Tendencies in the propagation of fires and ammunition explosions at fixed storage facilities

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Abstract. Aim. *To suggest an approach to identifying the common features of statistical series containing information on the time, place and external conditions of the development and propagation of emergency situations associated with fires and ammunition explosions at fixed storage facilities, to synthesize the function of partial risk indicator of such situations, i.e., the energy susceptibility to external effects of ammunition storage systems.* **Methods.** *The paper uses methods of mathematical analysis of statistical series and probability theory. For the first time ever, individual external conditions of emergency situations involving ammunition are analysed using statistical series (rate of insolation).* **Results.** *The paper has collected and classified statistical data on emergencies involving fires and explosions in ammunition storage facilities that took place in the current century in a number of countries of the world, whose emergency nature was confirmed by extensive media coverage. Using statistical series analysis, an exponential relationship has been established between the rate of fires and explosions and the total power saturation of the ammunition storage system.* **Conclusions.** *The frequency of emergencies involving fires and explosions depends on the overall power saturation of the storage system that is defined by the solar intensity in the area of the ammunition storage facility that depends on its latitude and season. The suggested approach allows, by analysing empirical data on the time and place of emergencies, identifying the specific survivability values of a hazardous storage facility characterizing the energy susceptibility of the system to the effects that trigger explosions and fires.*

Keywords: *ammunition, explosives, fire, explosion, factor, arsenal, survivability.*

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Introduction

The emergency of any phenomena of the real world is determined by comparing them with similar phenomena on the basis of the frequency of their onset and the extent of the transformation of the environment in the course of such events. The trends in the occurrence of rare events with potentially major consequences are the subject matter of the risk theory. The quality of risk assessment and analysis defines the efficiency of the management of complex potentially hazardous systems, including missile and ammunition storage facilities.

Today, along with analytical models, simulation, event and solution tree analysis, heuristic methods of knowledge acquisition, neural network programming and learning are widely used for assessing the risks associated with the behaviour of complex systems. The validity of the estimates obtained using a certain method of analysis of phenomena and synthesis of scientific knowledge depends on the quality and amount of the obtained information (initial data) and the quality of the analysis and synthesis mechanism. The higher is the number of factors taken into account as part of risk analysis, the more valid is the system behaviour model and higher is the accuracy of risk assessment. This approach allows synthesizing the emergency risk function in the form of a multiplicative convolution of partial indicators r_i.

$$R\left(r_1, ..., r_i, ..., r_n\right) = \prod_{i=1}^{n} f^{\alpha_i}\left(r_i\right).$$

In addition to the man-made, technology-related and natural factors that characterize the probability of events able to cause emergencies, the overall level of system susceptibility to energy effects that define the probability of emergency propagation in time and space should be examined as an additional partial indicator of the risk function.

In many previous studies [1-10], based on statistical data, the underlying causes of such fire and explosion emergencies (FEE) were analysed. This paper deals with environmental energy conditions that contribute to the propagation of fires and explosions. The primary source of energy for all processes on the Earth's surface is the radiant energy of the Sun called solar radiation. The energy of stellar radiation and heat coming to the surface of the Earth as the result of the processes taking place within it are negligible compared to solar radiation [11]. The formation of organic matter that constitutes the basis of combustible and explosive materials is essentially the process of accumulation in the course of billions of years of biotransformation of the primary source of energy within the molecular bonds of the substrate.

The purpose of the paper is to identify new correlations between a system's energy saturation and the frequency of FEEs at ammunition storage facilities.

1. Problem definition

The ability of explosive and flammable materials to initiate cascading combustion and explosions of other substances underlies the potential hazard of ammunition storage facilities. Stored ammunition is essentially accumulators of destructive energy connected by potential initiation relationships. The damage caused by the destructive operation of such energy depends on the energy potential of the chemical elements in the ammunition, the energy potential of the fire load at the storage facility (crating, structures, vegetation) and the degree of loss of control over the energy release. Thus, the level of emergency of the ammunition fires and explosions is defined not only by the level of intentional control input, but by the intrinsic properties of the system, its energy capacity. It is obvious that if a system's energy saturation is zero (absolute zero temperature), no chemical processes within materials are possible. Another boundary condition for the onset and propagation of FEEs is the energy saturation of the system reaching energy-releasing reaction in organic materials. For black powders, ignition becomes possible after hours-long exposure to temperatures in excess of 400° K. Thus, the frequency of explosions and fires at each storage facility is supposed to depend on the energy input into the system. Under known boundary energy conditions of reliable or impossible onset of the event of explosion and fire initiation, it is required to define the function of the effect of a system's energy saturation on the frequency of explosions and fires in order to determine the partial indicator of risk, i.e., the system's susceptibility to energy effects.

