Mathematical estimation of surface zone polluted by rocket fuel upon falling of separated parts of carrier rockets

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The calculations of possible pollution zones of the surface by residual rocket fuel upon the fall of second stages of Proton carrier rockets launched from Baikonur Cosmodrome have been analyzed. The model developed was used to simulate the fall of an ensemble of unsymmetrical dimethylhydrazine (UDMH) drops in the atmosphere. Telemetric information on the descent trajectories of second stages of carrier rockets and input meteorological information obtained from Reanalysis (NCAR/NCEP) data were used.

Introduction

The problem of mathematical simulation of pollution of the surface atmospheric layer and the ground surface by rocket fuel upon the fall of separable parts of carrier rockets (CRs) is urgent by the following reasons.

The active parts of trajectories of the carrier rockets are designed so that the corresponding paths pass over sparsely populated regions, and CR separable parts fell in calculated regions of landing.[1] However, this does not exclude the pollution of the environment by rocket fuel remains and poses a threat to the people living in these regions. For more than forty years, this situation exerts an adverse effect on the people living in regions of falling of CR separable parts on the territory of Altai Republic.

Burned-out second stages of Proton rockets are separated from CR at altitudes of about 80–100 km and destroyed at altitudes of 30–40 km. Then the remains of rocket fuel (unsymmetrical dimethylhydrazine, UDMH) flow out into the atmosphere as the stages descend. The residue quantity of rocket fuel in second-stage tanks of Proton CR amounts up to 400–1000 kg UDMH.

To calculate the possible zones of surface pollution by the residual rocket fuel during the fall of the burned-out second stage of Proton CR launched from Baikonur Cosmodrome, we used the telemetric information about fall lines of the CR second stages.

The launches of heavy-weight three-stage Proton rockets from Baikonur Cosmodrome with orbit inclinations of 50.6–51.8°, 62.25–65.1°, and 70.0–71.7° correspond to the three second-stage impact areas (IAs) on the territory of Altai Republic with the central coordinates: IA-310 (50°54′N, 83°35′E); IA-326 (50°55′N, 88°35′E), and IA-327 (51°52′N, 87°34′E). The impact areas have the shape of an ellipse with an area of about 1500–5000 km^2. The calculations have been carried out for ninety episodes of the fall of second-stage remains in these three IAs from the period since 1980 through 2002.

Simulation of the atmospheric fall of an ensemble of UDMH drops

The developed model of the atmospheric fall of an ensemble of UDMH drops is described in Ref. 2 and based on results from Refs. 1, 3, and 4. The calculations were carried out in two versions: taking into account and neglecting the air humidity. The initial stage of drop formation was not considered, and the interaction between falling drops was ignored. It was assumed that the fuel flows out continuously along the descent trajectory of the second stage, starting from an altitude $H = 30$ km above the sea level. For four launches, the versions of point discharge of all fuel at different altitudes in a range from 30 km to the surface level were considered.

The input meteorological data needed for the calculations were obtained using the technology developed in the Russian Center for Hydrology and Meteorology. Within the framework of this technology, the initial fields, drawn on the basis of the results of objective analyses or NCAR/NCEP re-analyses, were used for three- or four-day forecast

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with the aid of the T40L15 global prognostic model. Thus, the calculations involved the actual meteorological information about the spatiotemporal distribution of meteorological fields of wind, pressure, temperature, and humidity.

The meteorological data corresponding to the second-stage impact areas were refined in the atmospheric boundary layer to provide for a more detailed temporal and spatial resolution of the calculations. For this purpose, we used a numerical-analytical model for the determination of the fields of wind velocity, temperature and humidity of air in the atmospheric boundary layer,[5] adapted to each impact area.

The model is based on the analytical solution of the system of equations for the atmospheric boundary layer taking into account orographic and dynamic surface inhomogeneities and a quasi-stationary sublayer. It accounts for the influence of the terrain altitude and the temperature of the surface on the wind velocity, temperature and humidity of air, as well as the turbulent exchange processes and, consequently, the spread of rocket fuel particles. The information about the terrain, types of the surface, and plant species was taken from the physical-geographic map of Altai Republic. Then, for every type of the soil and vegetation, the dynamic and thermophysical characteristics of the surface were determined using the reference data. The spatial distribution taken in the calculations was 4 min (latitude) by 2.5 min (longitude) and 100 m along the vertical with the total number of grid nodes equal to $76 \times 73 \times 21$.

