Evaluation of the characteristics of rocket fuel dispersal by its content in the lake water

V.F. Raputa, A.P. Sadovsky, S.E. Olkin,
S.V. Zykov, I.K. Reznikova, and A.I. Smirnova

Institute of Computational Mathematics and Mathematical Geophysics,
Siberian Branch of the Russian Academy of Sciences, Novosibirsk
Scientific Research Institute of Aerobiology, SSC VB "Vektor,"
Kol'tsovo village, Novosibirsk Region
Institute of Chemical Kinetics and Combustion,
Siberian Branch of the Russian Academy of Sciences, Novosibirsk

Received November 29, 2000

We present a model of the spread of an evaporating aerosol impurity from a model high-altitude source. Based on this model, the inverse problem for evaluating the fields of the locality contamination is considered. Analysis of the data obtained is performed for the case of direct experimental detection of the rocket fuel in a number of lakes located in the area where the second stages of rockets descend. The predominance of the kinematical spread of the rocket fuel toward the underlying surface is shown, taking into account the current meteorological conditions, hydrological characteristics of lakes, the trajectory of the rocket stage descent, and the limitations on the guaranteed fuel supply.

Introduction

When separating the used rocket stages with liquid jet engines the emission into the atmosphere is possible of a great amount of highly toxic fuel components. The rocket fuel emission is accompanied by a series of interlinked physicochemical processes: diffusion, coagulation, droplet fragmentation, motion of mixture under the action of wind and so on. One of the most important characteristics is the regime of impurity emission along a trajectory of the rocket stage descent. The accuracy of quantitative estimates of a possible pollution of the ground surface and the atmospheric boundary layer essentially depends on how detailed is the description of the parameters of a mobile high-altitude source of impurity emission, current meteorological conditions, coagulation, and droplet evaporation.

In Ref. 1 it was evaluated the behavior of the rocket fuel droplets in the atmosphere when falling out from high altitudes in the Baikonur area. The results of this paper show that the main bulk, about 90% of asymmetric dimethylhydrazine (ADMH) is in the droplets of 1 to 3 mm radius and due to the processes of evaporation only relatively large droplets of radius more than 2 mm falling from 10 km altitudes, can reach the Earth's surface.

Under conditions of the "cold" atmosphere the probability of reaching the Earth's surface by droplets increases since the evaporation processes decrease markedly. Nevertheless, according to Ref. 1, even at low temperatures and the ADMH emission at 10 km altitude only about 0.19% of the total bulk of droplets reach the surface. Thus, taking into account the droplet scatter by the wind, we draw a conclusion that the soil contamination by ADMH in the areas where the second rocket stages descend is practically excluded.

Reference 2 considers in a similar way the evolution of ADMH droplets in the dry atmosphere over Yakutiya. The calculations when applied to winter conditions of the city of Verkhoyansk have shown that the probability of reaching the Earth's surface by droplets of radius more than 2 mm increases significantly that creates a real threat of pollution to the atmospheric boundary layer and the underlying surface.

The calculations carried out in Refs. 1–4 are only conventional since the data on the drop size distribution, the falling drop deformation, the source operation mode, etc. are of hypothetical nature. In this connection the supplementary experimental studies are necessary.

Statement of the problem

The description of processes of aerosol impurity transfer and diffusion from a mobile high-altitude source can be obtained based on a solution of semiempirical equation of turbulent diffusion[5,6]:

$$\frac{\partial q}{\partial t} + u(z)\,\frac{\partial q}{\partial x} - w(t,\, z)\,\frac{\partial q}{\partial z} = \frac{\partial}{\partial y} K_y \frac{\partial q}{\partial y} + \frac{\partial}{\partial z} K_z \frac{\partial q}{\partial z} + Q(t)\, f(\mathbf{s}) \qquad (1)$$

with the boundary and initial conditions

$$q\,\big|_{t=0} = 0,\ q\,\big|_{z=0} = 0,\ q \to 0 \text{ at } |\mathbf{x}| \to \infty, \qquad (2)$$

where $t > 0$, q is the volume particle concentration, x, y are the horizontal coordinates; the x axis is oriented along the direction of the mean wind $u(z)$, the z axis is directed upward, $w(t, z)$ is the gravity rate of particle precipitation; K_y, K_z are the coefficients of transverse and vertical turbulent diffusion, $Q(t)$ is the intensity of emission of the rocket fuel to the atmosphere, $f(\mathbf{s})$ is the function describing the trajectory of the stage descent, **s** are the point coordinates on the trajectory.

