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SAFETY PYRAMID ANALYSIS IN ENERGY SYSTEMS

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A B S T R A C T

Energy systems are key elements of critically important infrastructures, as they provide the required quality of life for the population, as well as create the necessary conditions for the reliable functioning of various branches of the economy. One of the priorities is to ensure the safe functioning of such systems, and in recent years, considerable attention has been paid to proactive safety methods. Within the framework of these methods, the main efforts are aimed at early identification of violations and deviations in the operation or maintenance of the facility. The building and use of the safety pyramid is one of the areas of implementation of a proactive approach. The paper presents the analysis of statistical data on incidents and detected violations at Russian energy facilities. The analysis made it possible to build the corresponding safety pyramids, as well as to identify that the ratio between the levels of the pyramid significantly depends on the specific type of facility. The possibility of using the safety pyramid to assess expected prevented damage in case of elimination of detected violations is also shown. Examples of assessing the value of prevented damage for energy facilities are given.

1. INTRODUCTION

Energy systems (electricity, gas supply, oil supply, heat supply) are key elements of critically important infrastructures, as they provide the required quality of life for the population, as well as create the necessary conditions for the reliable functioning of various sectors of the economy. Most energy facilities are hazardous production facilities and that is why one of priorities is to ensure their safe functioning. There is several approaches, methods and tools for ensuring the safe and safety functioning of such facilities (regulatory, organizational, engineering, economic), in recent years considerable attention has been paid to proactive safety methods. Within the framework of these methods, the main efforts are aimed at early identification of violations and deviations in the operation or maintenance of the energy facility and their elimination before violations and deviations become prerequisites for events with negative consequences.

The building and use of the safety pyramid is one of the areas of a proactive approach implementation. For the first time, the safety pyramid was built by H. Heinrich (Heinrich, 1959), he proposed a certain ratio between industrial accidents with different degrees of severity of consequences. In later works, F. Byrd developed an idea of building the safety pyramid for analyzing events in

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the field of industrial safety and supplemented it with new levels. Currently, safety pyramids are used as a convenient form of graphical interpretation of statistical data as well as one of the safety tools for hazardous production facilities. In particular, opponents of a wide interpretation of the pyramid pointed out that in their works neither H. Heinrich nor F. Byrd ever pointed to a direct connection between the lower level and the upper levels of the pyramid. On the other hand, it is this connection that, in principle, allows us to talk about the possibility of justifying measures to reduce the risk of incidents, even if the levels of events are only partially related (Lesnykh et al, 2021). Also the paper (Lesnykh et al, 2021) describes an approach to assessing expected prevented damage to events in the field of industrial safety.

The earlier studies required the statistical data analysis of misfortunes and events in the field of industrial safety of varying severity for the energy industries. Such an analysis was necessary for the building of a generalized safety pyramid, considering the results of inspection control activity at the facilities of oil and gas industry.

2. SAFETY PYRAMID ANALYSIS IN THE FIELD OF LABOR SAFETY

One of the tasks of the present study was in assessing the sustainability of the ratios of the number of events at different levels of the safety pyramid.

First of all, the data on labor safety events contained in the reports of the International Organization of Gas and Oil Producers (IOGP) were analyzed. This organization considers four levels of severity of events: fatalities; severe injuries; minor injuries; microtraumas (Safety performance…, 2019; Safety performance…, 2020). The results of the calculation of the ratios between number of events for these categories in some regions of the world in 2019 and 2020 are presented in Table 1.

Table 1. Coefficients of safety pyramid of labor safety incidents at oil and gas facilities for different regions

Level of event	The whole world		Europe		North America		Asia and Australia	
	2019	2020	2019	2020	2019	2020	2019	2020
Fatalities	1	1	1	1 (0)	1	1	1	1
Severe injuries	28	38,5	114	170	17,6	27,5	77	15,7
Minor injuries	26	27,3	52	68	27,8	39	117	25,3
Microtraumas	55,5	56,2	144,5	185	56	69	161	35

The analysis of the data shows that the ratio between the levels of the safety pyramid varies significantly not only for different regions, but also for different periods of time. In addition, they are significantly different from the coefficients of classical Heinrich pyramid.

Further, we considered the results of the analysis of statistical data on events in the field of labor safety for the oil and gas industry (oil and gas production facilities, hydrocarbon transport and storage facilities, hydrocarbon processing facilities) for the period 2016-2020 according to the data of the Federal Service for Environmental, Technological and Nuclear Supervision of the Russian Federation (Annual report…, 2016; Annual report…, 2017; Annual report…, 2018; Annual report…, 2019; Annual report…, 2020). It should be noted that unlike IOGP statistics, Rostekhnadzor reports provide only data on the number of fatalities, as well as data on the number of detected violations in the field under consideration (labor safety). Table 2 shows data on the ratio of the number of detected violations to the number of fatalities at oil and gas facilities.