2. Overview of previous research

Normally, FEE is a consequence of factors of intentional or unintentional human influence (man-made factor), errors or failures of technology (technology-related factor) and stochastic natural effects (natural factor). Each of these factors depends on the spatiotemporal characteristics of the system.

In [1-9], it is noted that the "human factor" dominates in the causality of FEE. Thus, in [6], based on the analysis of a large set of statistical data, it is noted that the number of technology-related fires following a temperature increase goes down [$r = -0.72$], while the number of fires due to social causes increases [$r = 0.73$] instead. The number of fires caused by other factors is not associated with temperature dynamics.

The yearly distribution of incidents was examined in [1, 2]. Those works identified trends for higher frequency of incidents in fire hazard periods. For instance, out of 73 FEEs at ammunition storage facilities examined in [2] 93% took place during the warm season from March to October. The authors attribute that to the fact that most scheduled activities involving ammunition are carried out during the warm season, whereas they start in May and the end in October

[2, p. 32]. However, it should be noted that as the ambient temperature rises, within the system, the intensity of chemical processes increases, the energy threshold of initiation of combustion and explosion reactions decreases and the fire load on the storage facility premises grows. Thus, growing overall energy saturation of the system affects the frequency of explosions and fires.

3. Definition of input data

Achieving the designated goals involved examining the distinctive features of FEE development identified as part of the analysis of publicly available statistical data on the time, place and external conditions of mass explosions of ammunition at fixed storage facilities in a number of countries starting from 01.01.2001. The very fact that information on such incidents was covered in the media allows qualifying them as "extraordinary" and indicates that the examined energy connections are manifest in the sequence of mass explosions and fires.

The environmental temperature and humidity, the rates of thermal currents and static voltage in the air masses that affect the explosion and fire safety of the storage system, depend on the radiant energy of the Sun. The causality is clear: high temperature and low humidity dry out the fire load in the FEE area and increase the sensitivity of the explosives and powders to the initiating effects; the flows of oxygen-rich air facilitate the combustion reaction; the static voltage discharges, forming lightnings of hot plasma.

Almost all (90%) the radiation energy from the Sun is received by the Earth at the upper boundary of the atmosphere [11]. The amount of heat delivered by solar radiation per 1 cm^2 of a surface perpendicular to the beams of sunlight per 1 min of time is called solar intensity and is determined using the formula:

$$I = S/4\pi r^2,$$

where: S is the radiating power (radiant emittance) of the Sun equal to about $4\cdot10^{20}$ MW; r is the distance between the Earth and the Sun.

Given the average distance between the Earth and the Sun r = 149.600 mil km, the solar intensity is 1.98 cal/(cm^2 min) or 1.37 kW/m^2. This value is called the solar constant. The energy spectrum of solar radiation at the boundary of the atmosphere is close to that of the absolutely black body with the temperature of about 6000 K.

The distribution of solar radiation at the outer fringe and its change over time depend on the following causes:

1. Solar activity. In the peak years, the power of solar radiation can increase by 2%. As the solar activity grows, the Earth experiences increased intensity of magnetic and ionospheric disturbances affecting the man-made and technology-related factors of FEE;

2. Distance between the Earth and the Sun. Since the Earth's orbit is an ellipse, in January, the distance r_1 = 147.100 mil km, while in July, r_7 = 152.100 mil km. On the day of the winter solstice, the solar intensity is about 3.3% stronger than in spring and autumn, while on the day of the summer solstice it is 3.3% weaker.

3. The incident angle. The amount of incoming solar radiation (insolation) changes over time due to the deviation of the earth axis from the perpendicular to the orbit plane by 23°30'.

