УДК 629.76017: 614.83 https://doi.org/10.33136/stma2024.01.040

E. H. Hladkyi, Dr. of Engineering Sciences; A. F. Sheiko

ASSESSMENT OF RISK OF TOXIC DAMAGE TO PEOPLE IN CASE OF A LAUNCH VEHICLE ACCIDENT AT FLIGHT

Despite stringent environmental requirements, modern launch vehicles/integrated launch vehicles (LV/ILV) burn toxic propellants such as NTO and UDMH. Typically, such propellants are used in the LV/ILV upper stages, where a small amount of propellant is contained; however, some LV/ILV still use such fuel in all sustainer propulsion stages. For launch vehicles containing toxic rocket propellants, flight accidents may result in the failed launch vehicle falling to the Earth's surface, forming large zones of chemical damage to people (the zones may exceed blast and fire zones). This is typical for accidents occurring in the first stage flight segment, when an intact launch vehicle or its components (usually individual stages) with rocket propellants will reach the Earth's surface. An explosion and fire following such an impact will most likely lead to a massive release of toxicant and contamination of the surface air. An accident during the flight segment of the LV/ILV first stage with toxic rocket propellants, equipped with a flight termination system that implements emergency engine shutdown in case of detection of an emergency situation, has been considered. To assess the risk of toxic damage to a person located at a certain point, it is necessary to mathematically describe the zone within which a potential impact of the failed LV/ILV will entail toxic damage to the person (the so-called zone of dangerous impact of the failed LV/ILV). The complexity of this lies in the need to take into account the characteristics of the atmosphere, primarily the wind. Using the zone of toxic damage to people during the fall of the failed launch vehicle, which is proposed to be represented by a combination of two figures: a semicircle and a half-ellipse, the corresponding zone of dangerous impact of the failed LV/ILV is constructed. Taking into account the difficulties of writing the analytical expressions for these figures during the transition to the launch coordinate system and further integration when identifying the risk, in practical calculations we propose to approximate the zone of dangerous impact of the failed LV/ILV using a polygon. This allows using a known procedure to identify risks. A generalization of the developed model for identifying the risk of toxic damage to people involves taking into account various types of critical failures that can lead to the fall of the failed LV/ILV, and blocking emergency engine shutdown during the initial flight phase. A zone dangerous for people was constructed using the proposed model for the case of the failure of the Dnepr launch vehicle, where the risks of toxic damage exceed the permissible level (10^{-6}). The resulting danger zone significantly exceeds the danger zone caused by the damaging effect of the blast wave. Directions for further improvement of the model are shown, related to taking into account the real distribution of the toxicant in the atmosphere and a person's exposure to a certain toxic dose.

Key words: launch vehicle, critical failure, flight accident, zone of toxic damage to people, zone of dangerous impact of the failed launch vehicle, risk of toxic damage to people.

Сучасні ракети-носії/ракети космічного призначення (РН/РКП), незважаючи на жорсткі екологічні вимоги, використовують токсичні компоненти ракетного палива АТ і НДМГ. Зазвичай такі компоненти використовують на верхніх ступенях РН/РКП, де міститься незначний об'єм палива, проте окремі РН/РКП досі застосовують таке паливо на всіх маршових ступенях. Аварії під час польоту РН/РКП, що містять токсичні компоненти ракетного палива, можуть призводити до падіння аварійної РН/РКП на поверхню Землі й утворення значних за розмірами зон хімічного ураження для людей (можуть перевищувати зони ураження від вибуху та пожежі). Це притаманно аваріям на відрізку польоту першого ступеня, коли поверхні Землі досягатимуть незруйновані РН/РКП або її складові частини (як правило, окремі ступені) з компонентами ракетного палива. Вибух і пожежа під час такого падіння, найімовірніше, спричинить залповий викид токсиканту та забруднення приземного шару атмосфери. Розглянуто аварію на етапі польоту першого ступеня для РН/РКП з токсичними компонентами ракетного палива, яку обладнано системою польотної безпеки, що реалізує аварійне вимкнення двигуна у разі виявлення аварійної ситуації. Для оцінювання ризику токсичного ураження людини, що знаходиться у певній точці, необхідно математично описати зону, в межах якої можливе падіння аварійної РН/РКП спричинить токсичне ураження людини (названо зоною небезпечного падіння аварійної РН/РКП). Складність цього полягає у необхідності враховувати стан атмосфери, насамперед вітер. З використанням зони токсичного ураження людини при падінні аварійної РН/РКП, яку запропоновано подавати сукупністю двох фігур: півкола та півеліпса, побудовано відповідну зону небезпечного падіння аварійної РН/РКП. Ураховуючи складності запису аналітичних виразів для цих фігур під час переходу до стартової системи координат і подальшого інтегрування при визначенні ризику, у практичних розрахунках зону небезпечного падіння аварійної РН/РКП запропоновано наближати багатокутником. Це дозволяє використати відому процедуру визначення ризиків.

Узагальнення розробленої моделі визначення ризику токсичного ураження людини передбачає урахування різних типів аварійних відмов, які можуть спричинити падіння аварійної РН/РКП, та блокування аварійного вимкнення двигуна на початковому відрізку польоту. Для випадку аварії РН «Дніпро» з використанням запропонованої моделі побудовано небезпечну зону для людини, у якій ризики токсичного ураження перевищують допустимий рівень (10^{-6}). Отримана небезпечна зона значно перевищує небезпечну зону, яка зумовлена уражальною дією вибухової хвилі. Показано напрямки подальшого удосконалення моделі, що пов'язані з урахуванням реального поширення токсиканту в атмосфері й отримання людиною певної токсодози.