The steady rate of the drop fall (r is the drop radius) is determined in accordance with the Stokes law

$$w = 2\rho\, g\, r^2/(9\mu\, F/Fs), \qquad (3)$$

where ρ is the liquid density, F/Fs is the ratio between the deviation of a real force of medium resistance F and the Stokes force Fs, μ is the air dynamic viscosity, g is the free fall acceleration.

The deviation of the ratio F/Fs, depending both on the mode of streamline flow and on the falling drop deformation, is determined experimentally and described by the empirical formulae.[7,8] The droplet evaporation occurs when fuel droplets fall down. The rate of droplet evaporation in the atmosphere from the Earth's surface to the 60 km altitude is limited by the diffusion. In the diffusion-convective mode the evaporation rate is proportional to the droplet radius r[1]:

$$\mathrm{d}m/\mathrm{d}t = -\,4\pi\, D\, r\, (p - p^{\infty})\, F\eta, \qquad (4)$$

where m is the droplet mass, D is the diffusion coefficient of vapor molecules in the air, p^{∞} and p are the vapor density of an evaporating component in the ambient air and at the droplet surface, $F\eta$ is the correction factor, taking into account the effect of leading flux and the mode of streamline flow on the evaporation rate of a falling droplet.

The process of droplet evaporation is multifactor and significantly depends on the air temperature and on a large number of parameters, which call for the experimental determination.

For solving the problem (1)–(4) it is necessary to have a significant bulk of input data that makes its numerical realization difficult. In this connection it is appropriate to take the data of direct measurements of the rocket fuel content on the underlying surface and in different atmospheric layers that allows one to turn to the statement of an inverse problem of the impurity transport.

The unknown parameters should be evaluated by minimizing the square-law functional[9,10]:

$$J(\theta) = \sum_{i=1}^{N} \sigma_i^{-2}\, [p_i - q(x_i, \theta)]^2 \qquad (5)$$

at the limitations of (1)–(4). Here θ is the vector of unknown parameters, p_i denotes the data of impurity concentration measurements at the points x_i, σ_i is the variance of the observation errors.

The efficiency of assessment of the results can be increased significantly by the inclusion of supplementary *a priori* information about the processes and by appropriately positioning the observation system. The two cases should be mentioned corresponding to the following sedimentation rates[5]:

$$U_\mathrm{m}/W \le 10, \qquad (6a)$$

$$U_\mathrm{m}/W > 60, \qquad (6b)$$

where U_m is the mean wind velocity, W is the sedimentation rate. The kinematical and diffusion schemes of the spread are realized.

In the case (6a) the maximum heptyl fallouts can be expected at a distance X_max along the direction of mean wind U_m from the tanks blast site. The value of X_max is estimated by the following ratio[5]:

$$X_\mathrm{max} \le H\, U_\mathrm{m}/W, \qquad (7)$$

where H is the emission altitude.

In the case (6b) the processes of vertical and horizontal turbulent diffusion strongly affect the impurity dispersal. Heptyl fallouts can be expected to occur over a very vast territory. In this case the value of X_max can be more than 1000 km.[11] The density of aerosol fallouts will be small and it varies slightly within the limits of this territory.

Evaluation of aerosol heptyl fallouts

The cases of direct experimental detection of large quantities of rocket fuel in the atmospheric boundary layer and on the underlying surface arouse great interest. Based on the use of inverse problems of impurity transfer the above-mentioned detection allows to improve the estimates of zones of possible pollution, dispersed composition, and time of passage of aerosol cloud, regimes of fall out of rocket fuel from used rocket stages. In our opinion, the exploration should be made of water objects and snow surfaces fitting largely the conditions of homogeneity and having the preserving characteristics that makes it possible to study the above objects regularly within wide time and spatial limits.

As an example we consider the data on the exploration of lake water in the region where the second rocket stages descend on the territory of the Chistoozerny district of Novosibirsk region (FR 213). Heptyl, i.e., asymmetric dimethylhydrazine, was found in some lakes (Table 1, Fig. 1) after launching the rocket "Proton" from Baikonur on October 26, 1996. Its specific content detected in the lakes varies within wide limits from 1 μg/l (lake Krugloe, No. 18) to 20 μg/l (lake Kazenoe, No. 20), 24 μg/l (lake Gorko-Solenoe, No. 13). These distinctions can be explained by several factors: the position of the lake relative to the trajectory of the descending rocket parts, the wind direction, the area and the bulk of water in the lake.

