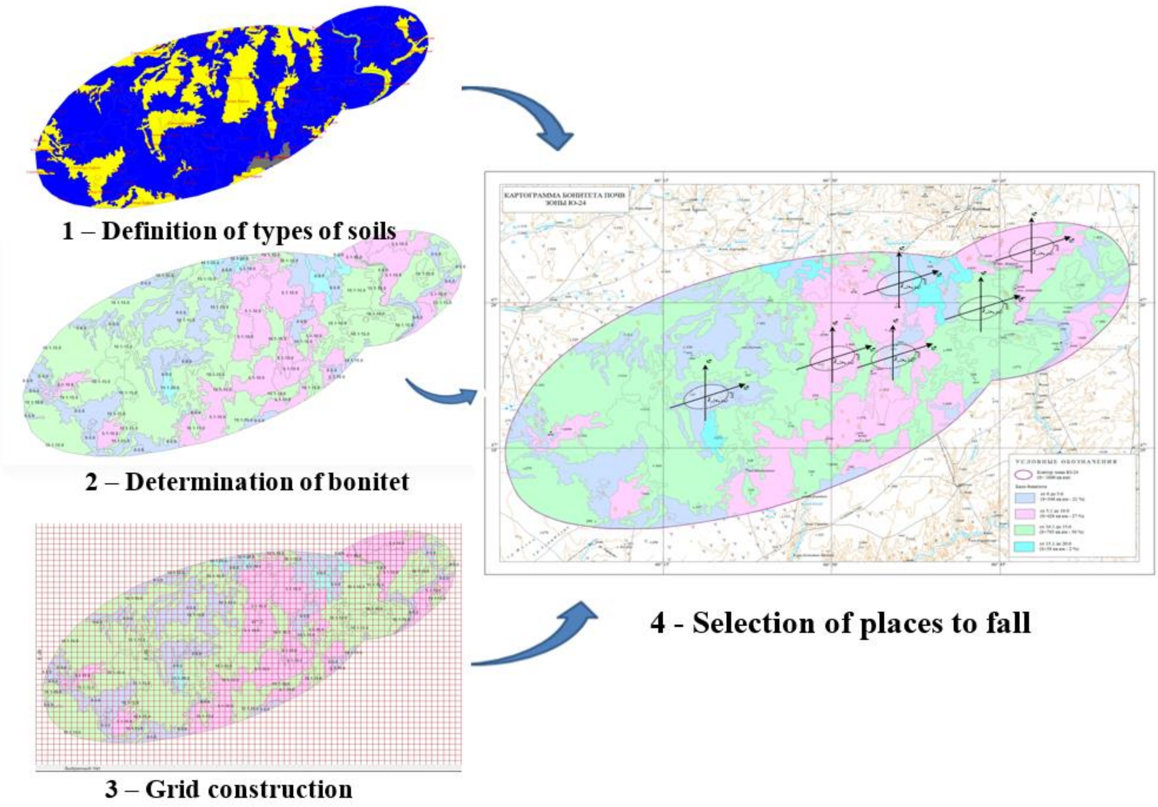


Figure 2: Algorithm for determining potential target pointsin a given IA using the example of the Yu-24 zone

6. Ensuring fire-explosion safety and controlled WS descent

6.1 Ensuring fire-explosion safety

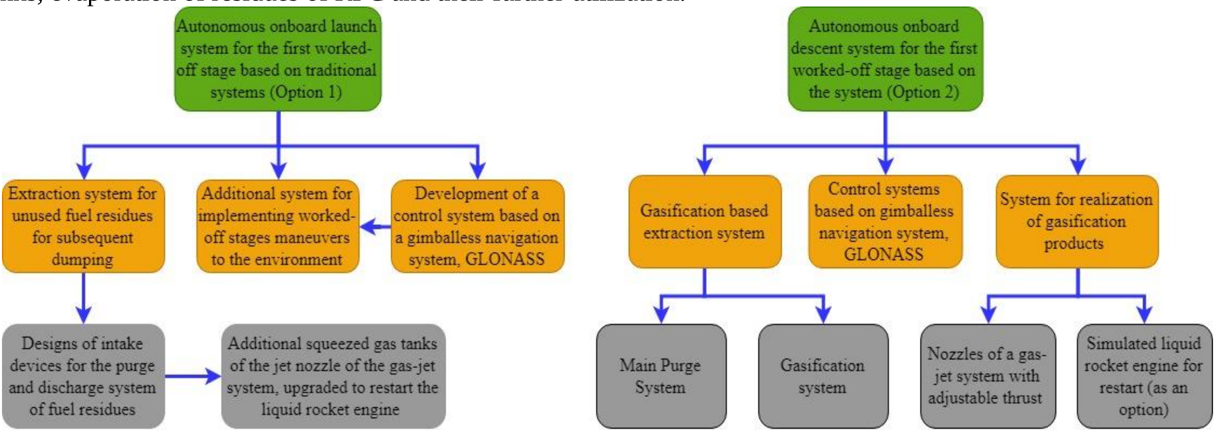
After separation of WS from LV in fuel tanks and main lines of WS, unused liquid residues of RFC always remain, which is the main cause of increased technogenic impact on the environment in the IA [1-2, 10, 26].