Ключові слова: ракета-носій, аварійна відмова, аварія на етапі польоту, зона токсичного ураження людини, зона небезпечного падіння аварійної ракети-носія, ризик токсичного ураження людини.

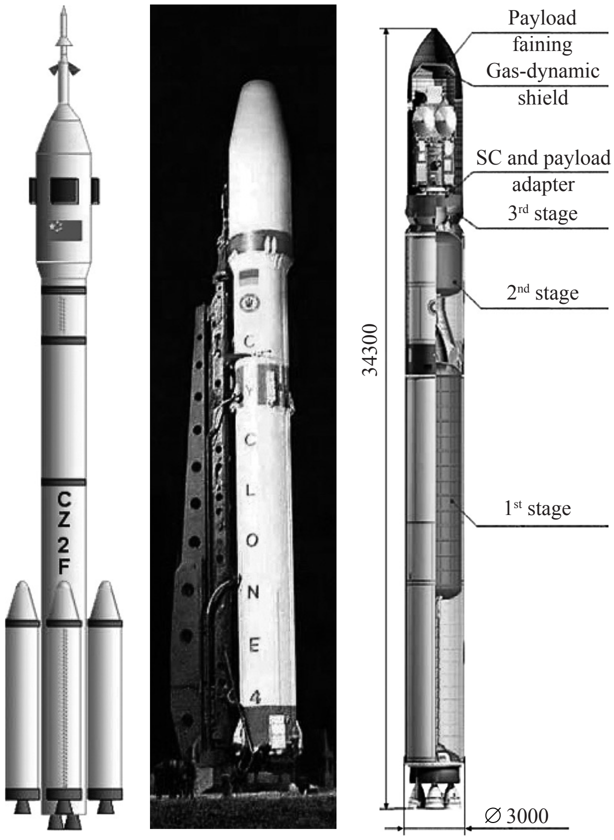
Introduction

Despite the fact that operational reliability of modern launch vehicles and integrated launch vehicles (hereinafter referred to as LV/ILV) while launching spacecraft into orbit has increased significantly, nevertheless, LV/ILV flight safety assurance issues remain relevant. This is due to the fact that there is still a small probability of critical failure (CF) which will lead to the fall of the failed LV/ILV and possible damage to people and facilities along the launch groundtrack. International and national standards define flight safety requirements in the form of acceptable levels of risk for people and facilities in the event of a LV/ILV accident during the flight segment (see, for example, [5–8]).

When analyzing flight safety, the greatest attention should be paid to LV/ILV accidents at the first stage flight segment, because such accidents have the most dangerous consequences. The fall of an intact failed LV/ILV with significant reserves of rocket propellants on board will be accompanied by a powerful explosion, a strong fire, and, in case of using highly toxic rocket propellants such as nitrogen tetroxide (NTO) and unsymmetrical dimethylhydrazine (UDMH) on board the LV/ILV, possible chemical contamination of the surface air. These factors determine the main hazards for people and facilities that may be in the zone of a possible impact of the failed LV/ILV, as well as the area affected by such an impact. The factor of toxic damage is considered exclusively in relation to people and can significantly increase individual risks and the size of the danger zone, where individual risks exceed acceptable levels. It turns out that in the event of an impact of the failed LV/ILV using toxic rocket propellants, the zone of toxic damage to people may exceed the danger zone created by blast and thermal effects; therefore, the zone of toxic damage to people will be determining for LV/ILV accidents in the first stage flight segment.

1. Using toxic rocket propellants in modern LV/ILV

Taking into account today's strict environmental requirements applied to space launch systems, toxic propellants such as NTO and UDMH are being used less and less in LV/ILV in operation (or in development). Preference is given to more environmentally friendly propellants: oxygen + kerosene, oxygen + hydrogen or oxygen + methane. Using NTO and UDMH in modern LV/ILV is usually limited to the upper stages, where a small volume of toxic propellant is contained. For example, the Cyclone-4M, which is being developed in Yuzhnoye SDO, uses the second stage burning NTO and UDMH. Similar propellants were used in the fourth stage of ESA's VEGA launch vehicle, second stage of Indian GSLV and PSLV launch vehicles, etc. Currently, it is the People's Republic of China that uses toxic fuel in its launch vehicles the most. This is a family of two- and three-stage launch vehicles Long March-2 (Fig. 1, a), -3 and -4, which is the main family in PRC's space programs (in particular, the manned program). The propulsion stages and strap-on boosters in these launch vehicles burn NTO and UDMH. Ukrainian-developed launch vehicles that used NTO and UDMH in the sustainer propulsion stages include the Cyclone-4 launch vehicle, whose development was discontinued, and the Dnepr launch vehicle converted from the 15A14 and 15A18 ballistic missiles (operation discontinued); see Fig. 1, b, c.



a b c

Fig. 1. LV/ILV with toxic propellants:
a – Long March-2F, PRC; b – Cyclone-4, Ukraine;
c – Dnipro, Ukraine

2. Scenarios of LV/ILV accidents accompanied by the formation of a toxic damage zone

The main factor in the formation of a toxic damage zone in case of an impact of the failed LV/ILV with NTO+UDMH is the integrity of its body in the passive fall segment. Calculations for the LV/ILV made by Yuzhnoye SDO show that for a significant portion of the first stage flight segment in the event of an accident, it is most likely that the intact failing LV/ILV will fall to the Earth's surface with the residual propellants on board. For example, for the Cyclone-4 launch vehicle and the Dnepr launch vehicle, in the event of an accident up to 60–70 seconds into the flight, the failing LV/ILV in the passive fall segment is not destroyed. Taking into account the blast and fire, the release/evaporation of the toxicant (unreacted part of the rocket propellant) can be considered as a salvo.