Table 2. Ratio of detected violations to incidents

	2016	2017	2018	2019	2020	Period average
Ratio of detected violations to number of fatalities	3074	4782	5676	4000	3725	4251

The analysis of Table 2 data shows a relatively small variation in obtained coefficients, but the maximum deviation from the average for the period is quite large (33.5% for fatalities).

Further we considered the results of the analysis of statistical data on events in the field of labor safety at the corporate level (PJSC Gazprom). Statistics on misfortunes (fatal, severe, light, detected violations) at PJSC Gazprom production facilities for the period of 2008-2019 derived from internal annual reports were analyzed. Based on the initial data, correlation analysis was performed to determine the linear dependence between the number of incidents of different levels. Pearson correlation coefficient was calculated between different types of injuries. The results of the analysis are given in Table 3.

Table 3. Results of correlation analysis (correlation coefficient)

	Minor injuries	Severe injuries	Fatalities
Minor injuries	1		
Severe injuries	0.8765	1	
Fatalities	0.5666	0.6946	1

The interpretation of the obtained correlation coefficient value depends on the purpose and context. A correlation of 0.8 can be considered very high in social sciences with a lot of factors, but also be very low to test physical laws using high-quality tools.

For this reason, the correlation coefficient value was assessed by Chaddock and E.P. Golubkov scales. The connection between events with minor and severe injuries is assessed as high, between fatal and severe injuries as medium and the degree of connection between fatal and minor injuries is defined as weak. A high correlation coefficient between events with minor and severe injuries represents a significant importance.

The authors proposed to add a lower level to the standard levels of the safety pyramid - violations detected during inspection activity. Analysis of the ratios of the number of events between the levels of the extended safety pyramid (ratio of the number of events at the i-th level to the number of fatal events cumulative) is given in Table 4.

Table 4. The ratio between the events of the safety pyramid in the field of labor safety and health cumulative

Year	Fatalities	Severe injuries	Minor injuries	Detected violations
2006	1	2.9	8.1	-
2007	1	2.1	5.2	-
2008	1	2.3	5.7	2866
2009	1	2.5	6.3	2471
2010	1	2.5	6.3	2054
2011	1	2.3	6.	1784
2012	1	2.3	6.1	1834
2013	1	2.3	6.7	1976
2014	1	2.2	6.2	1816
2015	1	2.2	6.5	1870
2016	1	2.2	6.6	1944
2017	1	2.2.	6.6	1879
2018	1	2.3	6.8	2070
2019	1	2.2	6.5	2092

The performed analysis of statistical data of events in the field of labor safety at PJSC Gazprom made it possible to establish that there are relatively stable ratios between events of different levels of the safety pyramid. This allows to use these ratios to assess the expected prevented damage. The ratios of the events in the field of labor safety for oil and gas facilities are got and recommended in the paper. They are presented in Table 5.

Table 5. Recommended safety pyramid coefficients values in the field of labor safety

Events in the field of labor safety	Calculated (recommended) values of events conversion factor coefficient
Fatalities	1
Severe injuries	2.2
Minor injuries	6.5
Detected violations without consequences (inconformities, deviations)	2055

To assess the number of possible events of different levels, let us suppose that as a result of inspection control activity, N_I inconformities (violations, deviations) were detected and during the year the share of eliminated violations is D_I. Then it can be supposed that measures to detect and eliminate violations potentially prevented a number of events, including incidents and accidents. It is noteworthy the fact that the prevented damage is determined by the possible events that could have occurred if the identified violations had not been eliminated.

It is advisable to assess the value of expected prevented damage for events in the field of labor safety for detected and eliminated violations in accordance with the following formula:

$$W = (1 + w_{\text{косв}}) N_I D_I \sum_{i=1}^{I-1} \frac{1}{K_{I-i+1}} \bar{Y}_i , \qquad (1)$$

where N_I is the number of violations detected during the year as a result of inspections; I is the number of pyramid levels; D_I is the share of eliminated violations; K_i is the coefficient of the i-th level of the safety pyramid; $\bar{Y}_i$ is the average value of direct damage from one event, at the i-th level of the safety pyramid; $w_{\text{косв}}$ is the share of indirect damage.

The N_I value is determined based on statistical data based on the results of inspections.