The use of cartographic data on the area and mean depth of lakes enables us to evaluate the content of rocket fuel in the lakes. Table 1 shows the estimates of heptyl mass in the lakes on the assumption that their mean depth is 1 m. From data of Table 1 it follows that the net mass of heptyl in the lakes is about 142 kg at the total area of water surface 21.6 km^2. Hence we obtain the value of mean density of fallouts $P = 6.5$ kg/km^2. Relatively high content of ADMH is observed in the lakes Nos. 13, 19, 20, 2, 10, that is closely connected with their location relative to the trajectory of a rocket stage descent and the wind direction. It should be noted that simultaneous presence of ADMH in the investigated lakes points to the continuity of the pattern of its fall out among the lakes. Because the area among the lakes is much larger than the area of the lakes, then with the account of the estimate of the net content of ADMH (142 kg) in the lake water it follows that the net fallouts of ADMH to the underlying surface can be compared with the amount of the guaranteed fuel reserves (500–1000 kg).

Table 1. Estimates of heptyl (C_7H_{15}) falling out to lakes of FR 213

Name of lake and number of sampling point	ADMH content, μg/l	Lake area, km^2	Mass of heptyl, kg
Solenoe (No. 2)	4	2.1	8.4
Teniz (No. 3)	2	0.8	1.6
Kulmakan (No. 10)	3	6.2	18.5
G.-Solenoe (No. 13)	24	1.1	27.1
Utinoe (No. 16)	2	2	4
Krugloe (No. 18)	1	1.5	1.5
Volshe-Ples (No. 19)	9	7.1	63.6
Kazenoe (No. 20)	22	0.8	17.3

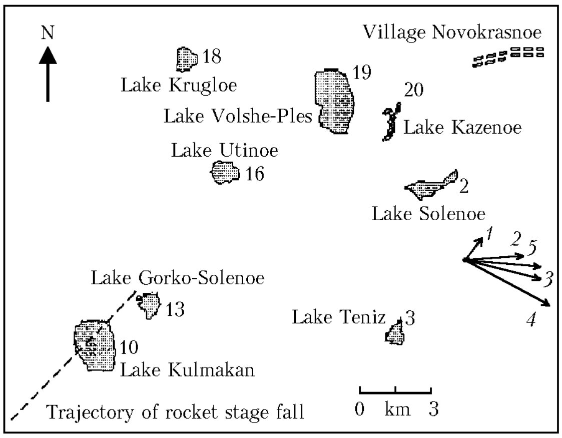

Fig. 1. Diagram of the area survey. Directions and wind velocities at altitudes: 10 m (4 m/s) (*1*); 1.5 km (10 m/s) (*2*); 5 km (14 m/s) (*3*); 11 km (17 m/s) (*4*); 16 km (14 m/s) (*5*) are indicated by arrows.

This conclusion can be drawn on a more precise basis if the territory of the area, on which the presence of ADMH was revealed, is characterized by a polygon constructed according to (encompassing) lakes located at its tops and numbered 10, 18, 19, 20, 2, 3. The area of this polygon is 260 km^2. On the other hand, the value of P calculated above allows for estimating the area of the main fallouts of ADMH, which at the guaranteed fuel reserves – 500–1000 kg is 80 to 160 km^2. Comparing the obtained values with the area of encompassing polygon, we can conclude that in this case the great bulk of ADMH is in the fall area.

Because of the limitedness of the dimensions of the area of rocket fuel fall out the conclusion can be drawn that mainly the kinematical sedimentation of ADMH has occurred in the form of large drops and aerosols, described by the inequality (6a). Really, according to Fig. 1 the angle between the trajectory of rocket stage descent and the direction of the mean wind is no less than 45°. In this case, taking into account (6a) the estimate

$$X^t_{\max}(H) \le 10\, H \sin 45°, \tag{8}$$

takes place, where $X^t_{\max}(H)$ is the distance from a horizontal projection of the rocket stage trajectory to the point of falling out of particles emitted at the altitude H.

Because the transverse dimensions of FR 213 do not exceed 22 km, then according to Eq. (3), the limiting values of $X^t_{\max}(H)$ can be obtained only for relatively small H of the order of 1–2 km that confirms the reality of the case (6a).