The formation of a toxic contamination zone (with a similar release pattern) should be expected as a result of the destruction of the failed LV in the passive fall segment, when individual fragments represent the intact stages with the rocket propellants. When they impact, an explosion and fire should also be expected. Calculations for the LV/ILV made by Yuzhnoye indicate that in the event of an accident after a certain point in time (let's denote it as t_*; in case of a CF, before this time the body of the failing LV/ILV is not destroyed during the fall) fragmentation of the failed LV/ILV in the passive fall segment due to unforeseen mechanical loads is quite regular and will occur along the lines of parts breakdown. The most likely scenario is when the failing LV/ILV is destroyed into two large fragments: the separated part of the first stage and the second stage, which reach the Earth's surface without destruction. For example, for the above-mentioned Cyclone-4 and Dnepr launch vehicles, for accidents within the next ~10–20 seconds into flight after t_* in the passive fall segment, this very type of destruction of the failing LV/ILV body is expected.

It should be noted that the toxic effect will also be the main damaging factor in case when the destruction of the failed LV/ILV occurs in such a way that the resulting fragments will include intact propellant tanks containing residual toxic rocket propellants. The main factor in this case is the integrity of the tanks and the non-mixing of the rocket propellants, which does not lead to either blast or fire, which means that the toxicant release pattern will differ from the salvo release. However, as shown by strength analyses of the Yuzhnoye developed LV/ILV in the passive fall segment, it is extremely unlikely for such an accident scenario when individual intact propellant tanks of the failed LV/ILV with residual propellants fall to be implemented. Usually, after the LV/ILV is split into two fragments, these fragments heat up and the tanks break down.

3. Building a mathematical model for identifying the risk of toxic damage to a person in case of an LV/ILV accident during the flight segment

Let us build a model for identifying the risk of toxic damage to a person in case of an accident of an LV/ILV with toxic propellants on board.

3.1. Basic assumptions

When building the model for identifying the risk of toxic damage to a person in case of an LV/ILV accident in the first stage flight segment, it should be assumed that:

– we will consider the LV/ILV which is equipped with a Flight Termination System that implements an emergency engine shutdown (EES) in the event of an emergency situation detected, e.g. loss of controllability or onboard computer failure. We will assume that all emerging CFs will lead to loss of flight control and EES. Consequently, to each CF corresponds the maximum zone of a possible impact of the failed LV/ILV (to be obtained by modeling the process of development of an emergency situation from the moment of failure to the moment of implementation of the EES and subsequent passive fall);

– we will consider a CF occurring in the flight time interval $[0, t_*]$, when an intact LV/ILV with residual rocket propellant falls in case of an accident;

– a salvo release of toxicant occurs due to the explosion and fire resulting from the impact of the failed LV/ILV;

– the state of the atmosphere, speed and direction of the wind at the time of LV/ILV launch are known and unchanged for a certain time (the direction of the prevailing wind and its average speed will be considered);

– the person remains motionless at the point in question for a certain time.

3.2. General relationships

In general, the formula for identifying the risk of toxic damage to a person located at a certain point relative to the launch point in the event of an LV/ILV accident in the first stage flight segment can be written as follows (see [3])

$$R = Q_I \frac{1}{t_I} \int_0^{t_*} P_{CF}(t) \cdot \Delta R(t) dt, \qquad (1)$$

where Q_I – is the probability of critical failure of the LV/ILV during the first stage flight segment; t_I – LV/ILV first stage operation time; t_* – point in time before which CF leads to the fall of an intact LV/ILV; $P_{CF}(t)$ – probability of CF at time t (more precisely, in the interval dt in the vicinity of point t); (more precisely – in interval dt at the neighborhood point t); $\Delta R(t)$ – is the probability of the failed LV/ILV being in the zone where a person will suffer a lethal toxic injury in the event of CF occurring at time t (we will call such a zone ‘the zone of dangerous impact of the failed LV/ILV’, or ZDI for short).

Using piecewise continuous approximation of the integrands, formula (1) takes the following form

$$R = Q \sum_{j=1}^{N_{\Delta t}} P_{\Delta t_j} \frac{1}{\Delta t_j} \int_{t_{j-1}}^{t_j} \Delta R(t) dt, \qquad (2)$$

where $N_{\Delta t}$ – number of intervals for dividing the first stage flight interval $[0, t_*]$; $P_{\Delta t_j}$ – probability of CF in the j^{th} time interval; $\Delta t_j = t_j - t_{j-1}$ (for CF t_j times, the development of emergency situations before EES is modeled and the impact zones for the failed LV/ILV after the EES are determined). In the last formula we write

$$\Delta R_{ZDI}(\Delta t_j) = \frac{1}{\Delta t_j} \int_{t_{j-1}}^{t_j} \Delta R(t) dt.$$

Determination of the components of relationship (2). The Q_I values are obtained by processing statistics using analogous launch vehicles or by analysis.