Thus, the cause of the annual and daily cycles of atmospheric phenomena is the rotation of the Earth around the Sun and the inclination of the Earth. If we designate the solar elevation as h_o, then a unit of the horizontal surface receives as much less radiation, as the surface area is larger than the flow area.

The solar intensity delivered to a surface at an angle of h_0 equals

$$I_h = I_0 \sin h_0,$$

where: I_0 is the rate of solar radiation per 1 min per 1 cm^2 of a perpendicular surface, h_0 is the flow incident angle. From astronomy, it is known that

$$\sin h_o = \sin \varphi \sin \delta + \cos \varphi \cos \delta \cos \psi \cos,$$

where φ is the site latitude; δ is the solar declination; ψ is the local hour angle of the Sun.

Consequently, the heat inflow from solar radiation to a horizontal surface depends on:

1. Site latitude φ that largely defines the differences between the climate zones;

2. Solar declination δ that changes during the year from δ = 23.44°N to δ = 23.44°S, which defines the seasons;

3. Local hour angle of the Sun ψ that defines the daily variation of the solar intensity;

4. Distance between the Earth and the Sun r.

For the purpose of the analysis of the parameters of the evaluated system, the geographical coordinates of the potentially hazardous facilities are the initially specified spatial characteristics.

The values of the solar declination (δ), time of sunrise and sunset for specific dates can be determined using the solar calculator: http://www.timezone.ru/suncalc.php.

With an error of ±0.2º, the solar declination is calculated using the known formula (Wikipedia):

$$\delta = -\arcsin(0.39779 \cos(0.98565^\circ (N+N_{ds}))+ +1{,}914^\circ \sin(0.98565^\circ (N-N_a)))$$

where: N is the sequence number of the estimated day from January 1; N_{ds} is the number of days since the December solstice before January 1 (N_{ds} = 10); N_a is the number of days after January 1 before the perihelion (N_a = 2).

The local hour angle of the Sun ψ is related to the latitude and solar declination with the formula:

$$\psi = \arccos(-\text{tg}\,\varphi\ \text{tg}\,\delta).$$

Table 1. Emergencies associated with fires and ammunition explosions

No.	Site	Latitude φ (degrees)	Date	JDN	Daily insolation Q (MJ/m^2)
1	2	3	4	5	6
1	Desselbrunn, District of Vöcklabruck, Austria	48.02	01.02.2018	32	12.635
2	Shirvan, Azerbaijan	39.92	26.07.2016	208	40.022
3	Giləzi, Khizi District, Azerbaijan	40.87	27.08.2017	239	34.957
4	Zemelan, Albania	41.32	06.05.2006	126	38.043
5	Gërdec, Albania	41.42	15.03.2008	75	26.792
6	Aïn Defla, Algeria	36.32	18.10.2015	291	24.974
7	Bashgah, Afghanistan	34.52	02.05.2005	122	38.331
8	Parwan, Afghanistan	35.02	23.03.2006	82	31.135
9	Chelopechene, Bulgaria	42.70	03.07.2008	185	41.771
10	Kostenets, Bulgaria	42.27	08.08.2014	220	38.144
11	Kostenets, Bulgaria	42.27	20.03.2015	79	27.434
12	Iganovo, Bulgaria	42.67	04.04.2015	94	31.076
13	Kazanlak, Bulgaria	42.62	25.04.2016	116	36.007
14	Maglizh, Bulgaria	42.60	27.05.2016	148	40.776
15	Hamburg, Germany	53.55	30.08.2002	242	30.118
16	Aden, Yemen	12.78	28.03.2015	87	37.158
17	Maharashtra, India	21.27	31.05.2016	152	39.728
18	Port of Tanjung Priok, Indonesia	-1.08	05.03.2014	64	37.934
19	Baghdad, Iraq	33.35	06.06.2018	157	41.279
20	Tokrau, Kazakhstan	46.83	08.08.2001	220	37.371
21	Arys, Kazakhstan	42.43	20.03.2009	79	27.358
22	Karaoy, Almaty Region, Kazakhstan	43.52	08.06.2009	159	41.596
23	Otar Station, Kazakhstan	43.55	27.08.2013	239	34.237
24	Arys, Kazakhstan	42.43	26.06.2014	177	41.994
25	Arys, Kazakhstan	42.43	24.06.2019	175	42.012
26	Hengyang, China	26.97	18.06.2014	169	40.848
27	Mbuji-Mayi, Democratic Republic of the Congo	-5.50	26.01.2014	26	38.373
28	Maputo, Mozambique	-25.23	22.03.2007	81	34.061
29	Lagos, Nigeria	6.45	27.01.2002	27	34.254
30	Podali, Khabarovsk Krai, Russia	50.55	17.01.2001	17	8.715
31	Nerchinsk, Chita Oblast, Russia	51.98	22.06.2001	173	41.797
32	Gusinoye Ozero, Buryatia, Russia	51.12	20.07.2001	201	39.885
33	Syzran, Samara Oblast, Russia	53.17	10.07.2002	191	40.881
34	Snegovaya Pad, Primorsky Krai, Russia	43.12	16.10.2002	289	21.853
35	Khabarovsk, Russia	48.48	13.06.2003	164	41.711
36	Norsk, Amur Oblast, Russia	52.33	18.06.2003	169	41.721
37	Kiparisovo, Primorsky Krai, Russia	43.47	13.07.2003	194	41.207
38	Achkhoy-Martan, Chechen Republic, Russia	43.18	07.12.2004	342	12.168
39	Kronstadt, Russia	60.00	17.05.2005	137	36.768
40	Ulan-Ude, Republic of Buryatia, Russia	51.83	16.06.2005	167	41.683
41	Yuzhnye Koryaki, Primorsky Krai, Russia	53.27	01.10.2005	274	20.459
42	Lodeynoye Pole, Leningrad Oblast, Russia	60.73	23.05.2008	144	38.208
43	Fokino, Primorsky Krai, Russia	42.97	30.09.2008	274	25.822
44	Karabash, Chelyabinsk Oblast, Russia	55.48	14.09.2009	257	24.647
45	Ulyanovsk, Russia	54.32	13.11.2009	317	8.711
46	Ulyanovsk, Russia	54.32	23.11.2009	327	7.089
47	Arga, Amur Oblast, Russia	51.27	28.10.2010	301	14.053
48	Dachny, Lipetsk Oblast, Russia	52.62	06.04.2011	96	27.590
49	Urman, Bashkortostan, Russia	55.47	26.05.2011	146	39.297