Assessment of the number of possible events at different levels of the safety pyramid is carried out for a given number of detected violations N_I in accordance with the following formula:

$$N_i = \frac{N_I}{K_{I-i+1}}, \qquad (2)$$

where $i = 1$ corresponds to fatal incidents, $i = 2$ - to incidents with severe injuries, $i = 3$ - to minor injuries.

To assess the direct and indirect expected prevented damage using the safety pyramid, we will consider that the inspection control activity revealed 25 thousand violations during the year, of which 90% were eliminated during the year. Using the obtained ratios between the levels of the safety pyramid in the field of labor safety (Table 5), with using the formula (2) we get the following values of prevented events: fatalities - 11, severe - 24, minor - 72. Analysis of statistical corporate data of PJSC Gazprom shows that the average payments per one accident are: fatalities - 6 million rubles, severe - 310 thousand rubles, minor - 90 thousand rubles subsequently, the direct prevented damage will be about 80 million rubles. The ratio between direct and indirect damage is an independent problem and varies quite widely. The ratio of 1:6 (Timofeev, 2009) can be used for preliminary assessments. In this case, the indirect prevented damage will be about 480 million rubles, and the total expected prevented damage for events in the field of labor safety will reach 560 million rubles.

3. SAFETY PYRAMID ANALYSIS IN THE FIELD OCF INDUSTRIAL SAFITY

Further, the paper analyzed the ratios between the events of the "safety pyramid" for industrial safety. It should be noted that in modern papers it is investigated what factors influence the shape of the safety pyramid in the field of industrial safety. For example, papers (Bellamy et al, 2008; Gilbert et al, 2018) show that the ratio of the number of events at different levels can depend on the type of activity and the risks considered. In addition, it should be noted that the identified conformities in the Heinrich and Byrd safety pyramids are used to justify measures to improve industrial safety in various sectors of the economy. As an example, papers in the field of railway transport (Tishanin at al., 2011; Lakin et al, 2013), the oil and gas industry (Penkey & Siddiqui, 2015), shipping (Johansen et al, 2019), etc.

Analysis of publications on this topic allows us to draw the following conclusions: despite the critical attitude to the possibility of practical application of level coefficients in the Heinrich and Byrd pyramids, it is inappropriate to deny the connection between levels (influence of levels); even a weak connection allows us to say that eliminating the sources of events (violations, inconsistencies) of the lower level of the pyramid for industrial safety events can potentially prevent events at the upper levels.

Further, we will consider the results of the analysis of statistical data on industrial safety events for the oil and gas industry (oil and gas production facilities, hydrocarbon transport and storage facilities, hydrocarbon processing facilities) for the period of 2016-2020 according to the data of the Federal Service for Environmental, Technological and Nuclear Supervision of the Russian Federation (Annual report…, 2016; Annual report…, 2017; Annual report…, 2018; Annual report…, 2019; Annual report…, 2020). Rostekhnadzor reports provide data on the number of accidents, as well as data on the number of detected violations in the field of industrial safety. Table 6 shows data on the ratio of the number of detected violations to the number of fatalities at oil and gas facilities.

Table 6. Ratio of the number of detected violations to the number of accidents

	2016	2017	2018	2019	2020	Average for the period
Ratio of the number of detected violations to the number of accidents	1431	1467	1723	2076	1354	1610

Analysis of the data of Table 6 shows a relatively small variation in the ratio of the number of events to the number of detected violations, however, the maximum deviation from the average for the period is quite large (28.9% for accidents).

Within developing an approach to assessment of the expected prevented damage, the statistics of events at PJSC Gazprom production facilities for the period of 2015-2020 were analyzed in accordance with the accepted classification (Safety Manual…, 2018). An analysis was performed on the number of accidents (level 1), incidents (level 2) and unconformities (level 5), data on levels 3 and 4 have been collected from the beginning of 2019 and are not representative. Levels 1-4 correspond to the classification levels of events given in Table 7, and level 5 corresponds to the level of violations (unconformities) detected during inspections.

Table 7. Classification of events in the field of industrial safety (Safety Manual…, 2018)

Level of event	Technogenic event	Danger features of technogenic event
1	Accident	Destruction of structures and/or technical devices used at a hazardous production facility, uncontrolled explosion and/or release of hazardous substances
2	Incident	Failure or damage of technical devices used at the hazardous production facility, deviation from the installed process mode
3	Prerequisite to incident	Change in the process parameters of the hazardous production facility operation mode, which may lead to an incident
4	Event of the 4th level	Changes in process parameters and/or disturbances in the operation of the industrial safety management system, which may lead to prerequisites for incidents

The analysis of statistical data shows that the ratio of events of different levels clearly does not correspond to the Heinrich conformity, which is quite expected, since they do not relate to injury statistics. In order to establish the level ratios for events related to industrial safety, the total indicators for the period under consideration were analyzed, including data on the number of detected violations. In this case, we obtain the conformity shown in Table 8.