To determine $P_{\Delta t_j}$ we can use statistics for LV/ILV-analogs. For example, an averaged model of the distribution of the moments of occurrence of first-stage failures can be used, obtained on the basis of processing statistical data on failures of the LV/ILV stages developed by Yuzhnoye [2]. According to this statistical model, the process of occurrence of failures according to the operating time of the stages is described as follows: an average of 25 % of the stage failures occur in the first 5 % of the flight time, approximately 15 % of the failures, in the last 15 % of the time, the remaining 60 % of the stage failures occur in the intermediate interval between 5 and 85 % of the stage running time. Here, the distribution of failures over the specified time intervals is assumed to be uniform. If such statistics are not available, in the simplest case we can assume a uniform distribution of the moments of occurrence of LV/ILV CFs during the stage flight time. Then,

$$P_{\Delta t_j} = \Delta t_j / t_I \ \ (j = \overline{1, N_{\Delta t}}).$$

In general, the probabilities of the failed launch vehicle getting into the ZDI are determined as follows:

$$\Delta R_{\text{ZDI}}(\Delta t_j) = \frac{1}{\Delta t_j} \int_{t_{j-1}}^{t_j} \left[\iint_{S_{\text{ZDI}}} f_{X,Z}(x,z;t)\,dxdz \right] dt,$$

where $f_{X,Z}(x, z; t)$ – common distribution for impact points of emergency LV/ILV in longitudinal and lateral directions in the event of CF in the time interval dt; S_{ZDI} – integration domain – ZDI area.

In most cases, the independence of the dispersion of the impact points of the failed LV/ILV in the longitudinal and lateral directions is assumed, and at the same time, normal distribution laws are used to describe them. Since the characteristics of the dispersion of the impact points of the failed LV/ILV in the longitudinal and lateral directions change at intervals Δt_j, to describe them we will use one-dimensional normal distribution with time-varying mathematical expectations and standard deviations. In this case, the probability $\Delta R_{\text{ZDI}}(\Delta t_j)$ for each time interval Δt_j can be found as follows:

$$\Delta R_{\text{ZDI}}(\Delta t_j) = \frac{1}{\Delta t_j} \int_{t_{j-1}}^{t_j} \left[\iint_{S_{\text{ZDI}}} N(x; m_X(t), \sigma_X(t)) \times \right.$$
$$\left. \times N(z; m_Z(t), \sigma_Z(t))\,dxdz \right] dt, \qquad (3)$$

where N(•) – normal density function; $m_X(t)$, $m_Z(t)$ – the dispersion center of emergency LV/ILV impact points in longitudinal and lateral directions in time moment of the failed LV/ILV impact points in the longitudinal and lateral directions for the CF time t ($m_X(t)$ corresponds to the failed LV/ILV impact range); $\sigma_X(t), \sigma_Z(t)$ – standard deviation of failed LV/ILV impact points dispersion in the longitudinal and lateral directions.

When finding the dispersion of the failed LV/ILV impact points, we will take into account that to each CF time t corresponds a random value of the duration of the development of an emergency situation before the EES implementation – t_{EES}. Realizations of this random variable are obtained by modeling the development of the emergency situation from the failure time (for the points that are the ends of the intervals) to the EES time. To build a calculation model for assessing the risk of toxic damage to a person R, we will match a mathematical expectation of the random value $t_{\text{EES}} - \overline{t}_{\text{EES}}$ to each time a CF occurs on board the LV/ILV t. By doing so, the failure time and the characteristics of the dispersion of the failed LV/ILV impact points after the EES are combined using the following logical chain (Fig. 2).

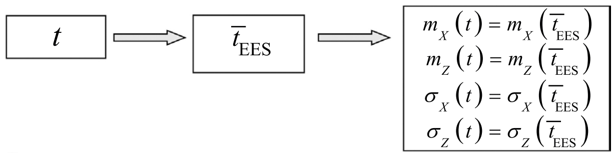


Fig. 2. Relationship between CF time and characteristics of failed LV/ILV impact point dispersion after EES

3.3. Building the LV/ILV zone of dangerous impact

To determine the probabilities $\Delta R_{\text{ZDI}}(\Delta t_j)$, it is necessary to construct and mathematically describe the ZDI of the failed LV/ILV relative to the person's location. To do this, let us consider the $X'O'Z'$ local coordinate system with the center at the person's location and the $O'X'$ axis coinciding with the wind direction (Fig. 3).

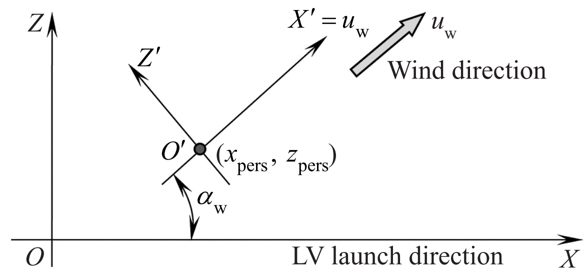


Fig. 3. $X'O'Z'$ local coordinate system

To obtain the ZDI, we will determine the zone of toxic damage to people (ZTDP) relative to the failed LV/ILV impact point. In practical calculations, the ZTDP can be represented as follows [4]. With no wind, the ZTDP is a circle whose radius during the explosion, to a first approximation, can be determined by the formula

$$R_D = 160\sqrt[3]{M}, \text{ m} \qquad (4)$$

where M – total mass of residual propellant at EES (tons).

If we take into account the wind, then in its direction the radius of the danger zone can be estimated as follows

$$R_{D1} = 160\sqrt[3]{M}\,(1+0{,}5u_{\text{w}}),\ \text{m} \qquad (5)$$

where u_{w} – wind speed (average speed of the prevailing wind).

As a first approximation, the ZTDP in case of wind can be taken in the form of a circle of with the radius R_{D1}. Note that such a conservative approach is typical for developers from NASA [7]. According to their recommendations, the danger area for people has the shape of a circle, whose radius is determined by the amount of propellant at the time of emergency flight abort, the state of the atmosphere, and the permissible concentration of the toxicant in the surface air.