No.	Site	Latitude φ (degrees)	Date	JDN	Daily insolation Q (MJ/m^2)
50	Pugachiovo, Udmurtia, Russia	56.60	02.06.2011	153	40.199
51	Surgach, Primorsky Krai, Russia	45.52	18.05.2012	139	39.480
52	Koltubanovsky, Orenburg Oblast, Russia	49.02	11.06.2012	163	41.639
53	Orlovka, Orenburg Oblast, Russia	48.83	09.10.2012	283	20.290
54	Chapayevsk, Samara Oblast, Russia	52.98	18.06.2013	169	41.689
55	Bolshya Tura, Zabaykalsky Krai, Russia	51.62	29.04.2014	119	34.384
56	Pugachiovo, Udmurtia, Russia	56.60	04.05.2015	124	34.270
57	Urman, Bashkortostan, Russia	55.47	03.06.2015	154	40.432
58	Yuganets, Nizhny Novgorod Oblast, Russia	56.23	04.08.2016	217	36.005
59	Samara, Russia	53.18	18.10.2016	292	15.238
60	Khalino, Kursk Oblast	51.73	21.04.2017	111	32.268
61	Galichny, Khabarovsk Krai, Russia	50.72	29.07.2017	210	38.522
62	Primorskoye, Abkhazia (Russian Base)	42.58	02.08.2017	214	39.017
63	Pugachiovo, Russia	56.60	16.05.2018	136	37.198
64	Kamenka, Krasnoyarsk Krai, Russia	56.27	05.08.2019	217	35.997
65	Zheltukhino, Ryazan Oblast, Russia	53.75	07.10.2020	281	18.063
66	Parachin, Serbia	43.97	19.10.2006	292	20.621
67	Deir ez-Zor, Syria	35.33	08.10.2017	281	27.710
68	Damascus, Syria	33.52	02.09.2018	245	35.600
69	Abu Dali, Syria	34.43	14.06.2019	165	41.596
70	Mashrua ad-Dummar, Syria	33.52	15.06.2019	166	41.547
71	Shayrat, Syria	34.48	03.08.2019	215	39.559
72	Rmelan, Syria	36.48	21.06.2020	173	41.824
73	Al-Hasakah, Syria	36.48	16.07.2020	198	40.995
74	Novaki, Slovakia	48.72	03.03.2007	62	19.452
75	Juba, Sudan	4.85	23.02.2005	54	36.607
76	Sagamihara (US base), Japan	35.57	24.08.2015	236	36.663
77	Letterkenny, USA	39.93	19.07.2018	200	40.815
78	Abadan, Turkmenistan	38.05	08.07.2011	189	41.544
79	Diyarbakır, Turkey	37.90	16.09.2015	259	31.608
80	Kilis, Turkey	36.72	13.07.2017	194	41.250
81	Hakkâri, Turkey	37.57	09.11.2018	313	19.621
82	Reyhanlı, Turkey	36.27	09.08.2019	221	38.739
83	Kogon District, Bukhara Region, Uzbekistan	39.72	10.07.2008	192	41.407
84	Artemivsk, Luhansk Oblast, Ukraine	48.60	10.10.2003	283	20.421
85	Novobogdanovka, Zaporizhzhia Oblast, Ukraine	47.05	06.05.2004	127	37.235
86	Novobogdanovka, Zaporizhzhia Oblast, Ukraine	47.05	23.02.2005	54	18.258
87	Tsvitokha, Khmelnytskyi Oblast, Ukraine	50.23	06.05.2005	126	36.363
88	Novobogdanovka, Zaporizhzhia Oblast, Ukraine	47.05	19.08.2006	231	35.058
89	Lozova, Kharkiv Oblast, Ukraine	48.88	27.08.2008	240	32.352
90	Svatove, Luhansk Oblast, Ukraine	49.40	29.10.2015	302	14.941
91	Geyevka, Ukraine	49.50	08.03.2016	68	20.719
92	Khmelnytskyi, Ukraine	49.42	22.07.2016	204	39.658
93	Balakliia, Kharkiv Oblast, Ukraine	49.45	23.03.2017	82	24.865
94	Mariupol, Ukraine	47.12	22.09.2017	265	26.280
95	Kalynivka, Vinnytsia Oblast, Ukraine	49.43	26.09.2017	269	24.000
96	Balakliia, Kharkiv Oblast, Ukraine	49.45	03.05.2018	123	35.887
97	Ichnya, Chernihiv Oblast, Ukraine	50.85	09.10.2018	282	19.436
98	Gazost, France	43.02	07.10.2003	280	24.229
99	Salawa, Sri Lanka	6.92	05.06.2016	157	36.159
100	Latacunga, Ecuador	-0.27	07.11.2016	312	37.136