In this regard, at the design stage and ground-based development of the LV, considerable resources and time are spent on the elimination of non-used residual RFC in the tanks and fuel lines of the LV. The problem of liquidation of liquid residues of RFC is complicated by the fact that they are in an uncertain position in the volume of tanks, in the gas-liquid phase.

In accordance with the proposed technology, ensuring the fire-explosion safety of WS_1 is achieved by a sequence of the following actions:

- purge of fuel lines, in which the entire mass of RFC, located in the lines, gets into the corresponding fuel tanks;
- submission to the fuel tanks of the required amount of heat to evaporate unused liquid residues of the RFC;
- discharge of the resulting gas-vapor mixture from each tank through the gas-jet nozzles of the control system;
- in the tanks WS_1 there remains a boost pressure, which ensures the necessary strength of the structure under aerodynamic loading;
- by the time of the landing of WS_1, all liquid residues should be evaporated, and the vapor-gas mixtures are dropped during the flight of WS_1 on the descent trajectory.

In Figure 3 (a, b), there are 2 options that implement various technologies and circuit solutions for this task for a spent booster of the first stage LV-WS_1. Option 2 is based on the traditional approach, which involves the use of a system for discharging LRE residues through the shutdown LRE, squeeze membrane tanks, using terminal control methods to the fully worked-off the most toxic RFC and the shutdown of the LRE, etc. Option number 1 is based on the evaporation of unused liquid residues of RFC after the shutdown of the LRE. This option provides for the supply of heat to the WS tanks, evaporation of residues of RFC and their further utilization.



a) b)

Figure 3: Technological and circuit options for solving the problem of eliminating unused RFC residues in the tanks and fuel main lines of the LV after shutdown of the main LRE. (a) Traditional version based on the use of proven technical solutions, (b) Proposed option based on evaporation of the residual of RFC.

As follows from the technological solutions given in Figure 1 for the traditional and proposed options, the essential differences are the systems for extracting unused residues of liquid RFC. Common are the need to install the navigation and traffic control systems on WS_1, including: gimballess navigation system (GNS); global navigation satellite system (GLONASS); gasification implementation systems for gasification products (evaporation) - gas-jet system; possible modernization of the LREs for the re-launch on gasified RFC residues.

Regardless of the implementation options for technological, schematic and design solutions, everything leads to the need to create an autonomous onboard descent system (AODS) of spent boosters from the trajectory of lower WS or descent of upper WS from the orbits [27].

6.2 The controlled descent of the WS_1

The specificity of using the AODS is that if it is on board of the LV, it is possible to remove one of the most important limitations when calculating the program for the controlling reentry of the LV on the active part of the trajectory (the pitch program) - conditions for the WS fall into the selected IA. The implementation of this requirement leads to a significant reduction in the mass of the payload [2]. One of the main tasks solved by the AODS is the calculation of the WS descent control program, transferring its motion path from an energetically optimal path leading to the aiming point located at a distance D_1 from the start, to the falling path that leads to a selected point located at a distance D_2 from the start and located in a dedicated area S_{opt}^{ws} (Figure 2).