When representing the ZTDP in the form of a circle, the corresponding ZDI of the failed LV/ILV will also have the shape of a similar circle, and to determine the risk of toxic damage to people, the approaches described in [3] can be used. However, in case of wind, the area of the ZDI, represented by a circle with the radius R_{D1}, increases significantly. This will lead to a significant increase in the level of toxicity risk for people.

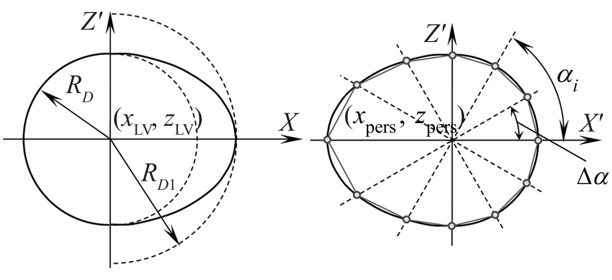


Fig. 4. ZTDP and ZDI in the $X'O'Z'$ coordinate system: a – ZTDP relative to the failed LV/ILV impact point; b – ZDI of the failed LV/ILV relative to the person's location

In case of wind, a more correct ZTDP shape will be with the danger zone radius R_D taken as the danger radius for the direction opposite and perpendicular to the wind direction and with the radius equal R_{D1} downwind. Consequently, the ZTDP relative to the LV/ILV impact point $(x_{\text{LV}}, z_{\text{LV}})$ will look as shown in Fig. 4, a, and will consist of two shapes: a semicircle and a semi-ellipse. For the latter, the semi-minor axis will be equal to R_D, the semi-major, to R_{D1} respectively. For the latter, the semi-minor axis will be equal to R_D, the semi-major, to R_{D1}, respectively. Let us note that the area of such ZDI, for example, in case of surface wind at a speed of 4 m/s at the time of the LV/ILV accident, will be 4.5 times less than the ZDI area having the shape of a circle with the radius R_{D1}.

We obtain the zone of dangerous impact of the failed LV/ILV relative to the person's location by mirroring it relative to the $O'Z'$ axis (Fig. 4, b). Analytical equations for describing the curves limiting the ZDI (Fig. 4, b) are written as:

$$\frac{x'^2}{R_D^2} + \frac{z'^2}{R_D^2} \le 1 \text{ for a semicircle (downwind);}$$

$$\frac{x'^2}{R_{D1}^2} + \frac{z'^2}{R_D^2} \le 1 \text{ for a semi-ellipse (against wind).}$$

Now, to find $\Delta R_{\text{ZDI}}(\Delta t_j)$ it is necessary to write these equations taking into account the rotation of the $X'O'Z'$ coordinate system by an angle $-\alpha_{\text{w}}$ (see Fig. 3) and perform integration according to (3) depending on the CF occurrence time. However, this procedure is quite complicated.

Let us represent the ZDI for the analyzed moments of the LV/ILV critical failure in a simpler form, which can be used in the general relationship (3). For practical calculations, let us represent the ZDI (Fig. 4, b) for each moment in time in the form of a polygon. The number of vertices of such a polygon will generally be equal to N_{ZDI}. Accordingly, the angular position of the polygon vertices relative to the $O'X'$ axis will be determined by the formula

$$\alpha_i = (i-1)\Delta\alpha \ (\ i = \overline{1, N_{\text{ZDI}}}\ ),$$

where $\Delta\alpha$ is the angular distance (step) between adjacent vertices $\left(\Delta\alpha = \dfrac{360^\circ}{N_{\text{ZDI}}}\right)$.

It is clear that the more vertices a polygon has, the closer such a polygon will be to the original ZDI.

In Fig. 4, b, for example, the ZDI is represented by a dodecagon, i.e. $N_{\text{ZDI}} = 12$, respectively, $\Delta\alpha = 30^\circ$.

The coordinates of the points of the polygon vertices in the *X′O′Z′* coordinate system will be found as follows:

– for angles $\alpha_i \in [0°;90°]$ or $[270°;360°]$, the coordinates of points on the semicircle

$$x'_{\mathrm{ZDI}_i} = R_D \cos(\alpha_i);$$

$$z'_{\mathrm{ZDI}_i} = R_D \sin(\alpha_i);$$

– for angles $\alpha_i \in [90°;270°]$, the coordinates of points on the semi-ellipse

$$x'_{\mathrm{ZDI}_i} = R_{D1} \cos(\alpha_i);$$

$$z'_{\mathrm{ZDI}_i} = R_D \sin(\alpha_i).$$

According to these formulas, for each moment of the LV/ILV CF $t_1 = 0$ s, t_2, …, $t_n = t_*$ (boundary points of the intervals for which the emergency situation development and the EES implementation were modeled and for which the fall of the intact LV/ILV will occur), it is necessary to find, in the *X′O′Z′* local coordinate system, the ZDI polygon points coordinates and represent them as matrices of the following form:

$$\mathbf{X}'_{\mathrm{ZDI}} = \begin{bmatrix} x'_{\mathrm{ZDI}_1(t_1)} & x'_{\mathrm{ZDI}_1(t_2)} & \cdots & x'_{\mathrm{ZDI}_1(t_n)} \\ x'_{\mathrm{ZDI}_2(t_1)} & x'_{\mathrm{ZDI}_2(t_2)} & \cdots & x'_{\mathrm{ZDI}_2(t_n)} \\ \cdots & \cdots & \cdots & \cdots \\ x'_{\mathrm{ZDI}_{N_{\mathrm{ZDI}}}(t_1)} & x'_{\mathrm{ZDI}_{N_{\mathrm{ZDI}}}(t_2)} & \cdots & x'_{\mathrm{ZDI}_{N_{\mathrm{ZDI}}}(t_n)} \end{bmatrix};$$