Table 2. Specific outflow of heptyl along the trajectory of the second stage

Altitude of the source, km	Horizontal velocity of rocket stage, km/s	Distance from the point of tank explosion L_i, km	Relative rate of heptyl outflow S_i, km^{-1}
30	2.301	23	0.04
25	1.062	33.6	0.09
22	0.503	38.7	0.20
19	0.378	42.4	0.27
17	0.295	45.4	0.33
15	0.251	47.9	0.40
13	0.22	50.1	0.45
11	0.2	52.1	0.50
9	0.171	53.8	0.59
7	0.154	55.4	0.62
5.5	0.141	56.8	0.71
4	0.131	58.1	0.77
3	0.122	59.3	0.83
2	0.115	60.4	0.91
1	0.109	61.5	0.91
0	0.104	62.6	0.91

In accordance with the telemetry data collected at a discreteness of 10 s, Table 2 shows the rocket stage altitude, its horizontal velocity, and the possible distance from the place of tank explosion. From the joint analysis of data, given in Tables 1, 2 and Fig. 1, it follows that in this case an instantaneous emission of ADMH to the atmosphere did not occur. The most probable is the realization of emission in the form of a linear source, especially in the low part of the trajectory, at 9–11 km altitudes. In particular, the regime of gradual emission does not contradict the available data. In this case the relative intensity S of a linear source in a discrete form is expressed by the set of equations

$$S_i = 1/(L_i - L_{i-1}),\ i = 1,\ \ldots,\ 15, \qquad (9)$$

where L_i is the horizontal distance from the place of the tank explosion.

From expression (9) and Table 2 it follows that because of a sharp decrease of the rocket stage velocity the emission increases essentially and the basic emission of ADMH occurs in the lower layers of the atmosphere.

Conclusion

The joint analysis of data on the ADMH pollution of lake waters, meteorological conditions, and characteristics of the trajectory and other limitations makes it possible to draw the following conclusions:

– the descent of the second stage of the rocket "Proton" on September 26, 1996 in RP213 resulted in the emission of a great deal of the guaranteed ADMH reserve that settled in this region;

– the relative compactness of the contamination zone is indicative of the primarily kinematical mechanism of the fall out of the rocket fuel in the form of large drops and aerosols;

– the ADMH income to the atmosphere was realized in the regime of a linear source along the trajectory of the rocket stage descent.

It should be noted that the description of the behavior of ADMH droplets in the atmosphere proposed in Ref. 1 calls for further essential correction. To increase the reliability of interpretation of the observation data on pollution of a locality and parameters of the ADMH emission source, proper allowance must be made for the hydrological and hydrochemical characteristics of the water basins and temperature and oxygen regimes.

When investigating the rocket fuel falling out on the snow surface, the volume characteristics of the ADMH specific content per unit volume of water can be found to be unrepresentative in violating the conditions of snow cover homogeneity and sampling uniformity. The data on the ADMH fall area are more stable. The optimization of the observation system is necessary in accordance with the current meteorological parameters, the conditions of locality, possibilities of properly positioning the sampling points, *a priori* information about regimes of rocket fuel emission into the atmosphere.

References

1. E.L. Aleksandrov, Meteorol. Gidrol., No. 4, 36–45 (1993).
2. I.N. Vasil'ev, Nauka i Obrazovanie, No. 1, 39–41 (1999).
3. A.P. Sadovskii, V.F. Raputa, S.E. Ol'kin, S.V. Zykov, and I.K. Reznikova, Atmos. Oceanic Opt. **13**, Nos. 6–7, 625–630 (2000).
4. L.V. Kudryavtseva, Meteorol. Gidrol., No. 3, 41–50 (1982).
5. G.M. Petrova and A.N. Miroshkina, Trudy Ins. Prikl. Geopfiz., Issue 7, 5–40 (1967).
6. N.S. Byzova, *Scattering of Impurity in the Atmospheric Boundary Layer* (Gidrometeoizdat, Moscow, 1974), 191 pp.
7. R.L.C. Flemmer and C.L. Bancs, Powder Technol. **48**, No. 3, 217–221 (1986).
8. E.L. Aleksandrov, Izv. Akad. Nauk SSSR, Fiz. Atmos. Okeana **26**, No. 8, 878–880 (1990).
9. V.F. Raputa and A.I. Krylova, Meteorol. Gidrol., No. 2, 49–58 (1995).
10. A.I. Krylova, V.F. Raputa, and I.A. Sutorikhin, Meteorol. Gidrol., No. 5, 49–58 (1993).
11. Yu.A. Izrael, A.S. Volkov, and A.F. Kovalev, Meteorol. Gidrol., No. 3, 5–11 (1995).