When determining the distribution of the UDMH mass falling on the surface, the spread of the drop cloud due to the atmospheric turbulent diffusion was taken into account. The turbulent exchange coefficients in the boundary layer were determined by the model of an algebraic type, similar to that described in Refs. 6 and 7, using the hypothesis that the components of the tensor of turbulent diffusion coefficients are proportional to the corresponding components of the tensor of Reynolds stresses, experimentally confirmed under the open-atmosphere conditions.[8]

Analysis of calculated results

The calculated results are shown as isolines of the UDMH fallout density on the surface in the administrative map of the regions.

Table 1 presents the calculated values of the fuel amount Q, settled on the surface (in percent of the total amount emitted at every launch) and the variation coefficients K_v (ratio of the standard deviation to the mean values) for every IA, calculated taking into account the humidity and averaged over all launches and seasons. From Table 1 we can see the difference between IAs and between seasons. Thus, the average amounts of the fuel, fell out on the surface for all launches for IA-326 and IA-327, roughly coincide. The seasonal difference between the winter and the summer is maximum; the fuel fallout is 2.9 times higher for IA-326 and 3 times higher for IA-327.

The results described above were obtained assuming the fuel flows out to be uniform along the second-stage descent trajectory, starting from 30 km and to the surface level. However, situations are possible that the second stage breaks completely at some altitude and the fuel flows out at this altitude almost instantaneously. Mathematically, it corresponds to a point source. To study the characteristics of surface pollution by the fuel in this case, we have calculated four launches taking place on the following dates: winter – December 25 of 1997; spring – April 9 of 1996; summer – June 18 of 1999, and fall – September 26 of 1996. For each of these launches, ten versions of location of a point source at altitudes from 30 to 2.5 km were considered. The results of these calculations are shown in Fig. 1.

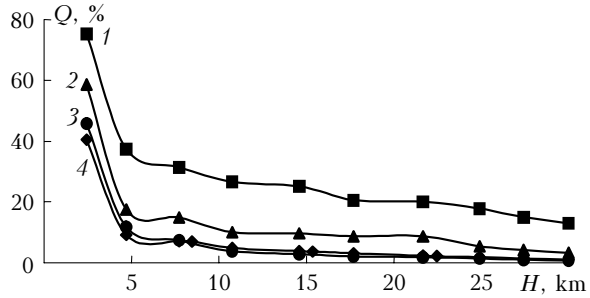

Fig. 1. UDMH fraction reaching the surface for the case that all the fuel flows out at an altitude H; seasons: winter (*1*), spring (*2*), summer (*3*), and fall (*4*).

The dependence of Q on the source altitude H is relatively weak in height range from 8 to 30 km and strong in the range from 2 to 8 km. This is explained by the fact that drops mostly evaporate in the troposphere. For comparison, in the case of a linear source Q = 5.4, 26, 11.7, and 5.4, respectively, for the fall, winter, spring, and summer.

Table 1. Fuel amounts Q (%), settled on the surface, and the variation coefficients K_v for each IA, averaged over all launches and seasons (N is the number of launches)

Impact area	All launches		Spring		Winter		Summer		Fall	
	N	Q, % (K_v)	N	Q, % (K_v)	N	Q, % (K_v)	N	Q, % (K_v)	N	Q, % (K_v)
IA-310	9	7.8 (0.22)	2	7.1 (–)	4	11.0 (0.26)	2	3.0 (–)	1	5.9 (–)
IA -326	57	7.1 (0.57)	14	6.0 (0.47)	16	11.0 (0.14)	13	3.8 (0.35)	14	7.1 (0.28)
IA -327	24	7.6 (0.45)	4	5.6 (0.38)	9	10.9 (0.23)	5	3.6 (0.35)	6	7.3 (0.20)

Figure 2 shows the dependence of the altitudes z of complete evaporation of the fuel drops on the initial radius for different altitudes of drop discharge, calculated by our model and presented in Ref. 3. Thus, for example, if a point source is at an altitude of 30 km, then the drops up to 1 mm in radius, falling from this altitude, evaporate at an altitude of about 22 km. All drops smaller than 1.5 mm in radius evaporate in air. Only particles having the initial radius larger than 1.5 mm reach the surface. If the source is at an altitude of 10 km, then drops larger than 0.8 mm in radius reach the surface. Thus, as in Ref. 3, *drops evaporate partly in the upper stratosphere and mostly in the troposphere below 10 km. Hence an important conclusion can be drawn: the increase of the altitude of UDMH discharge does not guarantee the evaporation of drops in the upper atmosphere.*