$$\mathbf{Z}'_{\mathrm{ZDI}} = \begin{bmatrix} z'_{\mathrm{ZDI}_1(t_1)} & z'_{\mathrm{ZDI}_1(t_2)} & \cdots & z'_{\mathrm{ZDI}_1(t_n)} \\ z'_{\mathrm{ZDI}_2(t_1)} & z'_{\mathrm{ZDI}_2(t_2)} & \cdots & z'_{\mathrm{ZDI}_2(t_n)} \\ \cdots & \cdots & \cdots & \cdots \\ z'_{\mathrm{ZDI}_{N_{\mathrm{ZDI}}}(t_1)} & z'_{\mathrm{ZDI}_{N_{\mathrm{ZDI}}}(t_2)} & \cdots & z'_{\mathrm{ZDI}_{N_{\mathrm{ZDI}}}(t_n)} \end{bmatrix}.$$

In this way, for each moment of CF time (t_j) we will have the coordinates of the ZDI polygon vertices (respective columns of $\mathbf{X}'_{\mathrm{ZDI}}$ and $\mathbf{Z}'_{\mathrm{ZDI}}$ matrices).

Now for further calculations, it is necessary to write down the coordinates of the ZDI polygon vertices in the *XOZ* launch coordinate system, taking into account the coordinates of the person's location and the wind direction (Fig. 5).

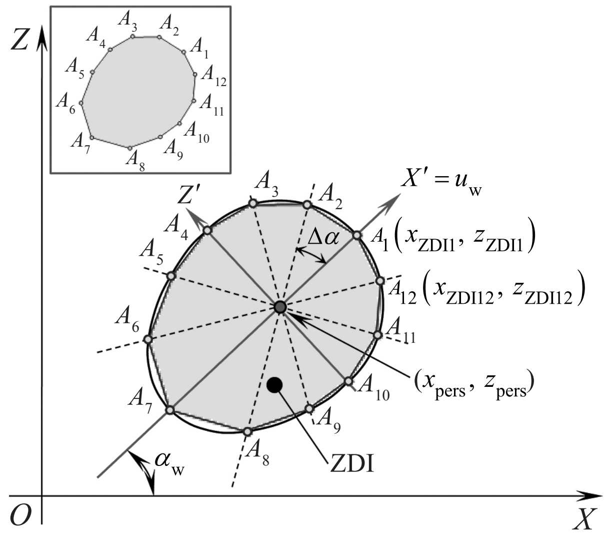


Fig. 5. LV/ILV ZDI in the *XOZ* coordinate system

This can be done using the following relationships:

$$x_{\mathrm{ZDI}_i} = x_{\mathrm{pers}} + x'_{\mathrm{ZDI}_i} \cos(\alpha_{\mathrm{w}}) - z'_{\mathrm{ZDI}_i} \sin(\alpha_{\mathrm{w}});$$

$$z_{\mathrm{ZDI}_i} = z_{\mathrm{pers}} + x'_{\mathrm{ZDI}_i} \sin(\alpha_{\mathrm{w}}) + z'_{\mathrm{ZDI}_i} \cos(\alpha_{\mathrm{w}}),$$

$$i = \overline{1, N_{\mathrm{ZDI}}}.$$

To determine the risk of toxic damage to people, let us imagine a convex polygon describing the ZDI in the form of a set of triangles (typical elementary figures). The number of triangles making up the polygon will be equal to $N_{\mathrm{ZDI}} - 2$. Then the risk of toxic damage to a person located at the point (x_{pers}, z_{pers}) will be determined as

$$R = \sum_{N_{\mathrm{ZDI}}-2} R_{\Delta i}, \qquad (6)$$

where $R_{\Delta i}$ – the probability of the failed LV/ILV getting into the i^{th} triangle constituting the ZDI. As a result, the task of determining the risk of toxic damage to a person was reduced to calculating the probability of the failed LV/ILV getting into the area limited by each triangle. Expressions for calculation of $R_{\Delta i}$ can be found in [1].

3.4. Generalization of the developed model for determining the risk of toxic damage to people

Formula (2) and the analytical relationships made for it are based on the assumption that all CF end with the EES and the failed LV/ILV impacting in a certain area (corridor) of maximum width. Such a model can be generalized as follows.

Firstly, we can consider various CFs that lead to flight termination and the fall of the failed LV/ILV. For example, we can consider critical failures of the first and second groups separately [2, 3], which either instantly lead to the failed LV/ILV flight termination or lead to the EES. For each type of critical failure we will have its own respective flight termination time (e.g., the LV/ILV accident time or the EES time), and, accordingly, the amount of propellant at the first stage main engine shutdown time, and its own impact area for the failed LV/ILV. This should be taken into account when determining the ZDI and $\Delta R_{\text{ZDI}}(\Delta t_j)$.

Secondly, EES blocking in the initial flight phase is widely used in the LV/ILV developed by Yuzhnoye to ensure the range safety. This can also be taken into account when determining the risk of toxic damage to people. Formulas for respective calculations can be found in [2].