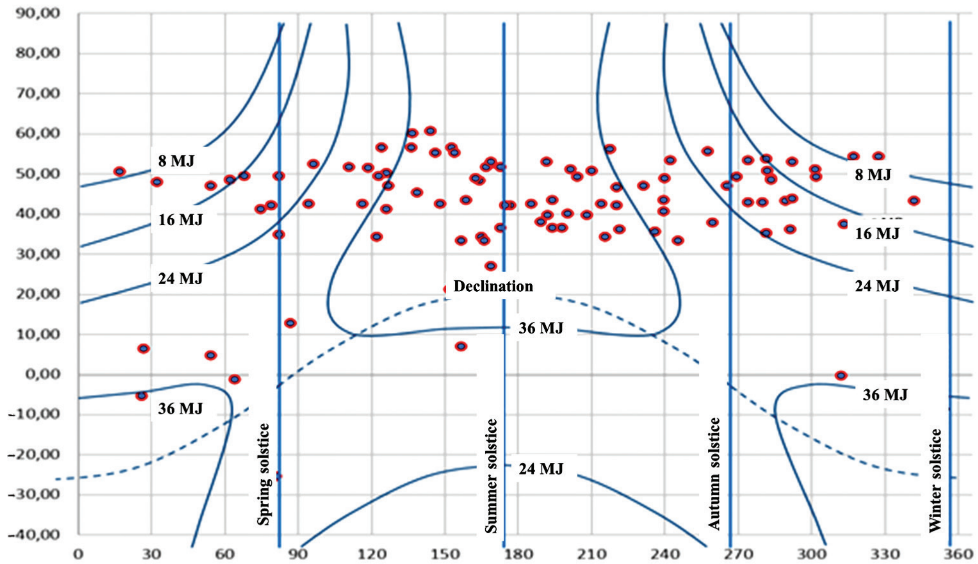

Fig. 1. Spatiotemporal distribution of FEE by day of year and by geographical latitude

The distance between the Earth and the Sun r is determined using the formula

$$r = \frac{r_0\left(1-E^2\right)}{1-E\cdot\cos\left(\dfrac{\pi}{2}-\arcsin\dfrac{\sin\delta}{\sin\varepsilon}\right)},$$

where: $r_0 = 149.6$ mil km is the average distance between the Earth and the Sun, $E = 0.0167$ is the Earth's orbit eccentricity, $\arcsin\dfrac{\sin\delta}{\sin\varepsilon}$ is the Sun's geocentric longitude.

Calculating all the arguments that affect heat inflow allows determining the daily insolation in FEE area on the day of occurrence Q by the formula:

$$Q = \frac{I_0 T}{\pi\left(r/r_0\right)^2}\left(\psi\sin\phi\sin\delta + \cos\phi\cos\delta\sin\psi\right),$$

where: Q is the total daily insolation, MJ/m^2; I_0 is the solar constant equal to 1.37 kW/m^2;

T is the period of the Earth's daily rotation (equal to 86 400 s).

Table 1 shows the input data and calculated daily insolation values for each FEE site and time.

The spatiotemporal distribution of the analysed set of FEE is shown in Fig. 1.

4. Determining the dependence of the FEE rate of the energy saturation

Certain values of daily insolation in the area of storage facilities at the moment of FEE enable statistical analysis based on this energy feature of the general population of exploded storage facilities (see Fig. 1).

The frequency distribution of 100 FEEs by daily insolation is presented in Fig. 2.

The power approximation of the integral indicator of FEE frequency with the insolation thresholds with the certainty of R^2=0.9976 allows estimating the dependence of the prob-

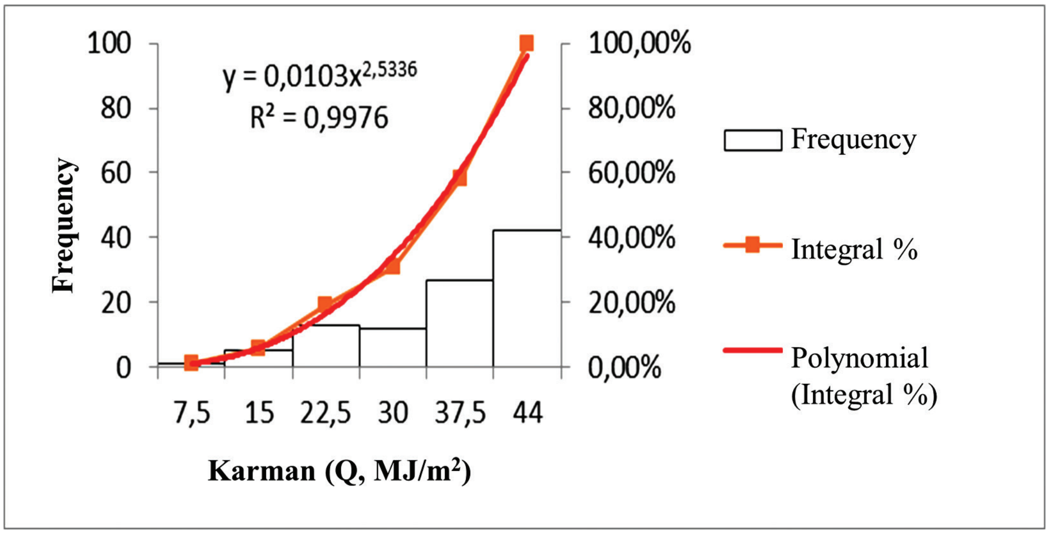

Fig. 2. Distribution of FEEs by daily insolation

ability of explosions and fires from the energy saturation of the environment.