Figure 2 shows the scheme of the descent of WS$_1$ from the energy-optimal trajectory of descent to the falling

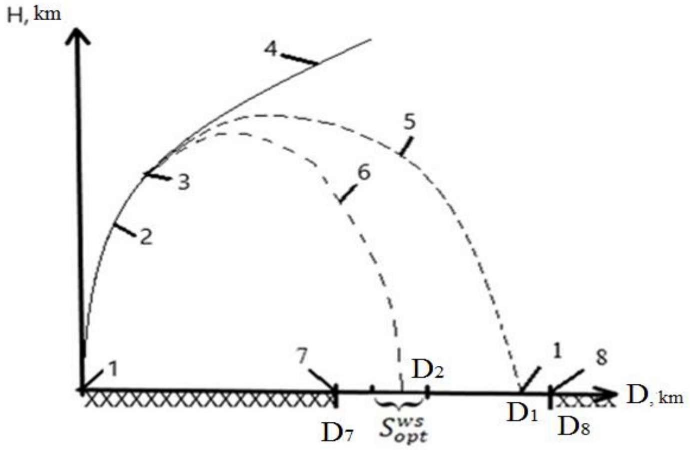


Figure 4: Scheme of controlled descent of WS$_1$ to the selected zone: 1 - launch point of the LV; 2 - the active part of the trajectory of the reentry of the LV first stage; 3 – separation of the WS$_1$; 4 - the active part of the trajectory of the re-entry of the LV second stage; 5 - ballistic trajectory of WS$_1$ descent, corresponding to the energetically optimal trajectory of the launch of the LV first stage; the point of WS$_1$ fall is at a distance of D$_1$ from the launch point of the LV; 6 - the falling trajectory of the controlled WS$_1$ descent to the selected zone S_{opt}^{ws}, the center of which is at a distance of D$_2$ from the launch point of the LV; 7 - the beginning of the territory of the IA, corresponding to the distance D$_7$ from the launch point of the LV$_1$; 8 - the end of the IA, corresponding to the distance D$_8$ from the launch point of the LV$_1$

When calculating the programmed motion of WS$_1$, which provides the transition from the optimal trajectory 5 to the falling trajectory 6, respectively, the fall of WS$_1$ into the selected zoneS_{opt}^{ws}, the center of which is at a distance D2 from the launch point of LV$_1$, corresponding energy resources are required onboard WS$_1$ (available energy reserves) as well as the available time T on the maneuver of the transition from trajectory 5 to trajectory 6.

The energy resources that can be placed when the WS$_1$ maneuver is performed are determined by the amount of residual of liquid RFC in the WS$_1$ tanks after shutdown of the LRE.

The available time for the T maneuver will be:

- From the total time of the passive flight of WS$_1$ along trajectory 6, determined jointly when calculating the program for the LV re-entry and controlled movement of the WS$_1$;
- Time to bring the AODS in working condition, i.e. carrying out a number of operations that provide for raising the pressure of vapor-gas mixtures in the tanks of the WS for their subsequent use as a working fluid in a gas-jet system.

To determine the design parameters of the evaporation system, it is necessary to develop an appropriate design methodology with subsequent experimental verification.

7. Conclusions

1. The analysis of the ecological status of the IA of the Baikonur cosmodrome has been carried out, the main negative factors influencing the launch of the launch vehicle have been identified. Technogenic factors affecting the launch of the launch vehicle are shown in chemical, mechanical and pyrogen-technical pollution of the IA environment.

2. To reduce the technogenic load, improve the efficiency of ecological surveys, IA monitoring and control, reduce the economic costs on eliminating the consequences of WS fall and restoring land, the following are taken:

   – determination of optimal sites for the WS fall in the selected zones of the IA with the highest resistance to technogenic impact, respectively, the minimum cost of work on restoring the soil grounds of the WS fall site to its original state;

   – controlled descent of the WS after separation from the LV in the designated site of the fall with an accuracy not exceeding the size of the selected optimal section.

3. To solve problems related to the управляемым спуском, it is proposed to create an additional IAS$_{IA}$, which is part of the ecological management system of the Baikonur cosmodrome. To solve problems related to direction B, possible design solutions are proposed based on the evaporation of unused liquid fuel residues in the WS tanks, ensuring its - fire-explosion safety, and using the resulting vapor-gas mixtures for controlled WS descent while moving on the descent trajectory to the optimum site located in a dedicated IA zone.

DOI: 10.13009/EUCASS2019-220

5. Within the framework of direction A, criterion assessments have been developed that characterize the main ecological indicators of the IA under study: fire hazard, soil cover, vegetation for subsequent inclusion in the IAS_{IA}. The objective necessity and the basic provisions for the creation of IAS_{IA}, which is a component of the ecological management system of the cosmodrome, are shown.

Acknowledgements

The studies were carried out with the support of the Science Committee of the Ministry of Education and Science of the Republic of Kazakhstan within the framework of grant No. AP05131162 “Theoretical and experimental studies of innovative technologies for developing a launch vehicle with improved ecological characteristics using the example of promising launch vehicles launched from the Baikonur cosmodrome”.

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