3.5. Building a toxic danger zone for people

Using the proposed model, we can identify the risk of damage to a person located at a certain point relative to the LV/ILV launch point. A more general (integral characteristic) is a danger zone where the risk of toxic damage to people exceeds acceptable levels (for the population, this individual risk is 10^{-6}). We will build a toxic danger zone for people using the net method (according to the method discussed in [3]). According to this method, a net is generated on the Earth's surface along the emergency groundtrack (ascent groundtrack), formed by a cross-section of axes in the longitudinal and lateral directions (parallel to the *OX* and *OZ* axes), llocated at a certain pitch. For each of the net nodes (axes intersection points), individual risks of toxic damage to people are assessed. According to the assumption made, wind speed and direction as well as atmospheric uniformity do not change for a certain time after the impact of the failed launch vehicle; therefore, for the same CF time and corresponding EES time, the polygon of the toxic damage zone for people will be the same for each location point of the person.

Having determined the risks at the nodes, we can, by interpolation, determine the corresponding points in each direction where the risk is exactly equal to the permissible value. In this way, we obtain the danger zone for people.

3.6. Example

The Dnepr launch vehicle failure which occurred in the first-stage flight segment was considered as an example (Fig. 1, c). Using the developed mathematical model for determining the risk of toxic damage to people, a danger zone for people was generated, where the risks of toxic damage to people in the event of a launch vehicle in-flight failure exceed the permissible level of 10^{-6}.

The calculations considered a trajectory for launching a 330-kg payload into a 730-km sun-synchronous orbit. The probability of critical launch vehicle failure (according to launch history) during the first-stage flight segment is 0.01. To distribute the time of Dnepr launch vehicle critical failures, we used a model obtained from the results of a statistical analysis of the launch failures of Yuzhnoye developed launch vehicles. When determining individual risks, the division of failures into two groups was taken into account, as well as the EES blocking within the first 11 seconds into flight. Launch vehicle strength analyses showed that in the event of a launch vehicle critical failure occurring within 64 s (from the liftoff switches operation), the failing launch vehicle will most likely reach the Earth's surface intact.

It was assumed that within the possible impact area of the failed launch vehicle, the angle between the wind direction and the launch direction was 50º, and the average wind speed was 4 m/s. In the calculations, the zone of dangerous impact of the failed LV/ILV was represented as a dodecagon.

The resulting danger zone for people is shown in Fig. 6. For comparison, the Figure shows the danger zone for people caused by the lethal effect of the blast shock wave. The Figure shows that the danger zone for people due to toxic damage in the event of an accident of the Dnepr launch vehicle turns out to be much larger.

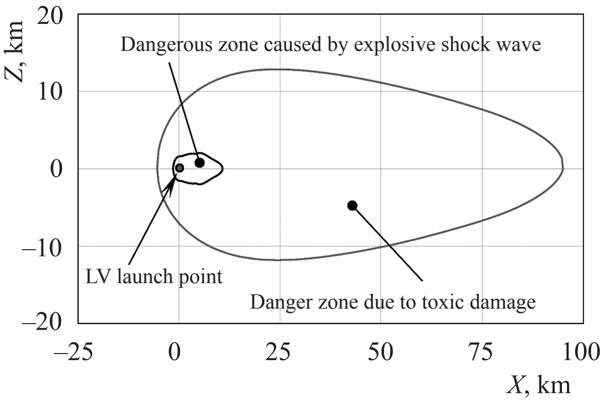


Fig. 6. Danger zones for people in the event of an accident of the Dnepr launch vehicle in the first-stage flight segment

4. Discussion of results

The use of formulas (4), (5) is an element of a heuristic approach. Generating an actual zone of toxic damage to a person should take into account the processes of distribution of the toxicant in the atmosphere, on the one hand, and the damage to humans by the toxic substance, on the other. The latter is that it takes time for a certain dose of the toxicant to accumulate in the body. To determine the ZTDP, the average lethal toxic dose LD_{50} is most often used [9], causing death in 50 % of unprotected individuals affected during exposure for $T = 5$ min. It is [10]: $LD_{50} = 2450.0$ mg·min/m^3 for UDMH; $LD_{50} = 8000.0$ mg·min/m^3 for NTO, respectively.

For a more correct determination of the ZTDP in the zone of a possible impact of the failed LV/ILV, we should take into account not only the direction of the prevailing wind, but also the wind rose (Fig. 7), containing data on the wind direction and strength (average wind speed).

For each wind direction, the danger distance is calculated according to the wind rose data, based on the permissible toxic dose for a person. To do this, let us consider one of the possible wind directions and enter the $X''O''Z''$ coordinate system associated with the failed LV/ILV impact point (Fig. 8). The $O''X''$ axis coincides with the wind direction.

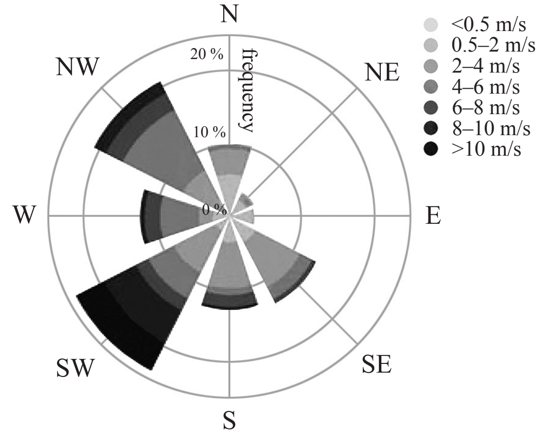


Fig. 7. Wind rose at the impact point of failed LV/ILV

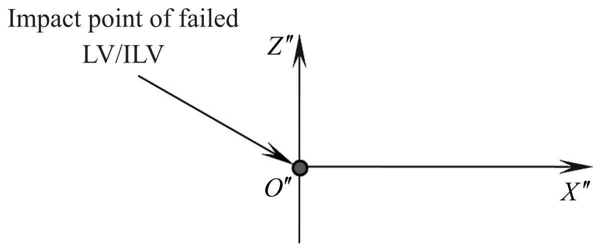


Fig. 8. $X''O''Z''$ coordinate system

As was mentioned above, the blast and fire caused by the failed LV/ILV impact allows us considering the release of the toxicant as a salvo. Dispersion of the toxicant in the atmosphere for a salvo release (instantaneous release source) can be described by the Gaussian model, according to which the concentration of the toxic substance at an arbitrary point relative to the impact point of the failed LV/ILV is determined by the formula [11]