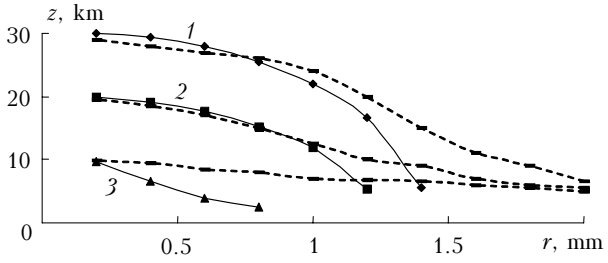

Fig. 2. Altitude z of complete evaporation of UDMH drops as a function of the initial drop radius r for a winter launch and different discharge altitudes H = 30 (*1*), 20 (*2*), and 10 km (*3*). The calculated results from Ref. 3 are shown by dashed lines.

The data presented in Ref. 3 correspond to the coldest month (January) over Kzyl-Orda station (44°46′N, 65°32′E) at the "minimum" vertical temperature profile, when the maximum fuel amount reaches the surface. A significant difference can be seen between the results presented. For example, if a source is at an altitude of 10 km, then, according to data from Ref. 3, all particles smaller than 2 mm in radius evaporate, not reaching the altitude of 5 km. However, according to our calculations, particles larger than 0.8 mm in radius reach the surface. It should be noted that, according to Ref. 3, *the mass fraction of drops reaching the surface at the "minimum" temperature profile upon the complete discharge at an altitude of 10 km is only 0.19% and poses no threat.* It can be seen from Fig. 1 that in our case this fraction is roughly equal to 27% in winter and 4% in summer. The average values, presented in Table 1, are roughly equal to 11% in winter and 3.8% in summer for IA-326 and 10.9% in winter and 3.6% in summer for IA-327. The values averaged over all launches are 7.1% for IA-326 and 7.6% for IA-327.

One of the causes for difference between our results and those presented in Ref. 3 is that our calculations account for possible effect of the atmospheric humidity on the process of droplet evaporation. To confirm this conclusion, we have carried out calculations on the determination of polluted zones in two versions, with and without the account of the atmospheric humidity. The comparison of these two versions was already considered in Ref. 2. Table 2 presents the calculated results for three launches in IA-326: two fall launches (on September 06, 1996 and September 26, 1996, relatively humid atmosphere) and one summer launch (on May 24, 1997, relatively dry atmosphere).

Table 2. Maximum density and mass of fuel reaching the surface as calculated taking into account and neglecting the humidity

Date	Humidity	$P_{max} \cdot 10^8$	Q, %
Sep 06, 1996	neglected	1.07	1.6
Sep 06, 1996	considered	2.11	5.2
Sep 26, 1996	neglected	0.38	2.0
Sep 26, 1996	considered	0.37	5.3
May 24, 1997	neglected	0.90	1.3
May 24, 1997	considered	0.88	1.8

Along with Q, Table 2 presents also the maximum surface density P_{max} of the fuel reaching the surface (kg/m^2) on the assumption that 1 kg of fuel flows out during the fall of the second stage (continuous flowing). The value of P_{max} is mostly determined by the altitude of the last point discharge. However, for all the launches presented in Table 2, this altitude is identical, which allows us to compare P_{max} for the three launches. It can be seen that the amount of the fuel reaching the surface with regard for the humidity is roughly 3.2 times larger than that with neglect of the humidity for the humid atmosphere (launch on September 06, 1996) and only 1.4 times larger for the relatively dry atmosphere (launch on May 24, 1997).

Another cause for a significant difference between our results and data presented in Ref. 3 is that the regions studied are at about 2–3 km above the sea level. In the experiment in Ref. 3, the surface lies at the sea level, that is, the difference between the altitudes of these two surfaces is 2–3 km. However, as was mentioned above, drops evaporate mostly just in the lower part of the atmosphere. Consequently, in Ref. 3 the drops continue to fall and evaporate in this layer, and the fraction reaching the surface is smaller than in our experiment.