Thus, the conducted analysis of empirical data allowed synthesizing the function of the partial risk indicator, i.e., a system's energy susceptibility to external effects r_e expressed through the value of daily insolation in a certain geographical region at a certain time

$$r_{\text{e}} = \frac{0,0103 \cdot Q^{2,534}}{0,0103 \cdot Q_{\max}^{2,534}} = (Q/44)^{2,534}.$$

The physical meaning of this indicator can be interpreted as the degree of correspondence of the environmental energy conditions with the conditions that most favour the development of FEEs.

Subject to the proposed partial risk indicator, the synthesized function of FEE risk (r_i) will be the product of four components:

$$r_i = r_{\text{val}}^a \cdot r_{\text{vul}}^b \cdot r_{\text{sc}}^c \cdot r_{\text{e}}^d,$$

where: r_{val}^a is the stock value indicator (affects the choice of the target of attack); r_{vul}^b is the stock vulnerability indicator (affects the attack effectiveness); r_{sc}^c is the indicator of social climate in the FEE area (indicates the aggressiveness of the social environment); r_{e}^d is an indicator of energy susceptibility (reflects the aggressiveness of the environment for the FEE development).

The specificity of using the convolution of indicators as multipliers is due to the fact that the human perception of expected losses has a logarithmic scale. In addition, the use of multiplicative convolution does not allow setting the partial indicators themselves that may have a natural expression, while only setting their weight coefficients: *a*, *b*, *c*, *d*.

5. Discussion of the results

A number of reasons can be associated with a rapid growth of the frequency of incidents as the insolation increases.

1. High-energy radiation (nuclear radiation) causes changes in the properties of powders. When affected by such radiation, destruction and structuring processes occur within them, ions and radicals may be generated that sharply increase the rate of chemical stabilizer consumption [5].

2. The cause of increased EA sensitivity to rising temperature is the weakening inter-molecular binding within the substance that facilitates the propagation of the initiating effects of wave, kinetic and thermal nature. As the temperature rises, the time it takes to heat the wooden package and gunpowder/ammunition to combustion temperature decreases, the depth of fragments penetration into the protective structures increases, wave attenuation in the environment weakens.

3. The power law dependence of the FEE on the level of insolation can be due to biological causes: growing fire load in ammunition storage facilities, intense growth and drying of vegetation, as well as the above-noted growing rate of operations involving ammunition. The existence of a dependence between the above and the comfortable climate conditions of work activity is beyond doubt.

4. Growing FEE frequency with rising insolation may be due to climate-related causes, e.g., increased frequency of thunderstorms, forest fires, peat fires, etc.

Conclusion

The conducted analysis of statistical data on incidents that caused fires and explosions at ammunition storage facilities allowed revealing a correlation between growing FEE frequency with rising environment temperature and the power law dependence of the susceptibility of items in the system to external effects on the overall energy saturation of the external environment.

The susceptibility to external effects reflects the correspondence between the actual external energy conditions and those that are most favourable for the propagation of FEE. This indicator should be used as an adjusting coefficient of the integral FEE risk indicator.

The inconsistency of the obtained findings regarding the effect of the environmental energy saturation on the emergencies involving ammunition explosions and regarding the low level of correlation between the frequency of forest fires and the air temperature stated in [6 – 9] defines the requirement to further examine the differences in the ways the environment's energy characteristics affect the more stochastic processes of mutual initiation of explosions and the more deterministic processes of fire front propagation.

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The author's contribution

Based on statistical data on emergencies involving ammunition fires and explosions in a number of countries of the world, the author suggested an approach to identifying the common features of statistical series containing information on the time, place and external conditions of the development and propagation of emergency situations associated with ammunition fires and explosions at fixed storage facilities and synthesized the function of partial risk indicator of such situations, i.e., the energy susceptibility to external effects of ammunition storage systems, identified the dependence between the rate of fires and explosions and the overall power saturation of an ammunition storage systems.

Conflict of interests

The author declares the absence of a conflict of interests.