$$c\left(x'',z'',y'';t\right)=\frac{M}{(2\pi)^{3/2}\sigma_X\sigma_Z\sigma_Y}\times$$

$$\times\exp\left\{-\frac{1}{2}\left(\frac{(x''-u_в t)^2}{\sigma_X^2}+\frac{z''^2}{\sigma_Z^2}+\frac{y''^2}{\sigma_Y^2}\right)\right\},$$

where M is the mass of the toxicant released into the atmosphere (in the absence of data, as a first approximation, we can assume 10 % of the total mass of residual propellant at the time of the LV/ILV accident); σ_X, σ_Z, σ_Y are standard deviations of the toxicant cloud dispersion along the axes (depend on the state of the atmosphere, wind speed, nature of the

Earth's surface; formulas for them can be found in [11]); u_w is the wind speed in the direction under consideration.

Then the dose of toxicant accumulated by a person will be determined as follows

$$D(x'', z'', y'') = \int_0^T c(x'', z'', y''; t)dt =$$

$$= \frac{M}{(2\pi)^{3/2}\sigma_X\sigma_Z\sigma_Y}\exp\left\{-\frac{1}{2}\left(\frac{z''^2}{\sigma_Z^2}+\frac{y''^2}{\sigma_Y^2}\right)\right\}\times$$

$$\times\int_0^T \exp\left\{-\frac{1}{2}\left(\frac{(x''-u_w t)^2}{\sigma_X^2}\right)\right\}dt.$$

Taking into account a lethal toxic dose, we have the following equation

$$LD_{50} = \frac{M}{2\pi\sigma_Z\sigma_Y}\exp\left\{-\frac{1}{2}\left(\frac{z''^2}{\sigma_Z^2}+\frac{y''^2}{\sigma_Y^2}\right)\right\}\times$$

$$\times\frac{1}{u_w}\left[\Phi\left(\frac{x''}{\sigma_X}\right)-\Phi\left(\frac{x''-u_w T}{\sigma_X}\right)\right].$$

In the direction of wind propagation ($z'' = 0$) and for the Earth's surface ($y'' = 0$), the equation will look like

$$LD_{50} = \frac{M}{2\pi\sigma_Z\sigma_Y}\frac{1}{u_w}\left[\Phi\left(\frac{x''}{\sigma_X}\right)-\Phi\left(\frac{x''-u_w T}{\sigma_X}\right)\right].$$

It is clear, that we need to find coordinate x'' as a solution to this equation.

By determining the dangerous distance in each wind direction according to the wind rose, we can thereby build the ZTDP polygon (the resulting polygon does not have to be convex). Now we need to transition from the ZTDP to the ZDI. Let us clarify the concept of ZDI: it is a geometric location of the points of a possible impact of the failed LV/ILV, for which, with a known toxicant release pattern, state of the atmosphere, wind direction and speed (the latter are assumed to be constant during the analyzed time), a person located at a certain point of the emergency zone (x_{pers}, z_{pers}) will accumulate a dose of the toxic substance not lower than level D_* for time T (exposure time). To obtain the ZDI, let us reflect the generated ZTDP as shown in Fig. 9 (mirror image for each direction; Fig. 9 shows such a reflection for the N-W/S-E direction).

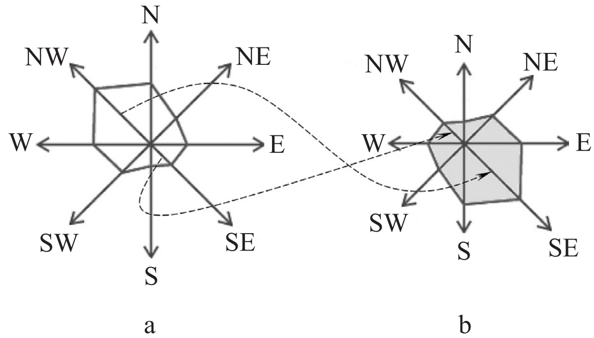


Fig. 9. ZTDP and ZDI obtained by reflection:
a – ZTDP; b – ZDI

Now, we can divide the obtained ZDI into separate triangles and, using the developed algorithm, assess the risk of toxic damage to a person located at a certain point.

In this way, the model will be more complex, but also more accurate.

Conclusions

The article develops a mathematical model for determining the risk of toxic damage to a person in the event of an accident of a LV/ILV with toxic propellants (NTO+UDMH) on board. It shows how the zone of toxic damage to a person is formed relative to the impact point of the failed LV/ILV and how the corresponding zone of dangerous impact of the failed LV/ILV is formed, where a person can receive toxic exposure. It is proposed to use polygons to describe the zones of dangerous impact of the failed LV/ILV which are used in the model for determination of individual risk. It is shown that in case of a failure of an LV/ILV with NTO and UDMH propellants on board, the possibility of toxic damage significantly enlarges the danger zone for people, where the risks exceed the permissible values.

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Article was submitted on 14.12.2023