Table 8. Safety pyramid coefficients in the field of industrial safety

Level of events	Sum of the events for the period	Calculated ratio	Recommended ratio, *Ki*
Accidents	33	1	1
Incidents	100	3,3	3
Prerequisite to incident (technologic)	no data		30
Prerequisite to incident (organizational)	no data		300
Violations without consequences (unconformities, deviations)	81 457	2627	3000

In order to assess the amount of expected prevented damage to industrial safety events in accordance with formulas (1) and (2), it is necessary to assess the average damage from a single accident or incident. Analysis of statistical data on accidents at PJSC Gazprom facilities shows that events in the period of 2015-2018 mainly occurred at gas trunk transport facilities (gas trunk pipelines - more than 75%, compressor stations - more than 5%, condensate pipelines - about 12%, etc.). The maximum possible damage at the listed facilities can be assessed using the corporate standard (Gazprom Recommendation…, 2019). Taking into account the corresponding share of the type of emergency facilities and the recommended values of damage, the average direct damage can be about 50 million rubles per accident.

It is advisable to assess damage from an incident using statistical data. Analysis of statistical data at PJSC Gazprom facilities for the period of 2015-2020 made it possible to assess the specific damage per incident, which is 4.5 million rubles.

Let us suppose that inspection control activity during the year revealed 25 thousand violations, the share of eliminated violations is 90% (corresponds to the indicators of 2018). Using the data of Table 7, it can be assumed that 8 accidents and 25 incidents were prevented. Taking into account the average direct damage, the prevented direct damage can be about 400 million rubles and 112.5 million rubles from incidents. Total direct damage will be 512.5 million rubles.

The amount of indirect losses in relation to direct losses is not constant, but varies depending on the type of production facility, type of production, range of production, etc. According to (Arkhipets, 2005), this ratio for the main industrial sectors can vary from 30 to 300%. In the same paper, based on the analysis of a number of studies, it was found that between the damage from the failure of industrial equipment and the total losses of the enterprise connected with the restoration of production, downtime and other economic losses there may be a larger ratio from 1:14 to 1:23. That is, indirect damage can be by an order and more superior to direct damage.

As a conservative assessment of potential indirect prevented damage, the ratio of 1:5 may be considered. In this case, indirect prevented damage will be 2562,5 million rubles. Thus, the total prevented damage will be more than 3 billion rubles.

4. GENERALIZED APPROACH TO ASSESSING EXPECTED PREVENTED DAMAGE

In general, inspection control activity at the corporate level may involve the operation of several types of inspection. For example, currently several inspections operates within PJSC Gazprom's corporate inspection body: technical, environmental, energy, construction, etc. In this case, it is possible to generalize formula (1), which will be as follows:

$$W_{\text{сумм}} = \sum_{m=1}^{\text{M}} \left[\left(1 + \text{w}_{\text{косв}}^{(m)}\right) N_I^{(m)} D^{(m)} \sum_{\text{i}=1}^{I^{(m)}-1} \frac{1}{\text{K}_{I^{(m)}-\text{i}+1}} \bar{Y}_i^{(m)} \right], \tag{3}$$

where M is a number of types of inspection; $N_I^{(m)}$ is a number of detected violations of m - th inspection.

In this case, it is possible to assess the total expected prevented damage for all types of inspections, which makes it possible to assess the effectiveness of the activity of all corporate control.

The possibility of using formula (3) is limited by a number of factors. First of all, it is necessary to have a classification of incidents by severity for each type of inspections. To obtain the conversion factor of the number of events at the i-th level of the safety pyramid, it is necessary to have a representative set of statistical data for a period of at least 5 years for each type of inspection. Further, the inspection objects should be relatively homogeneous, for example, production objects of one sector or company.

5. CONCLUSION

The analysis of statistical data on labor safety events for different levels of the hierarchy (the whole world, continents, energy industry, energy company) showed that the ratio between the number of events at different levels significantly depends on the facility under consideration, and the ratios characteristic for the classical Heinrich safety pyramid are practically not fulfilled. This conclusion confirms the fact that a stable ratio between the levels of the safety pyramid is characteristic only for relatively homogeneous industrial facilities (sector, company).

This paper provides stable ratios between the levels of the safety pyramid in the field of labor safety and in the field of industrial safety for oil and gas facilities within a single company. It is shown that using the safety pyramid and the indicator of the number of detected violations for the oil and gas company, assessments of the expected prevented damage can be obtained. This indicator can serve as one of the indicators of the effectiveness of corporate inspection control.

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