For comparison, Fig. 3 shows the isolines of the fallout density for the launch on September 26 of 1996, calculated taking into account and neglecting the atmospheric humidity.

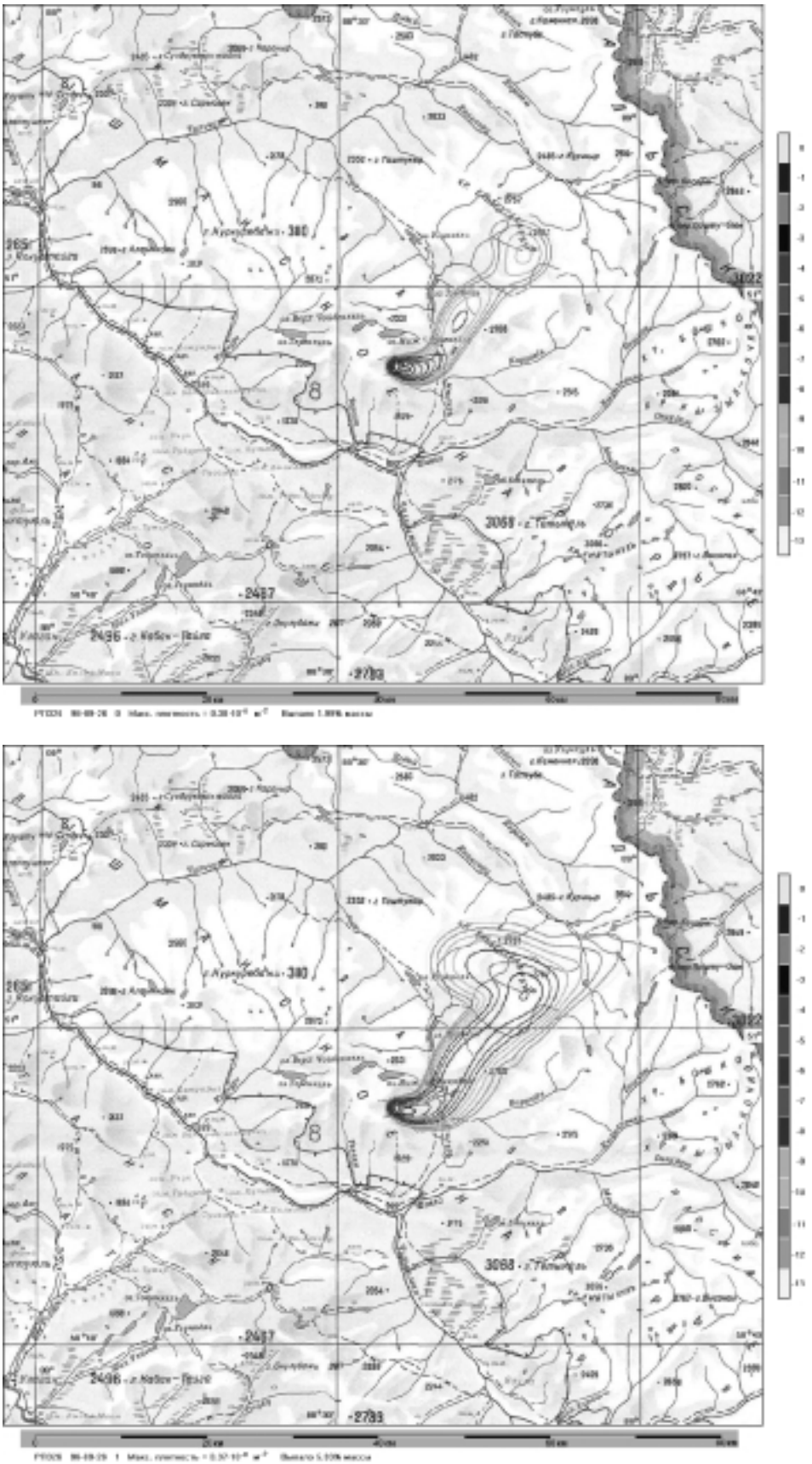

Fig. 3. Isolines of UDMH fallout density for the launch on September 26, 1996, calculated neglecting (top panel) and taking into account (bottom panel) the humidity of air.

Acknowledgments

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